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Invited 45

Plenary

I451 - Hidden, Entangled and Resonating Orders

Plenary

Nicola Spaldin[1]
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The concept of magnetic dipolar order -- for example ferro, ferri or antiferromagnetic -- is at the core of our understanding of the behavior of magnetic materials, and is invaluable in selecting and tailoring them for applications. Sometimes, however, magnetic materials surprise us, and behave in ways that can not be captured within our established paradigms, suggesting additional kinds of order that are not yet identified. The indicators and implications of such ``hidden order'' are the subject of this talk. Using multiferroic composite order consisting of coupled electric and magnetic dipoles as a model, I will first discuss hints of static hidden order in existing materials, the intriguing behaviors that such hidden order causes, and experimental efforts that could unambiguously reveal it. Next, I will describe new physics that can emerge when the order is explicitly quantum mechanical, specifically the occurrence and signatures of multiferroic quantum criticality. Finally, I will explore dynamical order, in which thermal effects or an external drive cause a time evolution of the coupled quantum mechanical wavefunctions. I will outline promising future directions in the heroic effort to unearth, explain and exploit these hidden, entangled and resonating orders, which will doubtless keep us entertained for many years to come.

I452 - Hysteresis design of magnetic materials for efficient energy conversion

Plenary

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Magnets are key components of energy-related technologies, such as direct drive wind turbines and e-mobility. They are also important in robotics and automatisation, sensors, actuators, and information technology. The magnetocaloric effect (MCE) is of strong interest for new and disruptive solid state-based refrigeration. Magnetic hysteresis – and its inherent energy product - characterises the performance of all magnetic materials. Despite considerable progress in the modelling, characterisation and synthesis of magnetic materials, hysteresis is a long-studied phenomenon that is still far from being completely understood. Discrepancies between intrinsic and extrinsic magnetic properties remain an open challenge and magnets do not operate yet at their physical limits. The design of hysteresis for the magnets for the above applications requires an expanded detailed knowledge on different length scales. Ultimately, new strategies for effective magnetic hardening mechanisms of permanent magnets resisting high external magnetic fields and temperatures and for strong thermomagnetic responses in low fields of magnetocaloric materials will need to be derived.

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I453 - Magnetoplasmonic nanodomes as a novel structure for biomedical applications

Plenary

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[2] Universitat Autònoma de Barcelona, Bellaterra, Spain

[3] CIC nanoGUNE, Donostia-San Sebastian, Spain

Advanced nanobiomedical applications have been traditionally based on chemically synthesized inorganic nanoparticles. Here we present a novel type of structure especially suited for diverse biomedical uses: magnetoplasmonic nanodomes [1,2]. The nanodomes are composed of a combined, magnetic and plasmonic, hemispherical shell deposited onto 100 nm diameter polystyrene beads. The variation of the materials and their thicknesses in the shell enables tuning both the optical and magnetic properties of the nanostructures. The very high plasmonic absorption of the nanodomes in the near-infrared is used for very efficient local optical heating, i.e., photo-hyperthermia for cancer treatment [1]. The nanodomes magnetic character allows to remotely manipulate them to easily regulate the level of photo-hyperthermia. Moreover, given their asymmetric shape they exhibit strong optic and magnetic anisotropies. Thus, the rotation of the nanodomes using alternating magnetic fields can easily tracked optically using their different absorption depending on the orientation. Since the rotation of the nanoparticles depends strongly on the viscosity of the medium, which in turn depends on the temperature, the optical tracking of the rotation can be used to accurately determine the local temperature around the nanodomes, i.e., nanothermometry [2]. Combining the nanodomes efficient photo-hyperthermia with their nanothermometry capabilities, allows in-situ tracking the efficiency of photo-hyperthermia treatments.

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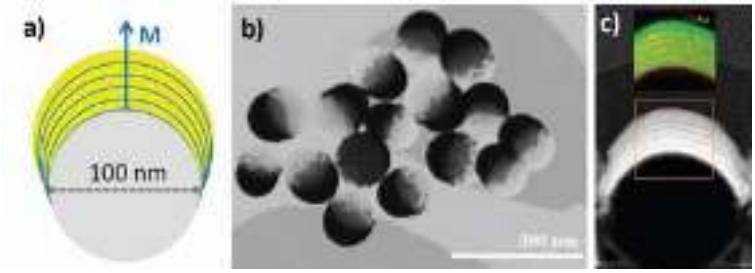

I454 - Novel functions observed in a topological antiferromagnet

Plenary

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Recently a chiral antiferromagnet Mn_3Sn has been demonstrated to exhibit a large anomalous Hall effect (AHE) at room temperature, the magnitude of which reaches almost the same order of magnitude as in ferromagnetic metals irrespective of a tiny spontaneous magnetization of about 1 mT [1]. The first principle calculation revealed that this large AHE originates from a significantly enhanced Berry curvature associated with the formation of Weyl points near Fermi energy [2,3]. Even more recently detailed comparison between angle-resolved photoemission spectroscopy (ARPES) measurements and density functional theory (DFT) calculations revealed significant bandwidth renormalization and damping effects due to the strong correlation among Mn 3d electrons. Magnetotransport measurements provide strong evidence for the chiral anomaly of Weyl fermions, i.e. the emergence of positive magnetoconductance only in the presence of parallel electric and magnetic fields. In this way all the characteristic electronic properties of Mn_3Sn implies that spin Hall effect (SHE) could also take place in the Mn_3Sn [4].

In this study we set up our device that consists of ferromagnetic NiFe (blue squares) and non-magnetic Cu electrodes formed on the top surface of a micro-fabricated single crystal of Mn_3Sn. We found that antiferromagnets have richer spin Hall properties than non-magnetic materials, that is, in the non-collinear antiferromagnet Mn_3Sn, the SHE has an anomalous sign change when its triangularly ordered moments switch orientation (see figure). Our observations demonstrate that a novel type of contribution to the SHE (magnetic SHE, MSHE) and the inverse SHE (MISHE) that is absent in nonmagnetic materials can be dominant in some magnetic materials, including antiferromagnets. We attribute the dominance of this magnetic mechanism in Mn_3Sn to the momentum-dependent spin splitting produced by the non-collinear magnetic order. This discovery further expands the horizons of antiferromagnet spintronics, and motivates a more universal outlook on spin-charge coupling mechanisms in spintronics [5].

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[3] H. Yang, *et al.*,New J. Phys. **19**, 015008 (2017) .
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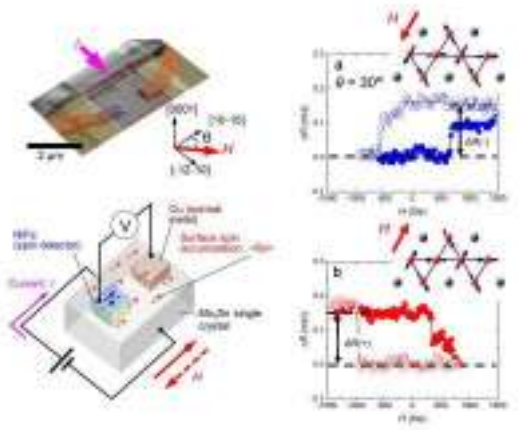

I455 - Spin meet electric dipoles: modelling, discoveries and perspectives

Plenary

Silvia Picozzi[1]

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The discovery of novel properties, effects or phenomena in modern materials science is often driven by the quest for the coexistence and/or coupling of several functional properties into a single system. Within this framework, I will focus on the microscopic mechanisms leading to the interplay between spin and dipolar degrees of freedom, along with their theoretical modelling. I will first address the coupling of long-range magnetic and electric dipolar orders in multiferroics, in particular in electronic ferroelectrics, where the spin/charge/orbital order induces an electric polarization. Second, I will discuss (non-magnetic) ferroelectric semiconductors, where the spin-orbit interaction leads to a tight link between Rashba spin-splitting in the electronic structure, spin-texture and electric polarization.
The common denominator is to achieve the electric-field control of magnetism and, therefore, the long-sought integration of spintronics with ferroelectricity.

Invited 40

Semi-Plenary

I401 - Artificial crystals and quasicrystals for nanomagnonics

Semi-Plenary

Dirk Grundler[1]

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Artificial crystals consisting of periodically modulated ferro- and ferrimagnetic thin films have generated large interest for mastering magnons on the nanoscale and functionalizing them in view of wave-based logic and computation (1). Specifically tailored magnonic crystals were operated as grating couplers (2) and exhibited reprogrammable magnon band structures (3). Here, artificial quasicrystals based on aperiodically patterned magnets represent an interesting alternative as non-stochastic switching suggests reprogrammable states controlled via global magnetic fields (4). Still, their experimental exploration in magnonics is at its infancy.

We have created and studied planar magnonic crystals and quasicrystals nanopatterned from either metallic ferromagnets (such as Permalloy and CoFeB) or the insulating ferrimagnet yttrium iron garnet via lift-off processing or plasma ecthing. Using broadband microwave spectroscopy, inelastic light scattering, micromagnetic simulations and magnetic imaging techniques we investigated one-dimensional and two-dimensional periodic lattices and aperiodic tilings (such as Penrose P2, P3 and Ammann tilings). Relevant feature sizes and lattice constants varied from about 100 to 800 nm. In case of aperiodic antidot lattices based on Penrose tilings we discovered worm-like nanochannels. They promise an unexpected functionality in that they offer dense wavelength-division multiplexing of magnons on the nanoscale.

The work has been performed in cooperation with K. An, K. Baumgaertl, V. Bhat, P. Che, C. Dubs, F. Kronast, and S. Watanabe. It is funded via EPFL COFUND Grant No. 665667 (EU Framework Programme for Research and Innovation (2014-2020) and through SNF under grant numbers 163016 and 171003.

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I402 - Complex domain interconnections in multiferroics

Semi-Plenary

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[1] ETH Zürich, Switzerland

The coexisting magnetic and electric order in the so-called magnetoelectric multiferroics leads to unique phenomena on the level of domains and domain-walls. A well-known example is the one-to-one coupling of antiferromagnetic and ferroelectric order in type-II multiferroics with spin-induced ferroelectricity, which can be used to generate ferroelectric head-to-head or tail-to-tail domain walls usually forbidden in conventional ferroelectrics. At the same time, the rigid coupling makes the independent manipulation of magnetic and ferroelectric domains almost impossible. Due to their inherently independent multiferroic orders, type-I multiferroics, on the other hand, allow for a higher degree of control over domain structures, but are also known for their comparable weak magnetoelectric coupling. Here, I will demonstrate that using multiferroics with three or more order parameters will combine the respective advantages of type-I and type-II multiferroics without showing their disadvantages. As an example, I will discuss the inversion of domains, i.e. the local reversal of the order parameters with an external field in each domain while not changing the overall domain pattern. Domain inversion in a magnetic or electric field is observed in the three-orderparamter systems Co_3TeO_6, Mn_2GeO_4, and $Dy_{0.7}Tb_{0.3}FeO_3$. The latter compound additionally allows the controlled transfer of a magnetic into a ferroelectric domain pattern and vice versa. On the level of domain walls, $Dy_{0.7}Tb_{0.3}FeO_3$ shows another uncommon behaviour, i.e. the existence of mulltiferroic domain walls in a purely antiferromagnetic environment. Finally, I will discuss the coupling of ferroelectric, antiferromagnetic and multiferroic order in hexagonal manganites. On a microscopic level, this coupling leads to novel types of magnetoelectric domain walls and vortex-like magnetic singularities. As a central technique to all the examples discussed here, we deployed nonlinear-optical microscopy. Nonlinear-optics in form of second-harmonic generation has been established as a versatile technique to its ability to simultaneously observe the multitude of complex ferroic orders in multiferroics.

I403 - Enhanced spin pumping into superconductors provides evidence for superconducting pure spin currents

Semi-Plenary

Chiara Ciccarelli[1]

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Unlike conventional spin-singlet Cooper pairs, spin-triplet pairs can carry spin. Triplet supercurrents were discovered in Josephson junctions with metallic ferromagnet spacers, where spin transport can occur only within the ferromagnet and in conjunction with a charge current. Ferromagnetic resonance injects a pure spin current from a precessing ferromagnet into adjacent non-magnetic materials. For spin-singlet pairing, the ferromagnetic resonance spin pumping efficiency decreases below the critical temperature (Tc) of a coupled superconductor. Here, we present ferromagnetic resonance experiments in which spin sink layers with strong spin–orbit coupling are added to the superconductor. Our results show that the induced spin currents, rather than being suppressed, are substantially larger in the superconducting state compared with the normal state; although further work is required to establish the details of the spin transport process, we show that this cannot be mediated by quasiparticles and is most likely a triplet pure spin supercurrent.

I404 - Field- and Pressure-induced phases in spin-orbit-coupled frustrated models and materials

Semi-Plenary

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In the search for novel materials' properties, the generation and manipulation of highly entangled quantum states is a grand challenge of solid state research. Amongst the most entangled proposed states are quantum spin liquids. In this context, the exactly solvable Kitaev Z_2 spin-liquid model, for which finely tuned anisotropic interactions exactly fractionalize spins into fermionic Majorana spinons and gauge fluxes has activated an enormous amount of interest. Most specially since possible realizations may be achieved in octahedral coordinated spin-orbit-coupled 4d5 and 5d5 insulators. However, the low symmetry environment of the known Kitaev materials also allows interactions beyond the Kitaev model that open possible new routes for further exotic excitations.

Based on *ab initio* and many-body simulations and comparison to experimental observations, we will discuss in this talk, the challenges that one faces in designing such materials and in identifying the origin of their excitations. We will further present recent results on possible field- and pressure-induced phases obtained by adding to the Kitaev model further interaction terms and will discuss the relevance of the results in relation to honeycomb iridates and α-$RuCl_3$.

I405 - Nanoscale magnetoelectric effects revealed by high-resolution imaging

Semi-Plenary

Neil D Mathur[1]

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I will present high-resolution imaging of ferromagnetic domains that undergo electrically driven switching via strain-coupling to ferroelectric domains. First, I will show XMCD-PEEM images of Ni films in which sub-90° switching reveals a hitherto unappreciated shear strain due to ferroelectric domain switching in PMN-PT substrates. Then I will show large magnetoelectric coupling between epitaxially grown manganite films that were transferred to a ferroelectric substrate of much larger lattice parameter. [Photoemission electron microscopy (PEEM) with magnetic contrast from x-ray magnetic circular dichroism (XMCD) was performed at Diamond Light Source (UK), PMN-PT is $0.68Pb(Mg_{1/3}Nb_{2/3})O_3$-$0.32PbTiO_3$.]

I406 - Single-layer spin and orbitronics in a compensated ferrimagnet

Semi-Plenary

Karsten Rode[1]

[1] CRANN, AMBER and School of Physics, Trinity College Dublin, Ireland

Antiferromagnets and compensated ferrimagnets offer opportunities to investigate spin dynamics in the `terahertz gap' because their resonance modes lie in the 0.3 to 3 Thz range. The compensated ferrimagnets are especially interesting as they combine the negligible net moment of antiferromagnets with a high (full) spin polarisation of the charge carriers close to the Fermi energy, leading to strong magnetoresistive effects. This unique combination of properties may in the future form the building blocks of chip-sized solid-state non-linear electronic components that will allow heterodyne modulation and demodulation with bandwiths exceeding the current state of the art by one to three orders of magnitude.
Despite some inherent advantages when compared to ferromagnets, these materials have not yet been extensively studied due to difficulties in exciting and detecting the high-frequency spin dynamics, especially in thin films. In this contribution we show that in a single layer of the highly spin-polarized, compensated ferrimagnet Mn_2Ru_xGa, spin-orbit torque resulting from spin-orbit interaction in crystals that lack inversion symmetry is remarkably efficient at generating effective fields $\mu_0 H_{\mathrm{eff}}$. They approach 0.1×10^{-10} T/(Am^2) in the low-current density limit -- almost a thousand times the Oersted field, and one to two orders of magnitude greater than the effective fields in heavy metal/ferromagnet bilayers. In order to compensate the magnetic losses during precession, the current-induced fields need to include an anti-damping component. From an analysis of the harmonic Hall effect which takes account of the thermal contributions from the anomalous Nernst effect, we show that the antidamping component of the spin-orbit torque is three times stronger than the field-like component and that it is sufficient to sustain self-oscillation. This result demonstrates that spin electronics has the potential to underpin energy-frugal, chip-based solutions to the problem of ultra high-speed information transfer.

I407 - Spin Dynamics in Complex Magnetic Nanostructures for Magnonics

Semi-Plenary

Adekunle Adeyeye[1] , *Goei Shimon*[1], *Arabinda Haldar*[1], *Chang Tian*[1]

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Advances in nanofabrication and novel detection techniques are providing researchers worldwide with unprecedented understanding of magnetization reversal and control of their dynamic behavior at nanoscale. This talk will be divided broadly into two parts:

The first part will focus on the direct probing of magnetization dynamic of individual elements (such as dots and rings) using micro-focused Brillouin light scattering (BLS) spectroscopy. The role of dipolar coupling on the dynamic behavior of individual disk has been directly mapped in as systematic way using pairs of identical $Ni_{80}Fe_{20}$ disks with varied inter-disk spacing in the range from 50 nm to 500 nm . Marked spectral and spatial shift in the resonant mode is observed with increasing dipolar interaction. It is shown that when nanomagnets are placed in close proximity in an array or cluster, their lattice arrangement induces additional configurational anisotropy and largely modify their dynamic properties [1,2].

The second part will focus on design and fabrication strategies for synthesizing nanomagnetic networks with deterministic magnetic ground states [3]. Using micro BLS, Reliable reconfiguration between ferromagnetic (FM), antiferromagnetic (AFM) and ferrimagnetic ground magnetic states will be shown in rhomboid nanomagnets which stabilize to unique ground states upon field initialized along their short axis [4]. A novel waveguide consisting of dipolar coupled rhombic shaped nanomagnetic chain that eliminate the requirement of a stand-by power during operation will be presented. Spin waves signal transmission, channelling and gating operations at zero field will be demonstrated in dipolar coupled rhombic shaped nanomagnetic chain [5].

This work is supported by Ministry of Education Singapore Tier 2 funding via grant number: R-263-000-C61-112.

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I408 - The potential and challenge of molecular spins for quantum technologies

Semi-Plenary

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The spin is intrinsically a two-level system which can be coherently manipulated by electromagnetic radiation, and spin impurities in inorganic semiconductors have been proposed 20 years ago by Kane as a potential platform for quantum computing. Magnetic molecules have been widely investigated because of the many quantum effexts in their spin dynamics. More recently, molecules have been proposed as an alternative approach to other quantum bit realizations, because they have the advantage of high tunability of the relevant Spin Hamiltonian parameter through molecular design.

As far as the stringent Di Vincenzo criteria are concerned, magnetic molecules present advantages and disadvantages compared to other qubit physical realizations. Decoherence is clearly an issue, especially at high temperature, as a consequence of the softness of molecular lattices. A rational design of the molecule can however limit the decoherence. Our research has been focused on molecules comprising light transition metal ions with asymmetric coordination mode to reduce orbital contributions and with rigid environments preserve spin coherence even at room temperature [1].

On the other hand, molecules can be designed to host several qubits with a precise control of their interaction allowing for the realization of quantum gates and quantum simulator [2]. Molecules can also be processed to be deposited on surfaces allowing single molecule addressing through scanning tunnel microscopy as well as the realization of hybrid architectures. For instance the vanadyl-phthalocyanine molecule of Figure 1 can be deposited intact on different substrates retaining the S=1/2 features of the unpaired electron in the well protected d_{xy} orbital. When deposited on a superconductor such as Pb ultra thin films it shows a tuneable interaction of the molecular spin with the Cooper pair of the underlying superconductor[3]. Such tuneability is not achievable with atomic spin impurities.

Organization of magnetic molecules on surface is also of relevance to achieve an electric control of the interaction between molecular spin qubits, as recently proposed for defects in silicon. Recent results by employing electrically modulated EPR spectroscopy [4] have demonstrated that the magnetic exchange interaction between molecular spins can be controlled by an electric field without relying on large spin-orbit coupling.

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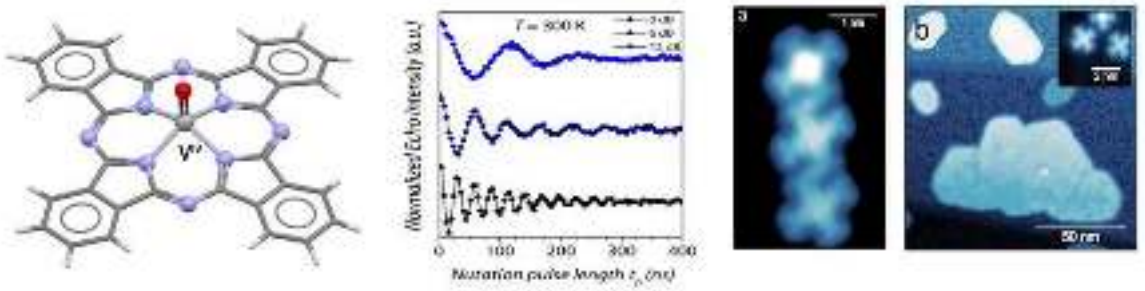

Fig. 1 Left: Molecular structure of Vanadyl-phthalocyanine (VOPc); Middle: Rabi oscillations recorded for different microwave attenuations at X-band frequency (9.3 GHz) on a sample containing 0.1% of VOPc in diamagnetic TiOPc [1]. Left: Low temperature STM of VOPc on Pb islands on Si(111)-7x7 [3].

I409 - Topological Magnon Materials

Semi-Plenary

Ingrid Mertig[1] , *Alexander Mook*[1], *Jürgen Henk*[1]
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Topology has conquered the field of condensed matter physics with the discovery of the quantum Hall effect. Since then the zoo of topological materials is steadily increasing. In this talk, I demonstrate how to realize different topological phases with magnons: the magnon pendants to topological insulators [1] as well as Weyl [2] and nodal-line semimetals are presented [3].

Magnon bulk spectra are characterized by topological invariants, dictating special surface properties. For instance, the bulk bands of topological magnon insulators (TMIs) carry nonzero Chern numbers, causing topological magnon edge states that revolve unidirectionally the sample [1]. Magnon Weyl semimetals possess zero-dimensional band degeneracies acting as source and sink of Berry curvature; at their surface they feature "magnon arcs" connecting the surface projections of Weyl points [2]. Magnon nodal-line semimetals exhibit one-dimensional band degeneracies, i. e., closed loops in reciprocal space. Surface projections of these nodal lines host "drumhead" surface states whose details depend strongly on the surface termination [3].

Similar to the electronic case, nonzero Berry curvature causes transverse transport, that is, magnon Hall effects [1]. I show how these effects can be quantified by classical spin dynamics simulations of the TMI Cu(1,3-benzenedicarboxylate) [4] and a skyrmionic TMI [5].

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I4010 - Ultrafast pathways for all-optical reversal of magnetization

Semi-Plenary

Andrei Kirilyuk[1]

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The incessant increase in the amount of digital data boosts the demand for faster, smaller, and energy-effective data-recording technologies. One viable possibility is the all-optical approach, which allows to control the magnetization of a medium using fs laser pulses only [1].

First of all, it has been demonstrated that the magnetization of ferrimagnetic RE-TM alloys and multilayers can be reversed by single fs laser pulses, without any applied magnetic field [2]. This switching is found to follow a very peculiar pathway, that crucially depends on the dynamic balance of net angular momentum, set by the two sublattices. The switching is of a toggle nature, where every next laser pulse switches the magnetization to the opposite direction.

Recently it has been shown, moreover, that the ferromagnetic Co/Pt and FePt layers can also be switched optically, with the unambiguous dependence on the light helicity [3]. However, the observed effect is multi-pulse in nature and proceeds via stochastic nucleation of reversed domains followed by a helicity-dependent deterministic growth [4].

Most exciting, recently an all-optical switching was demonstrated in transparent films of magnetic dielectrics [5]. A linearly polarized fs laser pulse resonantly pumps specific $d-d$ transitions, creating strong transient magneto-crystalline anisotropy. Selecting the polarization of the pulse changes the direction of switching. This mechanism outperforms existing alternatives in terms of the speed (less than 20 ps) and the unprecedentedly low heat load.

Moreover, yet another mechanism of laser-induced switching was found in magnetic garnets in the presence of strong in-plane magnetic field [6]. This mechanism is based on an ultrafast heating of the lattice resulting in a rapid change of magneto-crystalline anisotropy.

In this talk various switching mechanisms will be considered and compared, with the goal to provide a clear picture of the processes accompanying the reversal at these ultrafast time scales.

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Invited 30

1. Biomagnetism and medical applications

I301 - Magnetic labelling efficiency as a limiting performing indicator for magnetic biochips

1. Biomagnetism and medical applications

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Spintronic biosensors, as many other types of biosensors, rely on labels for indirect target detection and quantification, namelly, magnetic nanoparticles (MNPs). The magnetic properties (magnetic moment and susceptibility) of those particles will greatly influence sensor response, as well as the analytical figures of merit of the system [i.e. sensitivity, selectivity, limit of detection (LOD), dynamic range and signal-to-noise ratio (SNR)]. However, other factors, such as particle size, surface functionalization, clustering tendency and the number of labels per target unit (labelling efficiency), may also be determinant. For dynamic platforms (eg. magnetic flow cytometers) where target entities are detected inside a microfluidic channel while passing over the sensors, labelling efficiency and clustering phenomena are particularly critical [1].
Improvement of the labelling efficiency can be achieved through the optimization of the label bio-functionalization with a specific ligand. P*seudomonas aeruginosa,* a bacterium with growing clinical importance as a multidrug resistant pathogen, associated with serious hospital-acquired infections, was used as experimental model. When the labelled bacteria flow over the sensors, a characteristic bipolar peak is generated, which amplitude depends on the number of labels attached to the cell [2]. The maximum number of phages per MNP and maximum load of MNPs per cell, considering 250 nm diameter MNPs, were estimated to be approximately 9 phages/MNP and 50 MNPs/cell, respectively. Using this input, analytical simulations indicate maximum sensor signals of approximately 50 µV coming from those magnetically labeled cells while passing close to the sensors surface. Experimental tests were developed to assess both the MNP-phage conjugation, as well as cell labelling and capture efficiencies, using conventional biotechnology methodologies (culture plate, PFU and CFU).
Additionally, we will discuss clustering of the MNP, which may cause interference on the detection signals and lead to misanalysis and false positives [1]. Two different approaches were investigated, including the physical separation of the free particles from the labelled cells or the use data analysis algorithms to distinguish between signals coming from free magnetic MNPs (false positives) and magnetically labelled targets.
Finally, some key applications for the lab-on-chip magnetic cytometer will be described, from veterinary to human health, biodefense and food industry. Examples include the counting of pathogenic bacteria in milk, causing mastitis in dairy cows; the detection of bacteria associated with human diabetic foot ulcer on samples of pus collected from patient’s wounds; the analysis of anthrax spores in environmental air samples; or the detection of food-borne bacteria in mayonnaise samples from a packaging line. The challenges in magnetic labelling in these cases will be discussed.

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I302 - TMek: A QUANTITATIVE LAB-ON-CHIP RAPID DIAGNOSTIC TEST FOR MALARIA

1. Biomagnetism and medical applications

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The search for new rapid diagnostic tests (RDT) for malaria is a priority to fight this endemic disease, according to WHO recommendations[1]. In fact, available RDT based on the detection of antigens, suffer from several limitations: they are not quantitative, remain positive for up to 1 month after last malaria attack, exhibit prozone effect at high parasitaemia and also some false negatives. For these reasons WHO strongly recommend the development of novel RDTs with same sensitivity of the gold standard (optical microscopy examination) but a lower percentage of false positives.

In this paper, we disclose an easy to operate lab-on-chip diagnostic test, for the quantification of the plasmodium parasitaemia, which could revolutionize the world of malaria diagnostics. The method is based on the paramagnetic susceptibility of hemozoin crystals [2] (the malaria pigment produce by plasmodium as by-product of hemoglobin degradation) which are found within the infected red blood cells and free in the blood. A silicon microchip, with an array of Nickel posts underneath suitable electrodes, is put in contact with a smear of patient blood (7 microL) diluted with an anticoagulant and PBS, in the magnetic field produced by external magnets. Due to the competition between the magnetic and gravity force, only infected RBC and hemozoin crystals are attracted towards the concentrators, thus altering the impedance between electrodes. The entity of the impedance variation turns out to be proportional to the parasitemia and/or the hemozoin concentration, thus allowing for quantification.

Microchips with micron size Nickel concentrators and gold electrodes are fabricated using optical lithography and lift-off. The chip is placed in a cartridge, defining the top of a cell where the blood smear is introduced. The cartridge is then inserted in a portable reading unit, containing the external magnets and the electronics for the impedimetric detection in the MHz range.

TMek [3] has been first tested at the Sacco Hospital (Milano) on control blood samples from healthy donors as well on some samples from patients affected by malaria, diagnosed by haemoscopy and LAMP (Malaria Illumigene – Meridian EU). The test turned out to have a limit of detection for parasitaemia around 0.003%, comparable with that of available RDT, associated with an execution time of just 10 minutes, to be compared with the 20 min of current TDR. A full clinical validation in endemic zone has been instead carried out in Cameroon during April 2019 [4]. On more than 120 cases of patients suspected of malaria, we checked our TMek test against the gold standard and conventional RDT. At variance with RDT a negligible number of false positives was found, while in more than 80% of cases the result of TMek is in perfect agreement with the therapeutical decision of the doctor.

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2. Electronic structure and strongly correlated electron systems including superconductivity

I303 - ABO3 perovskites with Active A-sites

2. Electronic structure and strongly correlated electron systems including superconductivity

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We consider ABO_3 perovskites with active A site like Bi or Pb, which has extended 6s orbitals. Using ab initio electronic structure and slave rotor theory calculations, we demonstrate [1] that *hybridization-switching induced Mott transition* happens in a class of these compounds, namely $BiNiO_3$ and $PbCrO_3$. We show that these systems exhibit a breathing phonon driven A-site to oxygen hybridization-wave instability which conspires with strong correlations on the B-site transition metal ion (Ni or Cr) to induce a Mott insulator. In contrast to perovskites with passive A-site cations, these Mott insulators with active A-site orbitals are shown to undergo a undergoing pressure induced insulator to metal transition accompanied by a colossal volume collapse due to ligand hybridization switching. Finally, we contrast this situation with that of BiFeO3 or PbVO3 which shows polar distortion rather than breathing distortion of A-O sublattice. We discuss the microscopic origin of this contrast.[2]

Work carried out in collaboration with Atanu Paul, Anamitra Mukherjee, Indra Dasgupta, Arun Paramekanti

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I304 - Possible Chiral Majorana fermion in Elemental Thallium

2. Electronic structure and strongly correlated electron systems including superconductivity

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Recently, chiral Majorana modes, which are different from Majorana bound states localized at point defects have attracted considerable attention because it can be used in non-Abelian quantum computations. However, materials realization of chiral Majorana modes still remains elusive, and a variety of possibilities have been investigated. While it has been shown that a bulk spinless p+i$p$superconductor can host Majorana modes, they are expected to be fragile against impurities. Although similar situation can be realized at the interface of a topological insulator and a conventional s-wave superconductor, it is not an easy task to observe Majorana modes in a heterostructure system since the quality of the sample must be extremely high.

On the other hand, we may think about exploiting topologically non-trivial band structure in superconductors such as β-$PdBi_2$, $PdTe_2$, and $PbTaSe_2$. However, in these materials, the crossing point in the surface Dirac dispersion is energetically far away from the Fermi level. While it has been recently shown that the surface Dirac point in Fe($Te_{0.55}Se_{0.45}$) is very close to the Fermi level, it comprises of three elements and fine-tuning of the component ratio is necessary.

Given this situation, it is an interesting challenge to seek for elemental metal for which superconductivity and toplogical band structure coexist and the surface Dirac point is very close to the Fermi level. In this talk, we will present our recent first-principles calculation indicating that elemental hcp thallium is a topological superconductor, and by depositing a ferromagnetic insulator, a chiral Majorana mode will appear at the edge of the ferromagnetic island.

3. Frustrated and disordered magnetism, artificial spin ice

I305 - Magnetic monopole dynamics in spin ice: An experimental study

3. Frustrated and disordered magnetism, artificial spin ice

Elsa Lhotel[1] , *Carley Paulsen[1], Sean R. Giblin[2], Steve T. Bramwell[3], Dharmalingam Prabhakaran[4], Kayuzuki Matsuhira[5], Gheeta Balakrishnan[6]*

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Among the original magnetic states which emerge from frustrated magnetic systems, spin ice has aroused a strong interest because beyond its macroscopically degenerate ground state, the excitations can be described as magnetic charges, called magnetic monopoles.

At very low temperature, below 200 mK, spin ice dynamics is governed by these monopoles. By performing thermal quenches in spin ice compounds down to these temperatures, through a specific protocol called "avalanche quench" [1], we are able to prepare samples with a very large out-of-equilibrium density of metastable magnetic monopoles. We used this method to study the monopole dynamics in the spin ice compounds $Dy_2Ti_2O_7$ and $Ho_2Ti_2O_7$, and could measure the monopole current as a function of magnetic field [2].

In this talk, I will present some of our recent magnetization measurements which show that even below 200 mK, there is a fast recombination of magnetic monopoles. The comparison between magnetic relaxation measurements performed on several samples with different isotopes gives insights on the quantum tunneling mechanism governing the hopping of monopoles on the lattice, and shows the role of the dynamic coupling between the hyperfine fields and the electronic spins associated with magnetic monopoles [3].

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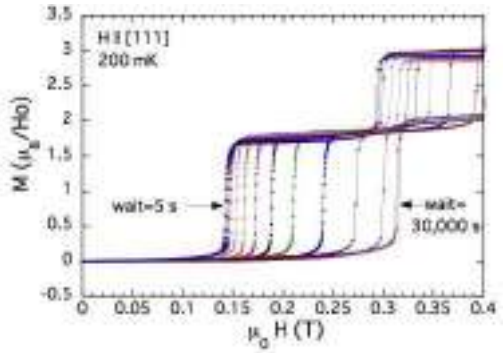

Figure 1: **Wait time dependence of magnetothermal avalanches in $Ho_2Ti_2O_7$** showing the existence of monopole recombination during the wait time. Avalanches of the magnetization were recorded while the field was ramped at 20 mT.s^{-1}. The samples were prepared using a quench protocol, called "avalanche quench", and then followed by various wait times before ramping the field.

I306 - Topological Magnetic Writing: Defining specific frustrated microstates in nanostructures

3. Frustrated and disordered magnetism, artificial spin ice

Will Branford[1]

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Networks of magnetic nanostructures are of interest across a range of topics from novel computation to magnonic crystals. One family of nanomagnetic arrays, characterized by strong and frustrated magnetic interactions are the artificial spin ices (ASI).[1] ASI structures have provided vast amounts of physical insight in recent years[1-4] in part due to their ability to model complex systems[5] and exhibit exotic phenomena such as ‘magnetic monopole’-like states[6]. The power of these networks stems from the extraordinary number of unique microstates, even in systems comprising relatively few nanostructures. However, magnetic nanoarrays in general, and ASI structures in particular, have yet to realise their full potential as the majority of microstates remain inaccessible due to the rudimentary state-writing tools currently available. An experimental means to prepare all potential microstates has huge implications, including realising ASI as a tunable-bandgap magnonic crystal[7] or reconfigurable neural-network[8]. We present a novel MFM-tip based state writing technique,[9] building on our previously demonstrated domain-wall injection process.[10] It requires no global fields and is applicable to all nanostructure architectures, providing control over the spin-configuration and access to every possible microstate. We demonstrate our method via realisation of several exotic and thus-far unobserved states, unachievable via global field-protocols: ‘magnetic monopole-defect’ chains and the spin-crystal ground state[11] of kagome ASI.

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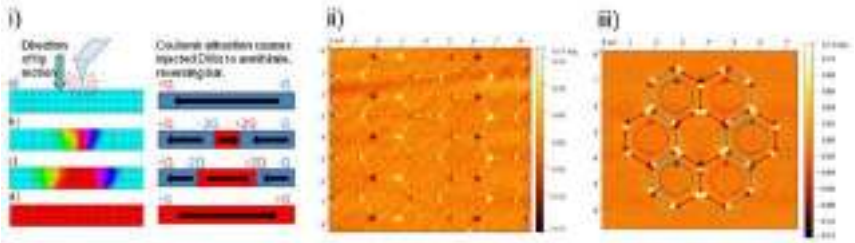

Figure 1: i) Micromagnetic simulation and accompanying schematic of writing process dynamics showing positions of magnetic charges (±Q). **ii)** MFM image of 'ladder' and 'zigzag' monopole-defect chain states written at RT on a NiFe ASI lattice. **iii)** MFM image of the spin-crystal chiral ground state of kagome ASI written at RT on a NiFe ASI rosette.

4. Magnetism in carbon-based and organic materials

I307 - 2D magnets based on metal-organic frameworks

4. Magnetism in carbon-based and organic materials

Eugenio Coronado[1] , *Javier López-Cabrelles[1], Samuel Mañas-Valero[1], Miguel Gavara[1], Guillermo Mínguez-Espallargas[1]*

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Graphene and other 2D materials are a hot focus of interest in physics, chemistry and materials science. These materials are almost exclusively based on inorganic lattices and cover a wide range of electronic and magnetic properties: from insulators to superconductors, from diamagnetic to ferromagnetic (FM) and from metallic to non-metallic compositions. They have attracted much attention in physics due to the specific 2D physics that can appear when a material approaches to the 2D limit and to the potential use of these materials as components in electronic devices in a new field known as graphene-based electronics, and in materials science since they can provide a source of advanced materials in a field known as graphene-based composites.

Still, the magnetism in the 2D limit has only been explored very recently. This has been mainly due to the chemical reactivity encountered in the exinsting families of inorganic layered magnets. Only in 2017 this topic has been put forward with the isolation and study of atomically-thin layers of the Ising ferromagnet CrI_3 [Navarro-Moratalla *et al., Nature* 546, 270 (2017)]. In this talk we will show that a molecular approach can be an alternative to obtain 2D magnets. This will be illustrated in a family of coordination polymers formed by divalent transition metal ions and imidazolate-type ligands. The resulting magnetic materials are chemically stable in open air, keeping their magnetic properties preserved upon functionalizing their surface with different organic molecules [Lopez-Cabrelles *et al.,Nature Chem.*10**,** 1001 (2018)]. In addition, they can be isolated as single layers using both top-down exfoliation techniques and bottom-up CVD techniques.

I308 - Magnetic tuning with molecular interfaces

4. Magnetism in carbon-based and organic materials

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The author has chosen not to publicise the abstract.

Field 5

Field 6

5. Magnetorecording media, magnetic memories and magnetic sensors

I309 - Curved magnetic thin films: fundamentals and applications

5. Magnetorecording media, magnetic memories and magnetic sensors

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Extending 2D structures into 3D space has become a general trend in multiple disciplines, including electronics, photonics, plasmonics and magnetics. This approach provides means to modify conventional or to launch novel functionalities by tailoring curvature and 3D shape. We study 3D curved magnetic thin films and nanowires where new fundamental effects emerge from the interplay of the geometry of an object and topology of a magnetic sub-system [1,2]. On the other hand, we explore the application potential of these 3D magnetic architectures for the realization of mechanically shapeable magnetoelectronics [3] for automotive but also virtual and augmented reality appliances [4,5]. The balance between the fundamental and applied inputs stimulates even further the development of new theoretical methods and novel fabrication/characterization techniques [6-8].

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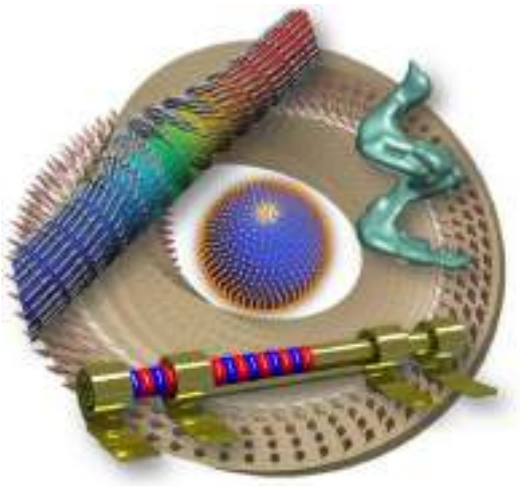

I3010 - High-density heat-assisted magnetic recording

5. Magnetorecording media, magnetic memories and magnetic sensors

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Heat-assisted magnetic recording (HAMR) is regarded by most experts as most promising storage technology of the future, which could ensure a steady increase in storage capacity over the next few years. The frequently mentioned fact that HAMR makes use of the decrease of coercivity with temperature to write hard magnetic materials such as FePt with limited magnetic fields is only half the truth when it comes to the potential of HAMR. Rather, it is the high temperature gradient that is produced during writing that supports the field gradient, enabling bits with narrow transitions. But the high temperatures that occur also cause serious drawbacks. Both hard drive manufacturers and researchers have made great efforts to understand these fundamental problems of HAMR that arise from the use of high temperature lasers and the associated high thermal noise in order to produce a reliable memory.

In my talk I would like to give an overview of what the biggest challenges of HAMR are today, what they will be in the future and how they can be overcome. I will introduce the effective recording time window model to qualitatively demonstrate how thermal noise affects and limits the storage density in an HAMR device [1]. Further, quantitative calculations will show which recording parameters are most important to achieve high density devices with high signal-to-noise ratios. Due to the timeliness of the topic, I want to show how the transition curvature of written bits can be reduced and how this affects the storage density.

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6. Magnetic thin films, multilayers, surface and interfaces

I3011 - Ab initio Insights into Spin-Orbit Phenomena (PMA and DMI) at Ferromagnet/Nonmagnet Interfaces

6. Magnetic thin films, multilayers, surface and interfaces

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First-principles insights are provided into spin-orbit coupling based phenomena such as perpendicular magnetic anisotropy (PMA) [1-6] and Dzyaloshinskii-Moriya interaction (DMI) [7-10] at interfaces comprising transition metals, insulators, or graphene. First, the nature of PMA at Fe|MgO interfaces is unveiled by evaluating orbital and layer resolved contributions to PMA in Fe/MgO interfaces and MTJs with different interfacial conditions [1-3]. Mechanisms of the optimization of effective anisotropy as well as of its electric field control are discussed [4-6]. Next, the main features and microscopic mechanisms of DMI behavior are elucidated in Co/Pt and other Co/heavy metal bilayers [7,8]. Furthermore, several approaches for DMI enhancement and manipulation will be presented including, in particular, physical mechanisms of DMI behavior in Pt/Co/MgO structures [8,9] allowing observation of room temperature skyrmions [9]. The behavior of PMA and DMI will then be addressed for nanostructures comprising Co/graphene interfaces [10,11] which may be of strong interest for graphene spintronics [12,13].

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I3012 - Low-energy muon spin spectroscopy and its application in magnetic thin films and heterostructures

6. Magnetic thin films, multilayers, surface and interfaces

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Muon spin spectroscopy (uSR) is a powerful local probe technique to address topical questions in a large variety of materials, covering fundamental and technologically relevant aspects of structural, magnetic and electronic phenomena in magnetic systems, superconductors, semiconductors, and insulators. Intense polarized muon beams with MeV energies are generated at high power proton accelerators (0.1-1MW) with proton energies between 500 MeV and 3 GeV. At muon energies of MeV the implantation depth of the muons is hundreds of micrometer in condensed matter. Therefore, uSR is usually applied to study physical properties in the bulk of a material. With the availability of low-energy positive muons with tuneable energies between 1 and 30 keV at PSI, it became possible to apply the uSR technique to investigations of thin film systems at tuneable mean depths of a few nanometers up to about 200 nm (low-energy muon spin spectroscopy, LE-uSR). In the talk we give an introduction to the low-energy muon beam facility LEM at PSI, and with selected applications in thin film and heterostructure studies, we show some of the strengths of the technique.

For instance in $LaNiO_3$ superlattices it was found that the collective phase behaviour of correlated-electron systems can be controlled by the thickness/dimensionality of the $LaNiO_3$ layers [1]. LE-uSR was essential to prove the occurence of a magnetic phase transition to an antiferromagnetic state while the system also exhibits a metal-insulator transition. Such a magnetic transition is not present if the system stays metallic.

As a second example we show the capability of LE-uSR to localize the occurence of ferromagnetic order at the interface between non-ferromagnetic layers, where electron transfer from nanometer thin Cu layers at the interface to a C_{60} layer leads to electron spin polarization at the interface [2].

Muons can be also used to study the magnetic homogeneity of a system on a nanometer scale. In a recent publication evidence for the development of a homogeneous ferromagnetic phase in epitaxial quaternary (Ga,Mn)(Bi,As) layers has been found [3]. This shows that the incorporation of a small amount of Bi, which enhances the spin-orbit coupling strength and thereby the magneto-transport effects, does not deterioate the magnetic properties. This finding is important for the application of this dilute magnetic semiconductor as a new type of non-volatile memory element, which

relies
on a nanometer scale magnetic homogeneity.

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7. Magnetism in alloys and intermetallics

I3013 - Inelastic neutron scattering to probe magnetic excitations in La(Fe,Si)x

7. Magnetism in alloys and intermetallics

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The $LaFe_{13-x}Si_x$ system (x<1.6) has a first order ferromagnetic, FM, to paramagnetic, PM, transition that is tunable in magnetic field and ends at a (tri)critical point (H_{crit}, T_{crit}) beyond which it is second order. In this large family of materials T_C can be easily tailored by changing the Fe content or by hydrogenation, and $La(Fe,Si)_{13}$ has attracted huge interest due to its potential for room temperature magnetic cooling[1] or harvesting of waste heat[2]. One of the fundamental reasons for this is that despite the magnetic transition being strongly first order, there is almost no magnetic or thermal hysteresis (an advantage for cooling applications).

We used a novel microcalorimetry method[3] to isolate the contributions to heat capacity and latent heat as a function of magnetic field and temperature, which can be used to distinguish between first and second order phase transitions. The results are compared for a series of intermetallics such as $Gd_5Ge_2Si_2$, $DyCo_2$, $LaCaMnO_3$ and $LaFe_{13-x}Si_x$ with respect to the hysteresis at the phase transition. For the $LaFe_{13-x}Si_x$ system, when x<1.6 we observed that a giant increase in the heat capacity evolved as the system approaches the tricritical point[4] and argue that this enhancement of the heat capacity is due to anomalously large spin fluctuations that are enabled by a multiple minima energy landscape.[5]

Inelastic neutron scattering of $LaFe_{13-x}Si_x$ where x=1.2 (strongly first order) and x=1.6 (tricritical point) was carried out in order to test this theory, where we found evidence of large paramagnetic fluctuations at q=0.11 A^{-1} above T_C. This suggests that enhanced magnetic scattering does indeed occur at T_C and plays a role in the evolution of the phase transition for this alloy.

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I3014 - Towards and understanding of the magnetocaloric effect.

7. Magnetism in alloys and intermetallics

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The magnetocaloric effect provides great hope for environmentally energy efficient cooling that does not rely on the use of harmful gasses. Fe_2P is a compound that has shown great potential for magnetocaloric devices. The magnetic behaviour in Fe_2P is characterised by a first order magnetic transition (FOMT) that coexists with and characterises the strong magnetocaloric effect. In this work, neutron diffraction and inelastic scattering, Mossbauer spectroscopy and first principles calculations have been used to determine the structural and magnetic state of Fe_2P around the FOMT. The results reveal that ferromagnetic moments in the ordered phase are perturbed at the FOMT such that the moments cant away from the principle directions across a small temperature region. The acoustic phonons modes reveal a temperature dependent non-zero energy gap in the magnetically ordered phase that falls to zero at the FOMT. The interplay between the FOMT and the phonon energy gap indicates hybridisation between magnetic modes strongly affected by spin-orbit coupling and phonon modes leading to magnon-phonon quaisparticles that drives the FOMT and thus the magnetocaloric effect.

8. Novel magnetic techniques

I3015 - Frontiers of magnetic force microscopy

8. Novel magnetic techniques

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Since it was first demonstrated in 1987, magnetic force microscopy (MFM) has become a truly widespread and commonly used characterization technique that has been applied to a variety of research and industrial applications. Some of the main advantages of the method includes its high spatial resolution (typically ~50 nm), ability to work in variable temperature and applied magnetic fields, versatility, and simplicity in operation, all without almost any need for sample preparation. However, the technique has historically provided only qualitative information, and the number of available modes was typically limited, thus not reflecting the experimental demands.

We present the recent progress and development of MFM as well as a summary of the current state-of-the-art techniques and objects for study. Aspects including quantitative MFM, the accurate interpretation of the MFM images, new instrumentation, probe-engineering alternatives, and applications of MFM to new (often interdisciplinary) areas of the materials science, physics, and biology are discussed. We outline the importance of the technique in emerging fields including skyrmions, 2D-materials, and topological insulators.

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I3016 - Vacuum resonance states as atomic-scale probes of surface magnetism

8. Novel magnetic techniques

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Spintronic devices raise expectations for meeting future technological demands for ever smaller and more efficient devices, exploiting the electron spin rather than its charge. Here, understanding the spin-dependent scattering of electrons at magnetic interfaces and surfaces is of high relevance for the control of electron transport. It is therefore in the focus of numerous electron reflection studies. However, atomic-scale variations of the scattering process, for example on non-collinear magnetic surfaces, remained inaccessible, due to the laterally averaging nature of the established experimental approaches.

In our spin-polarized scanning tunneling microscopy (SP-STM) experiments, we realize a spin-resolved electron vacuum interferometer on the atomic scale by placing a biased magnetic probe tip in front of a magnetic surface. Unoccupied electronic resonance states evolve between the tip and the surface that are expected to be highly sensitive to the electronic band structure of the sample. By tuning the bias, spin-polarized electrons from the tip are injected into individual resonance states, and the resulting spin-resolved tunnel current is recorded as a function of tip position [1]. Our experiments on atomic-scale spin spirals and skyrmions include a variety of resonance states, ranging from Stark-shifted image-potential states to field states [2]. With increasing electron energy, topographic features like atomic step edges tend to smear out in the microscopy image. However, the magnetic image contrast and local spin-resolved spectroscopy reveal that all resonance states with up to 20 eV above the surface Femi level are spin-split, exhibiting a local spin quantization axis that rotates on the atomic scale with the surface spin texture. Mapping the spin-dependent electron phase shift upon reflection at the surface on the atomic scale demonstrates the relevance of all magnetic ground state interactions like Heisenberg exchange, Dzyaloshinskii-Moriya and spin-orbit interactions for the scattering of spin-polarized electrons, even for energies far above the vacuum level. Experimental results will be presented and discussed in terms of magnetic contrast and the resonance state’s spin-splitting as a function of bias, as well as in terms of the atomic-scale nature of the spin-dependent electron reflection at the surface.

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9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

I3017 - Energy harvesting using thermomagnetic generators with magnetocaloric materials

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

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To date, there are only very few technologies available for the conversion of low temperature waste heat to electricity. More than a century ago, thermomagnetic generators were proposed, which are based on a change of magnetization with temperature, switching a magnetic flux, which according to Faraday's law induces a voltage. In this talk, we first describe the principle of thermomagnetic generators. Then we focus on the impact of topology of the magnetic circuit within thermomagnetic generators. We demonstrate that the key operational parameters strongly depend on the genus, i.e. the number of holes within the magnetic circuit. A pretzel-like topology of the magnetic circuit with genus =3 improves the performance of thermomagnetic generators by orders of magnitude. By a combination of experiments and simulations, we show that this topology results in sign reversal of the magnetic flux, avoids hysteresis as well as magnetic stray fields, and allows for versatile device design. Our demonstrator illustrates that this solid state energy conversion technology is on its way to become competitive with thermoelectrics for energy harvesting near room temperature. For all parameters, i.e. induced voltage, electrical output power, optimum frequency, and ratio between experiment and theory, a logarithmic scale is necessary to cover the orders of magnitude in improvement when using a topology with genus = 3. [1] In the next part of this talk we focus on the active magnetic materials used within a thermomagnetic generator. We present experiments using a thermomagnetic material close to a first-order type transition (La-Fe-Co-Si) in comparison to second-order type Gadolinium. We analyze the impact of the width of the magnetic transition and hysteresis on the conversion of thermal to electrical energy and comment on the suitabilitiy of magnetocaloric materials [2] for thermomagnetic power generation.

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I3018 - Permanent Magnets: Electrons Work to Rule

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

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The deliberately ambiguous title describes the role of electrons in permanent magnetism. They slavishly obey nature's rule and are difficult to trick into doing useful things while dominating almost all aspects of intrinsic magnetism. The two-faced role of electrons is particularly clear for elements in the middle of the iron series, such as manganese. Fully spin-polarized Mn would revolutionize permanent magnetism, but Mn often exhibits antiferromagnetic (AFM) rather than ferromagnetic (FM) exchange. It is sometimes assumed that this trend reflects the Bethe-Slater (Slater–Bethe–Néel) curve, associating the exchange with the distance between 3*d* shells, but the tetragonal alloy MnAl is a clear counterexample. In fact, the exchange is largely dominated by crystal structure and band filling, AFM exchange being particular common for half-filled 3*d* shells. On aspect of the AFM exchange is the occupancy of bonding and antibonding electron states, which is well-described by one-electron (independent-electron) theory based on a single Slater determinant, but there are also quantum spin liquid (QSL) effects involving two or more Slater determinants. Similar correlation effects are even seen in allegedly very simple systems, such as two electrons in a 2*p* shell ($S = 0$). They are more important in AFM than in FM systems and completely destroy long-range magnetic order in one dimension. In three dimensions, they yield exchange corrections that are largely ignored in present-day density-functional theory (DFT). Ground-state DFT is, in principle, exact, but little is known about the density functional, and it can be shown that finding the density functional requires the solution of the underlying many-electron problem. For example, the limitations of the local-density approximation are of the independent electron type and have little to do with the nonlocality of the density functional: the Hartree-Fock approximation is highly nonlocal but also suffers from the restriction to one Slater determinant. Many-electron effects become particularly important for the light rare earths, for example in $Nd_2Fe_{14}B$ and $SmCo_5$, where the density functional for fully localized 4*f* electrons bears little similarity with LSDA+*U* approximation. The latter is sometimes claimed to account for rare-earth correlations but yields huge errors in some cases, for example in orbital-moment and anisotropy calculations. This is of utmost practical and scientific importance in the understanding of present and search for future permanent-magnet materials. — Thanks are due to B. Balamurugan, R. Choudhary, A. Kashyap, P. Manchanda, D. Paudyal, and D. J. Sellmyer for stimulating discussions. This work is supported by DOE-BES (DE-FG02-04ER46152).

10. Micromagnetics and magnetization processes

I3019 - Micromagnetic study of THz spin-orbit torque oscillators based on antiferromagnets and ferrimagnets

10. Micromagnetics and magnetization processes

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The possibility to develop terahertz spintronics by means of antiferromagnetic materials has attracted a lot of attention from the scientific community [1]. Magnetization dynamics of antiferromagnets (AFMs) out of their equilibrium, in fact, is mainly driven by the large antiferromagnetic exchange interaction, which is the key ingredient for their resonance in the THz range [2].

In this field of research, a full micromagnetic framework for studying magnetization dynamics of antiferromagnets, in particular under the influence of spin-orbit-torques, is here presented [3]. The key idea in the modeling of those materials is considering two different sublattices which are antiferromagnetically coupled. This approach, moreover, turns out feasible also for the study of ferrimagnets (FiMs), whose sublattices have to be considered with different saturation magnetizations and gyromagnetic ratios. The magnetization dynamics of the two sublattices are calculated by solving two Landau-Lifshitz-Gilbert equations including a torque term due to the spin-Hall effect. The coupling between the two equations is directly connected with the exchange field, which takes into account the three main contributions, the inhomogeneous intralattice, the homogeneous interlattice and the inhomogeneous interlattice contributions.

Within this micromagnetic framework, antiferromagnetic spin-Hall oscillators, in particular, have been fully characterized, obtaining a successful comparison with analytical models [4]. The main device consists of an AFM layer coupled to a heavy metallic layer, as in Fig. 1(a). The AFM is square-shaped, with dimensions 40x40 nm^2, its thickness d varies from 1 to 5 nm in our study, and it is modeled with uniaxial anisotropy. The heavy metal is designed with 4 terminals that can be used to apply a charge current, and/or to read the device resistance. Dynamics of magnetizations is excited above a certain threshold current, and it is characterized by a precession of the two magnetizations $\mathbf{m_1}$ and $\mathbf{m_2}$ around the spin-Hall polarization direction **p**. However, the same dynamics can disappear at lower values of the driving current, highlighting a hysteretic behavior of the excitation. Such behavior has been studied as a function of different parameters, thickness, damping, exchange contributions, spin-Hall polarization direction [3]. The frequency of dynamics shows a blue-shift with the increase of the applied current, from hundreds of GHz up to several THz, as expected (see an example in Fig. 1(b)). The antiferromagnetic resonance frequency (AFMR) of that layer as a function of different parameters has been also studied. The most important result is that AFMR decreases with the increase of the direct electric current applied to the heavy metal and it converges to the self-oscillation frequency at the threshold current.

Self-oscillations in a ferrimagnetic spin-Hall oscillator have been also investigated. Here, frequency increases for higher saturation magnetization differences. As a counterpart, the amplitude of such oscillations decreases. This study also shows that the threshold currents decrease for higher saturation magnetization difference.

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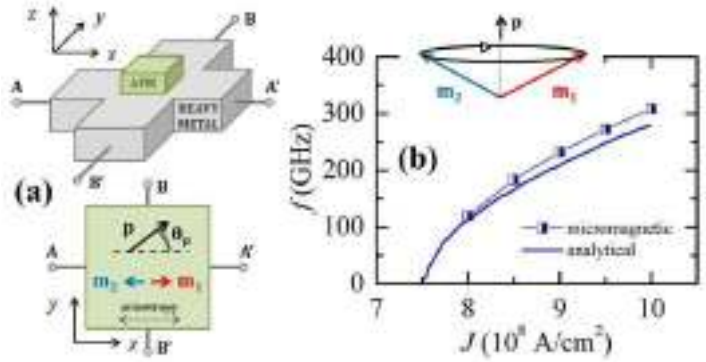

Fig.1 - (a) Antiferromagnetic spin-Hall oscillator. (b) Self-oscillation frequency vs current with (inset) sketch of the two magnetizations precessing around the spin-Hall polarization direction.

I3020 - Simulating spin-torque MRAM: From macrospin to self-consistent spin diffusion

10. Micromagnetics and magnetization processes

Claas Abert[1] , *Florian Bruckner*[1], *Christoph Vogler*[1], *Dieter Suess*[1]
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Since the enormous success of the giant magnetoresistance effect for sensor applications, a lot of research has been conducted in order to exploit spintronics effects for technological applications of all kinds. A promising example for such devices is the spin-torque magnetoresistive random-access memory (ST MRAM). Very fast read and write processes and its persistent nature result in a very low power consumption, making ST MRAM an excellent candidate for embedded applications. While first prototypes are already shipped by the industry, a number of issues still need to be resolved in order to make ST MRAM a reliable next-generation memory.
In order to understand and improve MRAM devices, numerical simulations are a valuable addition to experiments, since they allow a detailed investigation of the magnetization dynamics and give insights to the dependence of the MRAM system on system-parameter changes. The micromagnetic model is the model of choice for the description of magnetization processes at the nanoscale. However, in order to account for spintronics effects, various extensions have been proposed, each having its own limitations and drawbacks.
This talk gives an overview over a variety of models for the integration of spintronics and micromagnetics focusing on their applicability to ST MRAM. Depending on the flavor of the MRAM device, the applied models need to account for different spintronics effects such as giant magnetoresistance or tunnel magnetoresistance for the description read process and spin-transfer torque or spin-orbit torque for the description of the write process. A reasonable choice of models and algorithms should not only consider their principal applicability to the problem at hand, but also take into account their computational complexity [1].

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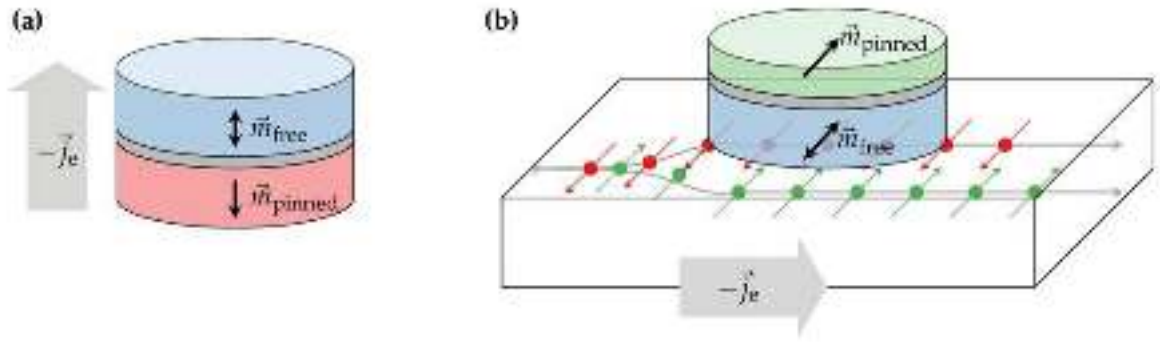

Figure 1: Schematic illustration of spin-torque MRAM (a) Spin-transfer-torque MRAM (b) Spin-orbit-torque MRAM.

11. Nanomaterials, patterned films, nanoparticles and molecular magnetism

I3021 - Coherent transfer of magnetic excitations in molecular spins and nanoparticles to microwave photons

11. Nanomaterials, patterned films, nanoparticles and molecular magnetism

Marco Affronte[1, 2] , *Claudio Bonizzoni*[1, 2], *Alberto Ghirri*[2]

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Resonant and coherent coupling of two level systems with electromagnetic radiation is a fundamental problem. This is particularly relevant in magnetism where spins or spin excitations can be coupled to microwave photons. Molecular spins have recently emerged as a versatile system with interesting performances in terms of quantum coherence and correlation. The challenge we address here is to understand and control the coherent transfer of magnetic excitations in molecular spin systems to microwave photons.
I shall first present our achievements in reaching coherent coupling between molecular spins with microwave photons in planar resonators [1]. To monitor molecular spin performances over a wide temperature and magnetic field range we have first developed microwave planar resonators made of high Tc superconductors, obtaining excellent performances up to liquid Nitrogen temperature and magnetic fields up to 7 Tesla [2]. Ensembles of different molecular spin systems are then systematically tested. The regime of high spin-photon cooperativity is achieved with molecular spins diluted in non magnetic matrix at 0.5K [3], while the strong coupling regime is observed with concentrated samples of organic radicals up to 50 K [2,4] and with nanoparticles of Prussian blue Analogues [5]. The possibility to create coherent states among distinct spin ensembles is further explored in similar spectroscopic experiments [4] while more recently we started to encode sequences of microwave pulses to coherently manipulate molecular spins embedded in superconducting circuits. These results show that molecular spins can be efficiently integrated in quantum devices and can be suitable for advanced applications such as quantum sensing [6].

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Acknowledgements: This work was partially supported by the Italian Ministry of Education and Research (MIUR) though PRIN project 2015HYFSRT and by the Air Force Office of Scientific Research under award number FA2386-17-1-4040.

I3022 - Magnetic behavior of binary assemblies of nanoparticles: A multiscale modeling study

11. Nanomaterials, patterned films, nanoparticles and molecular magnetism

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Multiscale modeling of the physical and structural characteristics of nanomaterials, consisting of magnetic nanoparticles, is a powerful tool for the understanding of their magnetic behavior [1]. *Models* at different length scales have been used to describe our systems [1]: An atomic scale model of a single nanoparticle that includes its size and morphology is first developed to describe the intraparticle characteristics. A mesoscopic model based on a Monte-Carlo approach is then introduced to simulate assemblies of nanoparticles by rescaling the atomic scale parameters of magnetic core/ surface nanoparticles by reducing the number of spins to be simulated to the minimum necessary to satisfactorily represent their magnetic structure. Two examples will illustrate the possibilities offered by our multiscale modelling approach in binary magnetic nanoparticle assemblies.

First, a diluted binary ferrofluid of $MnFe_2O_4$ and $CoFe_2O_4$ nanoparticles has been investigated. The simulations of the magnetic properties are getting input from cryogenic TEM images [2] for the spatial distribution of the nanoparticles. It is shown that even at a low particle concentration, $MnFe_2O_4$ and $CoFe_2O_4$ nanoparticles interact through short distance magnetic dipole interactions within small nanoparticle clusters, which results in the sizeable reduction of the coercivity and the blocking temperature of the $CoFe_2O_4$ component and in the increase of both the coercivity and the blocking temperature of the $MnFe_2O_4$ one.

Next, we study the magnetic behavior of a dense binary assembly of γ-Fe_2O_3 and Co-doped maghemite nanoparticles [3]. We start from a pure γ-Fe_2O_3 dense assembly and we gradually substitute maghemite with Co-doped maghemite. Our study shows that the hysteresis characteristics of the binary assembly at low temperature provide evidence of the weak dipolar coupling between the two different nanoparticle populations which however it is strong enough to modify the individual hysteresis behaviour. Interestingly, the blocking temperature increases non-linearly almost two times from the corresponding pure γ-Fe_2O_3 assembly through the binary assembly to the pure Co-doped maghemite nanoparticles assembly, in good agreement with experimental findings [3].

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12. Spin-orbit and topology driven phenomena

I3023 - Role of topology in domain wall dynamics

12. Spin-orbit and topology driven phenomena

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The talk will start by a few reminders about the real-space topological structures in magnetism, namely the topological defects, the topologically-stable structures (also called topological solitons) and their relation. The deep link between topology and the dynamics of magnetic structures will then be explained, starting with the motion of rigid structures (the Thiele equation) and continuing with the motion of deformable structures, using the concept of the canonical momentum introduced at the time of magnetic bubbles.

An illustration of all these concepts, in the present context, will be provided by the study of the motion under large easy axis fields of Dzyaloshinskii domain walls.

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I3024 - Skyrmion dynamics:from slow diffusion for stochastic logic to ultra-fast motion for racetrack memory

12. Spin-orbit and topology driven phenomena

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The three key requirements for competitive spintronics devices are: (i) stable spin structures for long term data retention; (ii) efficient spin manipulation for low power devices and (iii) ideally no susceptibility to stray fields as realized for antiferromagnets.
We explore different materials classes to tackle these challenges and explore the science necessary for a disruptive new technology. To obtain ultimate stability, topological spin structures that emerge due to the Dzyaloshinskii-Moriya interaction (DMI), such as chiral domain walls and skyrmions are used. These possess a high stability and are of key importance for magnetic memories and logic devices [1,2]. We have investigated in detail the dynamics of topological spin structures, such as chiral domain walls that we can move synchronously with field pulses [3]. We determine in tailored multilayers the DMI, which leads to perfectly chiral spin structures.
For ultimately efficient spin manipulation, spin torques are maximized by using highly spin-polarized ferromagnetic materials [2] and using spin-orbit torques, we can efficiently manipulate magnetization [4-6]. We then combine materials with strong spin-orbit torques and strong DMI where novel topologically stabilized skyrmion spin structure emerge [5]. Using spin-orbit torques we demonstrate in optimized low pinning materials for the first time that we can move a train of skyrmions in a “racetrack”-type device reliably [5,6]. We find that skyrmions exhibit a skyrmion Hall effect leading to a component of the displacement perpendicular to the current flow [6]. We study the field - induced dynamics of skyrmions [7] and find that the trajectory of the skyrmion’s position is accurately described by our quasi particle equation of motion.
While thus highly reproducible driven skyrmion motion is possible, we have recently developed new ultra-low pinning multilayer stacks, which exhibit thermally activated dynamics of skyrmions [8]. Here the energy landscape is sufficiently flat so that we observe pure diffusive motion of skyrmion quasiparticles at room temperature [8]. Furthermore, in contrast to the analytical calculations, we find a strong temperature dependence of the diffusion and explain these observations based on thermally activated excitations. Finally we can employ skyrmion diffusion in a skyrmion reshuffler device enabling novel stochastic computing approaches [8].

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13. Magneto-optics and magnetoplasmonics

I3025 - Hybrid magnetoplasmonics

13. Magneto-optics and magnetoplasmonics

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Abstract

Hybrid magnetoplasmonics enable giant tunable nonreciprocal effects in subwavelength-thick structures. We demonstrate experimentally Faraday rotation of up to 14° for structure thicknesses below 200 nm and describe the optical behaviour with an elegant analytical model.

Hybrid magneto-optical (MO) plasmonic systems have enabled large magnetic tuning as well as giant non-reciprocal MO effects. By leveraging localized plasmon modes, the MO response of conventional materials can be resonantly amplified and spectrally tailored. Among all MO effects the Faraday effect is of special practical interest as it allows for the strongest non-reciprocal optical response. Here, the polarization plane of transmitted light is rotated by an angle that is proportional to the applied DC magnetic field and to the material thickness.

The Faraday rotation [1] and also the transverse MO Kerr effect [2] of a dielectric film can be enhanced by an order of magnitude through inclusion of a resonant plasmonic grating as schematically shown in figure 1a. By varying the grating and nanowire geometry, the maximal polarization rotation enhancement can be tuned to arbitrary spectral positions [3]. Such structures exhibited a Faraday rotation of up to 4.2° for a thickness of 220 nm, while maintaining a high transmission of over 25%. Hence, they are very relevant for possible devices, such as thin-film Faraday rotators and isolators as their performance data exceed other approaches considerably. Recently, we demonstrated Faraday rotation of even up to 14° in the visible for a thin film geometry with a thickness below 200 nm [4].

While the experimental realization and numerical simulation of such systems received considerable attention, so far, there has been no analytical theoretical description. Here, we present a simple coupled oscillator model that reveals the underlying physics in such systems by providing analytical expressions for the MO response [5]. The figures 1b and 1c depict the model both in the general and in a simplified form. The Lorentz nonreciprocity of the oscillator model is intrinsically incorporated via the Lorentz force, which is proportional to $\mathbf{v}\times\mathbf{B}$. The predictions of our analytic model are in good agreement with rigorous numerical solutions of Maxwell's equations for typical sample geometries as displayed in figure 1d. Our ansatz is transferable to other complex and hybrid nanooptical systems and will significantly facilitate device design and optimization of its performance [6].

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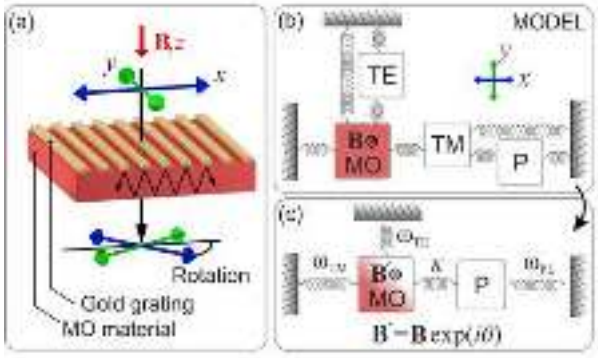
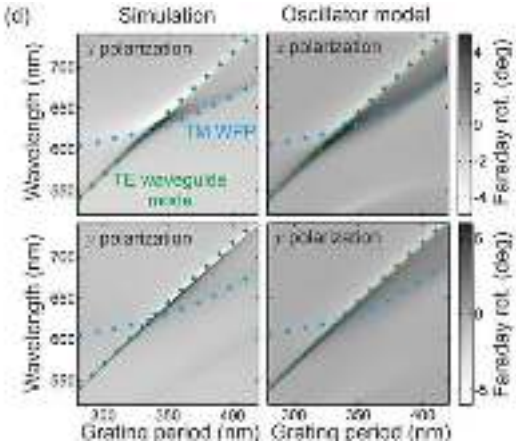

(a)
Rotation
Gold grating
MO material
(b)
MODEL
TE
TM
P
(c)
$\mathbf{B}^{+}=\mathbf{B}\exp(j\delta)$


(d)
Simulation
Oscillator model
x polarization
y polarization
TM WFP
TE waveguide mode
Wavelength (nm)
Grating period (nm)
Faraday rot. (deg)

I3026 - Magnetic-field controlled radiative heat transfer

13. Magneto-optics and magnetoplasmonics

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The combination of magneto-optically active and resonant materials (e.g. plasmonic modes), makes it feasible to control optical properties using magnetic fields in connection to the excitation of resonances [1] (magnetoplasmonics). It has been shown that these nanostructures can be employed to modulate the propagation wavevector of SPPs [2], which allows the development of label free sensors with enhanced capabilities [3] or to enhance the magneto-optical response in isolated entities as well as films, in connection with a strong localization of the electromagnetic field [4,5].

Here we will show that they also play a crucial role in the active control thermal emission and the radiative heat transfer between objects in the near and far field regime [6-8].

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14. Multifunctional magnetic materials: magnetic shape memory materials, multiferroics including artificial/composite multiferroics, and perovskites

I3027 - Non-volatile shell-ferromagnetic properties of multi-functional Heusler alloys

14. Multifunctional magnetic materials: magnetic shape memory materials, multiferroics including artificial/composite multiferroics, and perovskites

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Shell-ferromagnetism emerges as a newly exposed property of multi-functional Heusler alloys. The shell-ferromagnetic property occurs by the spinodal decomposition of $Ni_{50}Mn_{45}Z_5$ (Z: In, Sn, Ga, Al, Sb) alloys when temper-annealed at 650 K under a magnetic field of about 0.1 Tesla. An anti-ferromagnetic tetragonal $Ni_{50}Mn_{45}Z_5$ alloy decomposes magnetically and crystallographically into two different components with two different structures. These are the anti-ferromagnetic NiMn matrix with the $L1_0$ structure and ferromagnetic $Ni_{50}Mn_{25}Z_{25}$ nano-precipitates of about 2-5 nm in the $L2_1$ structure. We evidence that temper-annealing under a magnetic-field gives rise to strongly pinned interfacial moments between matrix and precipitate because of the strong anisotropy of the antiferromagnetic matrix. It is not possible to destroy the alignment of the interfacial spins even in magnetic-fields of up to 10-20 T and at temperatures up to 500 K, once they align in the external field direction. The technological relevance of this property is due to the non-volatility of the pinned magnetization at the precipitate/matrix interface. There is a high demand in technological areas, especially in magnetic memory devices, for such non-destructive and high coercive field unidirectional magnetic materials.

I3028 - Potential magnetoelectric spin textures at oxide interfaces

14. Multifunctional magnetic materials: magnetic shape memory materials, multiferroics including artificial/composite multiferroics, and perovskites

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In complex transition metal oxides, both magnetic anisotropy and magnetic interactions (exchange, Dzyaloshinskii Moriya (DM)) often are strongly correlated with the lattice structure (coherent elastic strain of films on substrates, rotations and tilts of oxygen octahedrons). Thus, oxides offer tools for structural tuning of spin textures which are not available in metals. In this talk, approaches for creating non-collinear spin textures at coherent interfaces between magnetic oxides will be discussed. These spin textures are expected to be associated with an electric polarization in the same way like the spin spirals in some bulk multiferroics (of type II) where ferroelectricity is a consequence of the magnetic structure [1]. Examples of ferromagnetic $La_{0.7}Sr_{0.3}MnO_3$ films coupled to another 3d, 4d [2] or 5d perovskite layer at a coherent interface grown by pulsed laser deposition will be shown. A little explored pathway to interfacial non-collinear spin textures in oxides is to utilize interfaces forming an exchange spring [2, 3], i. e., a kind of magnetic spring arising due to rigid exchange coupling of the components across the interface (Fig.1). In a magnetic field, such magnetic springs can be twisted or relaxed which is possible in moderate fields and is controllable by the thickness of the component driving the switching. Additionally, electric control could be accessible for interfaces with limited electrical screening (i. e., insulating character). We note that such magnetic springs get much more interesting in case of a well-defined spin chirality which may be obtained from a sufficiently strong DM interaction. Recent work indicates a substantial and electrically controllable DM interaction in $SrRuO_3$ [4]. The spin texture of interfacial magnetic springs can be topologically non-trivial, i. e., neighboring spins must be non-coplanar [5]. This is, e. g., the case when out-of-plane canting of spins is present leading to a conical spin spiral in an in-plane magnetic field (Fig.1). The design of topologically “active” interfacial spin textures which can be switched magnetically as well as electrically may be in reach and promises yet unexplored electronic functionalities.

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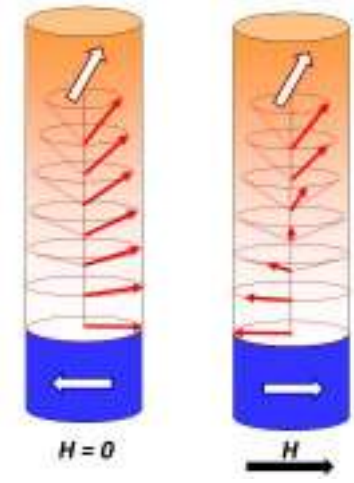

Fig.1. Magnetic spring in relaxed ($H = 0$) and twisted state in an in-plane magnetic field (H) at a coherent oxide interface.

The arrows indicate the direction of magnetic moments of Mn (blue layer, $La_{0.7}Sr_{0.3}MnO_3$) and Ru (red layer, $SrRuO_3$).

This spin texture has been suggested for the interface in $SrRuO_3/La_{0.7}Sr_{0.3}MnO_3/SrTiO_3$ (001) bilayers [2].

15. Spin waves, magnonics, ultrafast magnetization dynamics and optically driven spin excitations

I3029 - Controlling magnetic damping in thin films and nanostructures

15. Spin waves, magnonics, ultrafast magnetization dynamics and optically driven spin excitations

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Magnetic damping is one of the critical parameters that determine the speed and energy required to operate spintronic devices. For example, the critical current required to switch spin-transfer torque random access memory (STT-RAM) cells is calculated to be directly proportional to the damping parameter.[1] In addition, recently proposed technologies, such as spin-logic, require new materials that exhibit ultra-low values of the damping. Here, spin excitations with long lifetimes are used to transmit information and perform computation operations. As a result, it becomes increasingly necessary to engineer magnetic damping in thin films and nanostructures to make such technologies feasible. Significant progress has been made in developing quantitative theoretical models of magnetic damping in materials. This has the potential to predict and guide the discovery of new materials with exceptionally low values of the damping parameter. In fact, such models predicted an exceptionally low damping in a simple Co-Fe alloy that was later experimentally verified.[2,3] However, many factors contribute to the total damping of the complete system as it would be used in a device. These consist of mechanisms that are both intrinsic and extrinsic to the material. Such mechanisms vary from impurity scattering, electrodynamics, spin-current generation, spatial confinement, and even geometry induced effects. As a result, all of these sources must be taken into account and optimized for a specific application. To complicate matters, these sources may be coupled to other critical magnetic properties that prevents independent optimization. In this talk, I will review recent progress in understanding the origin of sources of damping with the ultimate goal of controlling damping in device structures. I will highlight some recent successes in applying this knowledge to achieve low damping in structures made of metals and half-metals.

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I3030 - Plasmon-Assisted Photoheating for Nanomagnetic Computation

15. Spin waves, magnonics, ultrafast magnetization dynamics and optically driven spin excitations

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Nanomagnetic logic, which uses arrays of magnetostatically-coupled single-domain nanomagnets for computation, is a low-power alternative to current charge-based computation in semiconductor devices and furthermore allows for integration of memory and information processing within the same architecture [1]. At the heart of the computation in nanomagnetic circuits lies the thermal relaxation from a field-set state towards a low-energy state of the interacting ensemble, and pathways for deterministic as well as probabilistic computation can be implemented [2].

Unfortunately, global heating schemes based on contact to a hot reservoir which are currently used to achieve thermal relaxation lack the speed and spatial selectivity required for the implementation in technological applications. By adapting ideas from the emerging field of thermoplasmonics [3], an alternative approach to heating of nanoscale magnets has recently been demonstrated by combining gold nanoantennas with magnetic elements [4]. Plasmon-assisted photoheating of such hybrid structures allows for temperature increases of up to several hundred Kelvins within time scales as short as a few tens of picoseconds. In addition, spatially-selective and sublattice-specific heating can be achieved by controlling the laser beam focal position and light polarisation, see Figure.

Using optical degrees of freedom, *i.e.* focal position, polarization, power, and pulse length, thermoplasmonic heating offers itself for the use in flexible, fast, spatially-, and element-selective magnetic thermalization, and we will explore its application to the control of relaxation pathways for nanomagnetic computation.

This work was supported by the Spanish Ministerio de Economía y Competitividad under the Maria de Maeztu Units of Excellence Programme – MDM-2016-0618 and the Project FIS2015-64519-R, as well as from the European Commission under the Project H2020-FETOPEN-01-2016-2017 “FEMTOTERABYTE” (project no. 737093).

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16. Magnetotransport, spintronics, spin orbitronics and spin caloritronics.

I3031 - Anomalous Hall and Nernst effects in Co2TiSn and Co2Ti0.6V0.4Sn Heusler thin films

16. Magnetotransport, spintronics, spin orbitronics and spin caloritronics.

Junfeng Hu[1, 2] , *Benedikt Ernst[3], Sa Tu[1, 2], Marko Kuveždić[4], Amir Hamzić[1, 4], Emil Tafra[4], Mario Basletić[4], Youguang Zhang[1], Anastasios Markou[3], Claudia Felser[3], Albert Fert[1, 5], Weisheng Zhao[1], Jean-Philippe Ansermet[2],* ***Haiming Yu***[1]

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The field of spintronics has been constantly searching for materials with large spin polarizations. The cobalt-based Heusler alloys are coming under intense scrutiny due to the promising applications in ultralow-energy spintronics, for their high spin polarization and half-metallic electronic structure. This study uses epitaxially grown magnetic Heusler compounds Co_2TiSn (CTS) and vanadium doped $Co_2Ti_{0.6}V_{0.4}Sn$ (CTVS) thin films to investigate the spin-dependent transport (magnetoresistance and anomalous Hall effect) and thermoelectric effects (Seebeck and anomalous Nernst effects). By using the Mott formula, we deduced the anomalous Nernst angle in analogy to the anomalous Hall angle, and the anomalous Nernst angle for CTVS is 15% at 220 K, whereas it is only 0.5% for the undoped film at 300 K. A direct comparison of the experimental results is shown in **Fig. 1** with both anomalous Nernst and Hall angle values. Considering the Mott relation, these experimental results may be accounted for by an enhanced energy derivative of the anomalous Hall conductivity near the Fermi level that is shifted by vanadium doping. These results may provide opportunities to realize spin caloritronic devices for efficient on-chip energy harvesting based on magnetic Heusler thin films.

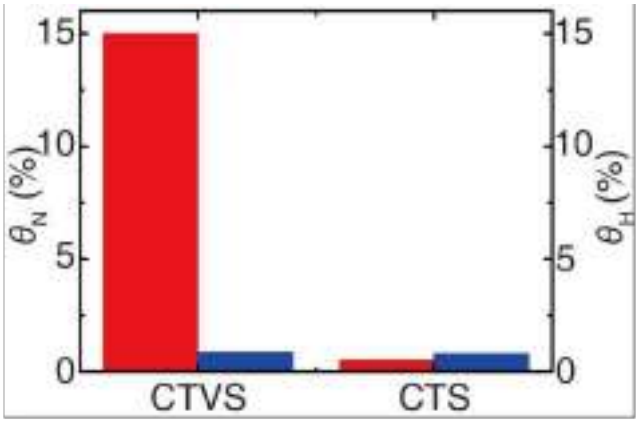

Fig 1. Anomalous Nernst angles (red column) and anomalous Hall angles (blue column) of the CTVS and CTS samples. The results are measured at 220 K for CTVS, at 300 K for CTS.

I3032 - Taming antiferromagnetic (squeezed) magnons to amplify spin transport and superconductivity

16. Magnetotransport, spintronics, spin orbitronics and spin caloritronics.

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Employing the concept of two-mode squeezed states from quantum optics, we demonstrate a revealing physical picture for antiferromagnetic magnons. Superimposed on a Néel ordered configuration, a spin-flip restricted to one of the sublattices is called a sublattice-magnon. We show that an antiferromagnetic spin-up magnon is comprised by a superposition of states with n+1 spin-up and n spin-down sublattice-magnons, and is thus an enormous excitation despite its unit net spin. Consequently, its large sublattice-spin can amplify its coupling to other excitations. This is achieved, for example, when an external excitation bath couples to the antiferromagnet via an uncompensated interface. Considering an antiferromagnet/conductor hybrid, we show that this increased magnon-electron coupling leads to an enhancement of spin pumping current across the interface. The same coupling enhancement results in a magnon-mediated superconducting phase in the conductor with critical temperature potentially much larger than 1 K. Employing von Neumann entropy as a measure, we show that the antiferromagnetic eigenmodes manifest a high degree of entanglement between the two sublattices, thereby establishing antiferromagnets as reservoirs for strong quantum correlations. Based on these novel insights, we outline strategies for exploiting the strong quantum character of antiferromagnetic (squeezed-)magnons.

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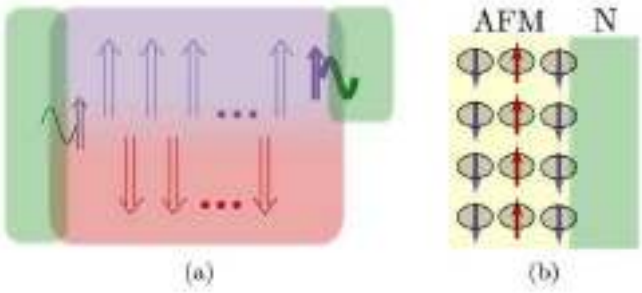

FIG. 2. (a) An external excitation bath (shaded green) interacts weakly with the AFM squeezed-magnon if coupled via its unit net spin (left), but strongly if exposed to only one of the sublattices (right). (b) Schematic depiction of a metal (N) coupled to an AFM via a fully uncompensated interface.

Oral

1. Biomagnetism and medical applications

Challenges of Metrology and Standardisation of Magnetic Nanoparticles

1. Biomagnetism and medical applications

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Magnetic nanoparticles (MNP) comprise one of the largest families of nanomaterials, with dependent products generating an annual turnover of over 2 billion Euros for European companies, alone. MNP are widely employed for biomedical purposes: for in-vitro diagnostics, specifically for the separation and extraction of cells, viruses, proteins, and DNA from blood. In addition, new cancer therapies like magnetic drug targeting or hyperthermia and technical applications like magnetic bearings, magnetic separation, or loudspeakers make intensive use of MNP. Besides these scientifically well-known uses, nanosized iron oxide materials also appear in the catalogue of nanomaterials used in cosmetic products in the EU and the annual production of nanoformed iron oxide is >100000 tons per year in the EU. Despite of these vast biomedical and technical applications, the MNP sector still lacks agreement on unified terminology, standardised measurement procedures of magnetic properties and certified reference materials (RM). However, standardized nanomaterials and measurement methods are essential for safe application, quality monitoring and trusted interaction between MNP producers and users in the market.

To partially address these issues, ISO/TC229 is working on the first standard for MNP: ISO 19807-1 “Liquid suspension of magnetic nanoparticles” (publication scheduled Summer 2019), which will define their main characteristics together with appropriate measurement methods. A second more application-oriented ISO standard (ISO 19807-2) is under preparation defining the main characteristics of superparamagnetic beads used for nucleic acid extraction.

The development of measurement standards to characterize basic magnetic MNP properties is still an outstanding task. This includes the definition of standard operating procedures for the measurements, detailed agreements on sample preparation and a harmonized methodology for evaluation and expression of the measurement results. Quantitative uncertainty budgets are an essential precondition for viability tests of the harmonized measurement protocols in ring comparisons. In addition to the characterization of magnetic MNP properties, there is a big need for the standardized assessment of MNP application performance, for example, magnetic separation performance or magnetic hyperthermia performance.

We present the current developments and challenges in the characterization and standardisation of magnetic properties of magnetic nanoparticles. In addition, we discuss the different and sometimes contradictory perspectives of developers, manufacturers, scientists, industrial and medical end users and other relevant societal stakeholders.

O1 - Atomistic spin dynamics of core-shell magnetite-maghemite and magnetite-cobalt ferrite nanoparticles

1. Biomagnetism and medical applications

Daniel Meilak[1] , *Richard Evans*[1]
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Magnetite nanoparticles are promising for a range of medical applications including magnetic hyperthermia, MRI contrast enhancement and targeted drug delivery. Both maghemite and cobalt ferrite benefit from similar properties including high Curie temperatures and moderate saturation magnetizations while having varying magnetic parameters. Forming core-shell particles from these materials will allow us to fine tune the particle properties to suit specific applications.

In this study, we look at core-shell nanoparticles made from these materials, to study the effects of varying core-shell thicknesses and temperature variation on the core and shell magnetisation and susceptibility. From this we achieve a better understanding of the heat producing ability of these materials. To do this, we use a Heisenberg model and the *VAMPIRE* software package developed at the University of York.

As the materials have similar structures, all inverse spinel cubic ferrimagnets with similar lattice parameters, they are able to form stable nanoparticles of various shapes such as spherical, truncated cube or cubic. The magnetization, susceptibility and hence the Curie temperature of the particles should then be dependent on the ratio of core to shell. In addition, by maintaining the overall particle diameter, even for particles with a core size of less than 5nm, finite size effects will not radically affect the properties of the material, such as lowering the Curie temperature, as the overall surface area is maintained.

We find that the Curie temperature of the nanoparticles fluctuates between the expected values of bulk magnetite and maghemite or cobalt ferrite, depending on core-shell ratio. The magnetic properties of the shell differ noticeably from those of the core as they do not show any statistical finite-size effects, whereas the core shows an increasing non-zero magnetization at high temperatures for lower diameters.

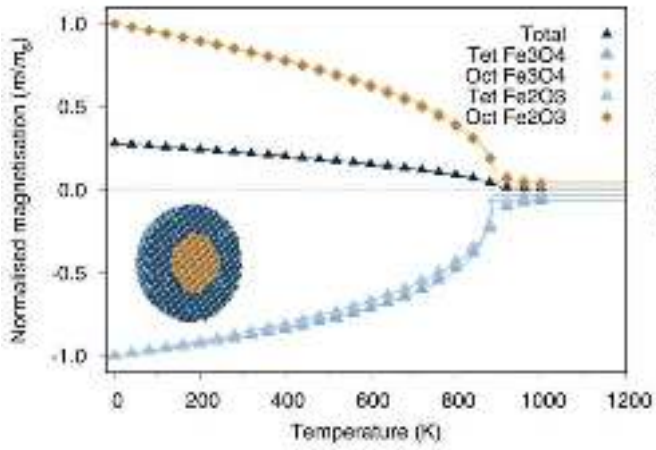

Figure 1. Magnetisation of a Magnetite-Maghemite nanoparticle including a breakdown of the magnetisation of each sublattice. The overall nanoparticle has a low saturation magnetisation and both materials are ferrimagnetic.

O2 - Au-Fe3O4-Nanoparticle in Radiotherapy: Novel therapeutic approaches by varying the surface chemistry

1. Biomagnetism and medical applications

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Heterostructured nanoparticles like Au-Fe_3O_4-nanoheterodimers are attractive candidates for advanced nanomaterials. These nanoparticles do not only benefit from the unique properties of each pristine material but can also exhibit novel physical and chemical properties. Both nanoparticles species have proved themselves as sensitizers for radiation therapy. The combination of gold nanoparticles, emitting photo-/Auger electrons during X-ray irradiation, with superparamagnetic Fe_3O_4-nanoparticles, as producing hydroxyl radicals by catalyzing the Fenton reaction by X-ray interaction, makes the nanoheterodimers ideal candidates as radio sensitizers.

The Au-Fe_3O_4-nanoheterodimers were synthesized by thermal decomposition of an iron precursor on the surface of pre-synthesized gold nanoparticles. Unfortunately, the oleic acid/oleylamine stabilized nanoheterodimers are not soluble in aqueous media. One strategy is ligand exchange, at which the hydrophobic ligands are replaced by hydrophilic ones. Among others we used nitrosyl tetrafluoroborate ($NOBF_4$) as a phase transfer reagent to attain water solubility. The Fe_3O_4-surface could stabilize the nitrosonium ions, so that the surface of the nanoheterodimers was covered by a mixture of oleic acid and nitrosonium ions. X-ray irradiation of these nanoheterodimers led to a simultanous generation of reactive oxygen and nitrogen species[1]. Another ligand exchange was achieved by using superoxide scavengers. Additionally to the application as radiosensitizers, these nanoheterodimers could also be used as radioprotectors in non-cancerous cells.

Another concept for achieving good water dispersibility consists of attaching amphiphilic compounds at the hydrophobic surface to create a hydrophilic shell around the nanoheterodimers. The used amphiphilic molecules determine the surface charge and architecture of the nanoheterodimers. This controls the cellular uptake in cancer and non-cancer cells and the cellular trafficking.[2]

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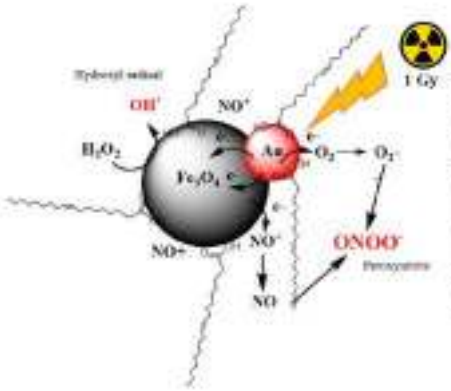

Figure 1: Possible reaction mechanisms during X-ray irradiation of the Au-Fe_3O_4-nanoparticles:
•Generation of the **hydroxyl radical** via the Fenton reaction
•Generation of the **superoxide** radical by electron transfer to adsorb oxygen
•Generation of the **nitric oxide** radical by electron transfer to adsorbed nitrosonium cation
•Generation of **peroxynitrite** by reaction of superoxide with nitric oxide

O3 - Design of magnetic particles for magneto-mechanical cells destruction

1. Biomagnetism and medical applications

Robert Morel[1] , *Caroline Thébault[1], Cécile Naud[1, 2], Eric Billiet[1], Thierry Chabrol[2], Hélène Joisten[1, 3], Marie Carrière[4], Yanxia Hou[4], François Berger[2], Bernard Dieny[1]*

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Magnetic nanoparticles have been widely investigated for biotechnological and biomedical uses. Some of the best-known applications concern the drug delivery, hyperthermia or as MRI contrast agent. In most cases, the magnetic particles consist in superparamagnetic particles of a few tens of nanometers. Another type of application is the use of magnetic particles for the application of force or torque on living cells or tissues. Under certain conditions, it is possible in this way to induce the death of targeted cells, including cancer cells. The magnetic particles suitable for these application are, however, very different from the superparamagnetic particles used for the aforementioned applications. Since the magnetic force is proportional to the volume, it is indeed preferable to use micron-size particles.

In this presentation we will describe some of the magnetic particles that we have developed [1], including vortex particles and magnetite particles (Fig. 1). The vortex particles are permalloy discs, fabricated using a top-down approach by optical lithography. The magnetite particles are obtained by the liquid-phase ball milling of a raw magnetite powder, with irregular grain size and shape. It will be shown that, despite their completely different nature, the magnetic properties of these particles make them suitable for magneto-mechanical cell destruction.

In addition to their magnetic properties, the physicochemical properties of the particle surface must be optimized to improve their stability and affinity with the cells, or to allow functionalization for specific cell targeting. The functionalization pathways for the different types of particles will be described in this presentation.

The low intrinsic cytotoxicity of the particles is evaluated by *in vitro* experiment with human glioblastoma U87-MG cells, measuring the viability by LDH and WST-1 tests to observe the membrane permeability and metabolic activity of the cell. Then, cancerous cells destruction is demonstrated *in vitro* with the application of a low frequency (~20 Hz) magnetic field using a Halbach ring device. On the other hand, *in vivo* test with mice, with particles injection into a brain tumor and subsequent magnetic field treatment, show a different outcome. These results have led us to question the relevance of the *in vitro* model, for the benefit of a 3D model of cells spheroids in agarose gel that will be described.

Acknowledgements: Funding for this work have been provided by EuroNanoMed II project NanoViber.

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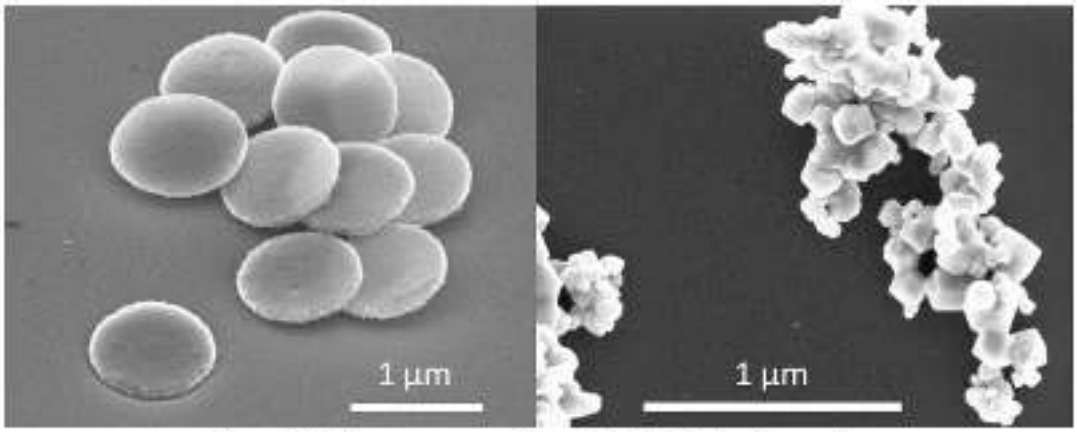

Figure 1. Left: Vortex type magnetic particles. Right: Magnetite powder.

O4 - Effect of geometrical properties and concentration on the specific loss power of magnetic nanodisks

1. Biomagnetism and medical applications

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In the last decade, magnetic nanomaterials have been intensively studied for future application in cancer treatment, thanks to the possibility of inducing cell apoptosis via hyperthermia or cell membrane mechanical stimulation [1, 2]. Focusing on hyperthermia, when an alternating magnetic field is applied to a distribution of magnetic nanoparticles dispersed in a tissue, different physical phenomena can concur to heat generation, e.g. Néel relaxation, Brownian relaxation and hysteresis losses. Their relative contribution depends on the size and physical properties of the used nanomaterials [3].
This work focuses on magnetic nanomaterials for which the prevalent heating contribution comes from hysteresis losses. In particular, we study magnetic nanodisks made of different materials, investigating the influence of geometrical properties (diameter and thickness) on the specific heating capabilities [4]. We also analyze the impact of material composition and geometry on the remanence state, in order to find the parameters that lead to a negligible magnetic moment (e.g. vortex state) and thus prevent aggregation phenomena at zero field. The analysis, performed via micromagnetic modelling [5], is extended to realistic scenario, where the nanodisks are randomly distributed with very high local concentrations. The aim is to derive an estimate of the specific loss power, as a function of the dispersion state of nanomaterials.
The obtained results demonstrate that, in the case of vortex formation, wider hysteresis loops and thus greater heating capabilities can be obtained by reducing nanodisk diameter and/or increasing nanodisk thickness (see the figure on the left). Moreover, we found that the heating efficiency is higher for well-dispersed nanomaterials, while a significant decrease in the heat release is found for dense and compact aggregates. In the latter case, the remanence state is strongly affected by the magnetostatic interactions between disks (see the figure on the right).

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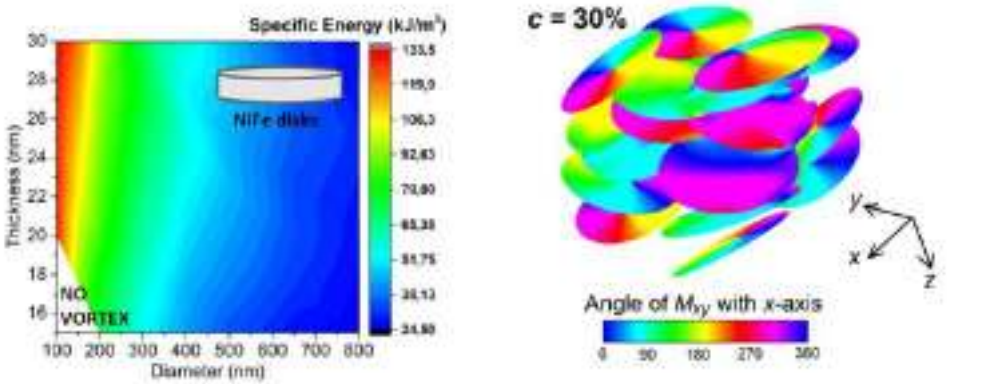

On the left: specific energy losses versus diameter and thickness for permalloy nanodisks.
On the right: remanence state for a dense aggregation of 680 nm diameter permalloy nanodisks.

O5 - Ferromagnetic Resonance Biosensor System for Homogeneous and Volumetric Detection of DNA

1. Biomagnetism and medical applications

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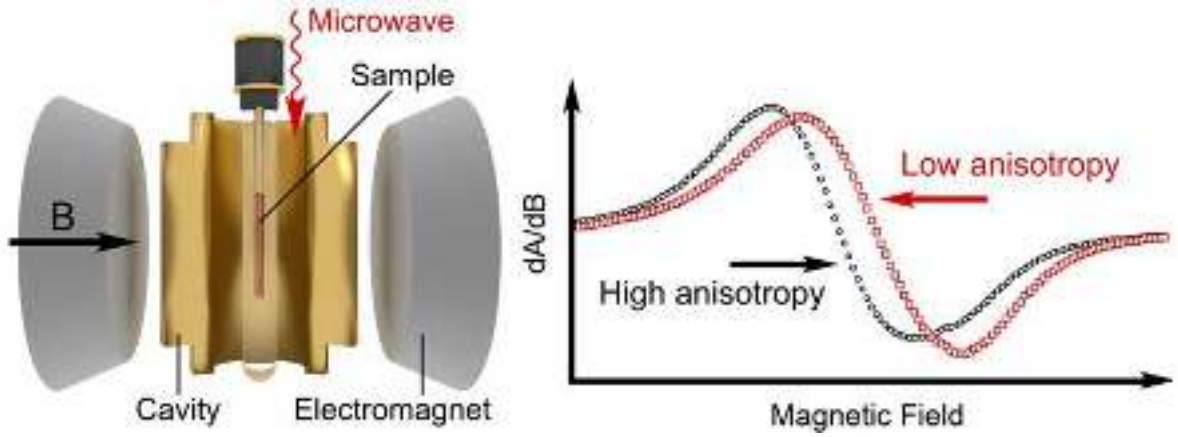
Novel biosensor technologies for rapid, user-friendly, sensitive, specific and cost-efficient detection of pathogens and different kinds of biomarkers at the point-of-care (POC) and in out-of-lab settings are increasingly demanded in applications such as human medicine, veterinary medicine, environmental monitoring and food safety. Magnetic biosensors using magnetic nanoparticles (MNPs) as read-out labels offer a number of unique advantages and are strong candidates for POC and out-of-lab diagnostic devices. Magnetic biosensors are commonly divided into two sub-groups; surface-based and volumetric (homogeneous) magnetic biosensors. The first type usually involves binding of MNPs on a magnetic sensor surface followed by detection of the magnetic moment of the MNPs (static read-out), whereas the second measures the magnetic signal (usually changes in the dynamic response of the MNPs) due to the entire sample volume. Having a homogeneous read-out offers particular advantages in terms of less sample preparation requirements and faster reaction. Herein, recent research advances using the ferromagnetic resonance (FMR) technique for homogeneous and volumetric DNA biosensing are presented. The FMR system measures the microwave absorption versus magnetic field and the resonance field of a suspension of MNPs varies with the net magnetic (shape-, magnetocrystalline-) anisotropy of the sample. Presence of a target analyte, which triggers an enzymatic amplification reaction, changes the net magnetic anisotropy of the suspension, leading to a shift of the resonance field that can be quantified by the read-out from the FMR spectrometer. Two different isothermal amplification methods, *i.e.*, rolling circle amplification (RCA) and loop-mediated isothermal amplification (LAMP) are employed for biosensing. For the RCA-based biosensing, binding of MNPs in RCA products of a synthetic *Vibrio cholerae* target DNA sequence leads to the formation of MNP aggregates which results in a decrease of the net anisotropy of the system and thereby an increase of the resonance field. A limit of detection of 1 pM was obtained with an average coefficient of variation of 0.16% and a total assay time of ca 90 min, which is superior to the performance of other reported RCA-based magnetic biosensors. For LAMP-based biosensing, formation of MNP aggregates by co-precipitation of MNPs and the LAMP by-product magnesium pyrophosphate increased the resonance field of the sample. End-point detection of a synthetic Zika virus target sequence in serum was demonstrated with a detection sensitivity of 100 aM and a total assay time of 16 min. Recently, efforts have been spent on extending the FMR-LAMP end-point biosensor to a biosensor for Newcastle disease virus (NDV) with a real-time read-out. The prototype system has integrated sample preparation and injection and can monitor the resonance field versus time. Preliminary results suggest that this system is capable of detecting a synthetic NDV target sequence with sub-fM sensitivity for a total assay time of 40 min. In summary, due to its fast measurement, high sensitivity and possibilities to be miniaturized, the FMR-system holds considerable potential to be developed to compact and low-cost DNA biosensors for POC and out-of-lab use.


Microwave
Sample
B
Cavity
Electromagnet
dA/dB
Low anisotropy
High anisotropy
Magnetic Field

O6 - Integrated optomagnetic platform for biosensing applications

1. Biomagnetism and medical applications

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Over the last years, the potential development of a range of biological sensors has been raising significant interest in the scientific area. Obviously, this mainly comes from health care, but other participants are looking into it like veterinary areas, food industries, pollutants monitoring and military application against bio-chemical threats. In our work, we developed a system that exploits the high sensitivity of integrated photonic platforms to detect whether or not an analyte is present on our sensing area [1].The sensor is based on a silicon photonics integrated microring resonator, suitably processed to expose the waveguide. The transfer functions of the drop and through ports of the resonatorpresent a peak-notch shaping in correspondence of the resonating wavelength λ_{res}, which depends on the ring length and on the effective refractive index n_{eff} seen by the electromagnetic field circulating in the guide. Due to the high sensitivity of the photonic platform to the surroundings, whenever the refractive index above the waveguide changes, e.g. a different fluid is on the chip, the optical response changes and the shift can be detected with high precision thanks to an electronic feedback loop which adjusts the laser wavelength, locking it to the crossing point of the through and drop transfer functions. Close to the chip an electromagnet was used to produce an oscillating magnetic field.Biomolecule measurements were performed on both label-free and label-based approaches, showing an enhanced system sensitivity when using superparamagnetic nanoparticles as passive labels [2]. The advantageous studied protocols were based on the formation of a sandwich structure of p24 protein (a component of the capsid of the HIV particle) in the middle of two artificial antibodies (as in Fig.1) or on the binding between two complementary DNA strands. On the top of such structures, 100-150nm diameter magnetic beads were attached. When the system is working, the oscillating magnetic field produced by the electromagnet generates a force on the magnetic beads. This effect forces the nano-labels to oscillate on the top of the microring resonators, which are part of the feedback loop, as shown in Fig.2. Being the beads present only if the whole protocol was followed (i.e. the desired compound - p24 or DNA - is present) the platform can notice an oscillating feedback correction whose amplitude depends on the concentration of the original assay, allowing the creation of a calibration curve.In conclusion this work investigated the performances of a system used as biosensor which joins integrated optics and magnetic nanoparticles. In particular, a significant reduction of false-positives and sensitivity down to pM range were achieved for molecular recognition.

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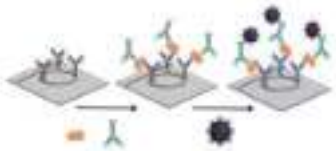

Figure 1: Binding process example: p24 protein "sandwiched" between two antibodies and a magnetic nanobead attaches on the top.

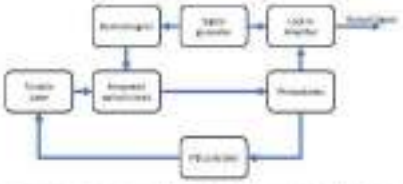

Figure 2: Schematic working principle: while the feedback keep the laser locked to the resonance wavelength of the microring, the lock-in amplifier extract the signal generated by the oscillating magnetic particles.

O7 - Magnetic microbead manipulation on soft-magnetic structures - numerical simulations and experiments

1. Biomagnetism and medical applications

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Manipulation of magnetic particles has gathered much attention for possible applications in bio applications allowing transport, separation and detection [1]. Functionalized superparamagnetic microbeads (SPMMB) are widely used in labelling and detection of biomedical species [2]. The control of SPMMBs using soft magnetic parent structures is a road towards utilizing functionalized SPMMBs for guided specific drug delivery across lab-on-a-chip systems.

The behavior of the SPMMBs is defined by the magnetostatic interaction between the SPMMBs and magnetic parent structures over which an external magnetic vector field is applied. Changing the external field and thereby the magnetic microstructure motion of the SPMMBs is achieved via changing the correlated potential energy landscape. The modeling of SPMMB behavior by quantitative descriptions of the magnetic forces between the superparamagnetic microparticles and the micromagnetic state of the parent structure as well as the hydrodynamic drag forces is of huge interest in the design of new parent structures to achieve specific functionalities.

We present an algorithm to predict SPMMB behavior in a wide range of structures, facilitating base functionalities of transport and sorting. Using the algorithm, it is possible to simulate arbitrary magnetic structures. To model SPMMBs progressing along an array of structures the possibility of periodic boundaries is implemented. In our code we can also calculate for arbitrary magnetic field sequences. Although for most applications a 2-dimensional simulation provides a good match with experimental results, in some cases the magnetic potential in the out of plane axis of the structures can lead to forces lifting SPMMBs of the ground. This behavior is addressed by expanding the calculated potential energy landscape and numerical solver to the third dimension.

We selected a variety of different application related systems to highlight these. Movement around a circular structure in a rotational field [3], along an array of eggs providing guided movement in rotating fields, along a grid of triangles guiding motion by switching between distinct field angles, and across exchange biased microstripes using four field steps including out-of-plane fields [4] will be discussed. For all examples experimental data exists and validates the results.

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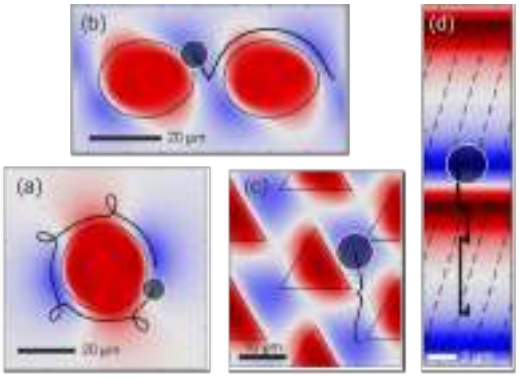

Movement paths of beads (a) around a disk in a rotational field experiencing looping, (b) along a path of eggshaped structures in a rotational field, (c) across a grid of triangles switching between two field states and (d) across a grid of parallel exchange biased microstripes using four field steps.

O8 - Study of magnetic beads-DNA coils binding kinetics using a differential homogeneous magnetic assay

1. Biomagnetism and medical applications

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The binding kinetics of magnetic nanoparticles (MNPs) to rolling circle amplification products (RCPs) is investigated using a differential homogenous magnetic assay (DHMA)[1]. The DHMA utilizes a microfluidic device to measure the differential ac susceptibility signal between a reference and a test sample, taking advantage of the symmetry in a high-Tc SQUID gradiometer sensor[2]. The DHMA signal is related to the relative differences in the particle distribution of the two samples, and the background magnetic signal is thus eliminated. Therefore, minuscule changes in the nanoparticle's concentration and size distribution of the test sample are directly detectable in the solution. This makes the DHMA a superior technique to characterize the binding interaction of the MNPs to biomolecules like RCPs specially at very low concentrations. The DHMA reveals that there is a competitive dynamic process between the MNP labelled RCPs and the unbound MNPs in the solution as a function of the RCP concentrations. The evidence of this dynamic in the signal fades as the MNP-RCP agglomerates are formed. The DHMA also shows that the smaller MNPs in the MNP size distribution take precedence over the larger MNP in immobilization on the RCPs. Comparing the DHMA responses with the turn-off detection method indicates that a full frequency range ac susceptibility observation is necessary when detecting low concentration of target RCPs. The findings are critical for understanding the underlying microscopic binding process and improving the assay performance.

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2. Electronic structure and strongly correlated electron systems including superconductivity

O9 - Band structure study of anisotropic magnetic interactions in Iridium oxides

2. Electronic structure and strongly correlated electron systems including superconductivity

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Because of strong spin-orbit coupling of Iridium magnetic interaction in Ir^{4+} oxides cannot be described by an isotropic Heisenberg-like model and anisotropic exchange interactions become important. In Sr_2IrO_4 and $Sr_3Ir_2O_7$ with corner sharing octahedra the dominant magnetic interactions are isotropic nearest neighbor coupling *J* and anti-symmetric Dzyaloshinskii-Moriya (DM) interactions. In α-Na2IrO3 and other honeycomb iridates with edge sharing IrO octahedra magnetic interaction were suggested to be bond-dependent and to be described by the Kitaev model. We performed LSDA+U band structure calculations for some iridates with corner or edge sharing IrO octahedra. Effective magnetic interactions were estimated by mapping the total energy differences between various magnetic structures onto a model which includes isotropic Heisenberg-like as well as bond-dependent anisotropic magnetic interactions. In Sr_2IrO_4 and pyrochlore $Y_2Ir_2O_7$ the dominant anisotropic exchange is the anti-symmetric DM interaction. In α-Na_2IrO_3 and other honeycomb iridates symmetric anisotropic terms are at least as strong as the isotropic ones.

O10 - Domain-Superconductivity in Nb/FePd with lateral inhomogeneous magnetization

2. Electronic structure and strongly correlated electron systems including superconductivity

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Ferromagnetism (F) and superconductivity (S) have long been considered as antagonist phenomena. When the magnetic state of the F-layer is inhomogeneous, magnetic domains can spatially confine the superconductivity in an adjacent S-layer [1]. Our goal is to obtain an understanding of such proximity effects between the two layers. The lateral magnetic depth profile near the S/F-interface and the dependence of the superconductivity on the magnetic configuration still needs to be investigated further.

As a prototype system we use thin film heterostructures of ferromagnetic FePd with a superconducting Nb toplayer. The heterostructures are grown using molecular beam epitaxy on an MgO(001) substrate. FePd is grown in the $L1_0$-ordered phase with a magnetic anisotropy perpendicular to the surface plane [2]. This ensures a lateral magnetic domain pattern. Resistivity measurements as a function of external magnetic field H reveal the effect of the magnetic stray fields on the superconducting state. When the superposition of the stray fields and H is below the second critical field, superconductivity nucleates over the domain with magnetization direction opposite to H [1]. Confining the superconductivity into domains leads to interesting new phenomena in the Nb thin film near its critical temperature T_c.

To investigate the depth profile of the magnetization in both the Nb and FePd layers we use neutron scattering techniques. Previously performed Polarized Neutron Reflectometry (PNR) measurements have revealed a change of magnetization for an in plane applied magnetic field as function of temperature. Grazing Incidence Small Angle Neutron Scattering (GISANS) gives insight into the lateral magnetic fluctuations, in this case caused by the domain pattern. Measurements at H=0 show a decrease of intensity in the GISANS peaks in the range of temperature where the resistivity decreases to zero with temperature. This is a strong sign for a change of magnetization in the periodic domain pattern and correlates with an increase in intensity of the specular spot (see Figure 1).

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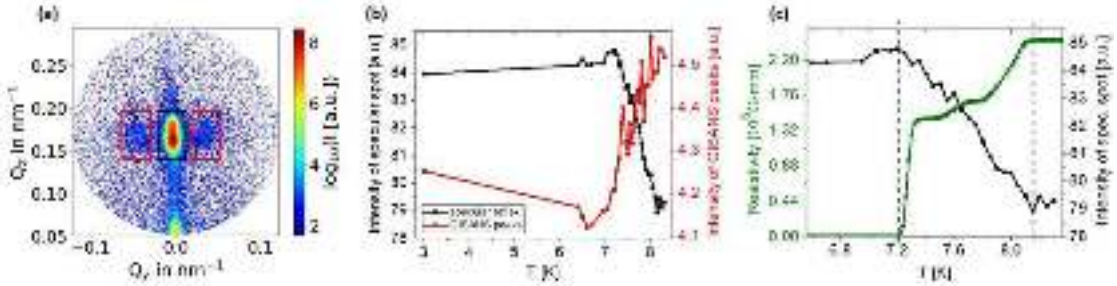

Figure 1: (a) Q_r-Q_z-map of a GISANS measurement of the Nb/FePd heterostructure. The specular spot is marked by a black rectangle, while the red rectangles mark the two GISANS peaks. (b) Along Q_z integrated intensity of the specular spot (black) and the GISANS peaks (red) as function of temperature. (c) Comparison of the temperature dependence of the specular spot from GISANS and the temperature dependence of resistivity in this sample.

O11 - From order to randomness: Onset and evolution of RS state in bond-disordered spin-chain compounds

2. Electronic structure and strongly correlated electron systems including superconductivity

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The study of electronic properties of physical systems in the presence of disorder spans many decades, starting with the *strong* (Anderson) *localization* ideas in the 1950s up to the present-day investigations of quantum confinement in nanostructures. The breadth of phenomena taking place in disordered systems, such as quantum percolation, ballistic transport, quantum glassiness, or many-body localization, have been studied primarily theoretically, e.g., as a function of dimensionality, nature of disorder, degree of interaction, etc. Of particular interest is the physics occurring in low-dimensional quantum magnets under a varying degree of disorder. At very low temperatures and high magnetic fields, close to a quantum phase transition, disorder suppresses the global phase coherence and induces novel quantum critical behavior. But even under less extreme conditions, the disorder-induced breaking of translational invariance promotes random couplings between individual spins and leads to a so-called random-singlet (RS) state, a regime where spins couple across arbitrary distances to form weakly bound singlets, which dominate the magnetic features and the related dynamics.

What exactly happens when a regular spin-chain is exposed to an increasing degree of disorder is not well known. Until recently, progress has been slow as far as numerical simulations and, especially, experimental investigations of *disordered low-dimensional systems* are concerned. The main reasons include computational difficulties due to the large size of realistic disordered systems and, regarding experiments, the scarcity of suitable systems in which disorder can be easily tuned over a broad range without changing the structural character of the material.

Starting from $BaCu_2Si_2O_7$, a typical spin-½ chain system, we investigate a series of compounds with different extents of bond disorder, where the systematic replacement of Si with Ge results in a remodulation of the Cu^{2+} exchange interactions. By combining magnetometry measurements with nuclear magnetic resonance studies, we follow the evolution of the disorder-related properties from the well-ordered $BaCu_2Si_2O_7$ to the maximally disordered $BaCu_2SiGeO_7$. Our data indicate that already a weak degree of disorder of only 5% Ge, apart from reducing the three-dimensional magnetic ordering temperature T_N quite effectively, induces a qualitatively different state in the paramagnetic regime. At maximum disorder our data indicate that this state may be identified with the theoretically predicted random singlet (RS) state. With decreasing disorder the extension of the RS regime at temperatures above T_N is reduced, yet its influence is clearly manifest, particularly in the features of nuclear magnetic resonance relaxation data. The implications of the above findings in a broader context will be discussed.

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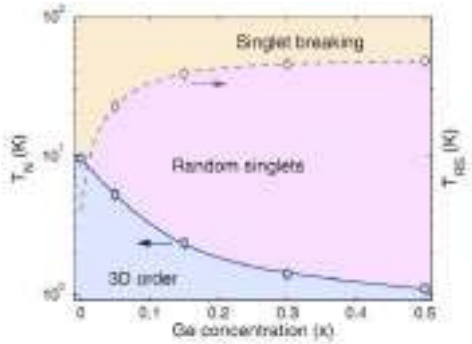

FIG. 1. Ordering temperature T_N and RS-regime crossover temperature T_{RS} (see text) vs Ge concentration x. T_{RS} reaches its asymptotic value already for $x > 0.1$, suggesting that even a weak degree of disorder is sufficient to achieve the random-singlet state. Schematically, the RS regime exists between the lower 3D magnetic order phase boundary and the upper thermal singlet-breaking region.

O12 - Interplay between superconductivity and magnetism in the LaAlO3/SrTiO3 interface

2. Electronic structure and strongly correlated electron systems including superconductivity

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The interface between two wide band-gap insulators, $LaAlO_3$ and $SrTiO_3$ (LAO/STO) has received much attention since it hosts a quasi-two-dimensional electron gas (q2DEG), two-dimensional superconductivity, ferromagnetism, and giant Rashba spin-orbit coupling [1]. Superconducting correlations are commonly known to be suppressed in the presence of magnetic fields and magnetic moments due to the Zeeman splitting and orbital effects. Here, we report an unexpected enhancement of the critical current by a small magnetic field in the nanowires fabricated from two-dimensional superconductor at the LAO/STO interface [2]. The enhancement of critical current is very similar in nano-structures with different geometries, which implies that it is of local origin, i.e., associated with magnetic spins rather than interference of supercurrents. At zero magnetic field, the critical current is suppressed by unpolarized magnetic impurities. A small magnetic field polarizes the spins that reduces spin-flip exchange scattering, resulting in an enhancement of the critical current, as observed in all our nanostructures [3]. Our results shed light on the microscopic nature of two-dimensional superconductivity and ferromagnetism in the LAO/STO interface, where the homogeneous superconducting layer is spatially separated from the magnetic spins originating from oxygen vacancies in the STO substrate. Our findings are important for designing superconducting devices based on the LAO/STO interface, in particular for realization of theoretically predicted odd-triplet superconductivity [4].

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O13 - Magnetic field dependence of spin stripes in highly underdoped LSCO superconductors

2. Electronic structure and strongly correlated electron systems including superconductivity

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In the quest to understand the interplay between magnetism and superconductivity (SC), our group investigates the behaviour of spin density waves, so called spin stripes, through elastic and inelastic neutron scattering experiments on $La_{2-x}Sr_xCuO_4$ (LSCO) compounds. It is a well-known fact that one signature of the emergence of superconductivity, is the opening of a spin gap in the excitations spectrum below the superconducting critical temperature [1]. However, in the underdoped region of the phase diagram, where magnetic order co-exists with SC, only a suppression of the low energy excitations, at the onset of SC is observed, also referred to as an incomplete spin gap [2]. In all the studies from the literature [1-4], the effect of applied magnetic field is to induce excited states within the gap while suppressing the superconducting phase.

Our most recent neutron scattering experiments show a change in behaviour of the magnetic signal, namely the stripes along the copper oxide bonds, correlated with the transition, as a function of doping, to SC. We performed measurements on a highly underdoped superconducting LSCO with Sr doping x = 0.07 and non-SC LSCO single crystals with x = 0.05. The SC sample showed a magnetic field induced suppression of the spin fluctuation between 0.5 meV and 1.5 meV concomitant with an enhancement of the elastic signal (Figure 1 b) and d)). Corroborated with results from the literature, we believe that our findings imply a coherent picture of spectral weight shift towards lower energy transfers for SC samples under applied magnetic field. A similar magnetic field suppression of the inelastic signal, below 2 meV, was observed in our non-superconducting sample, but the lost spectral weight was not recovered in the elastic channel (Figure 1 a) and c)). We speculate that the effect of an applied field on samples outside the SC dome is to move spectral weight towards higher energy fluctuations in contrast to the downward movement on the superconducting ones.

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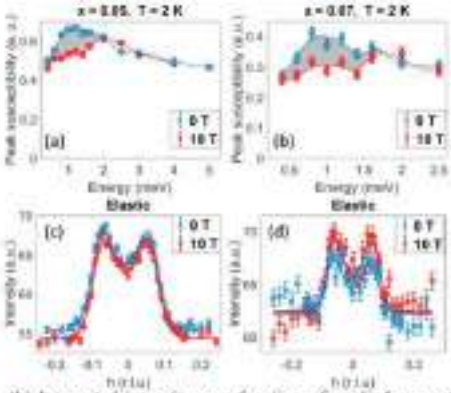

Figure 1 (a) - (b) Integrated intensity as a function of applied magnetic field and energy transfer. The title indicates the sample's doping. (c) - (d) Elastic scans measured at 2K with and without applied magnetic field on the x= 0.05 and x= 0.07 samples respectively. All data was normalized to the 2 meV acoustic phonon.

O14 - Magnetic properties of CoMnVAl: surface and heterostructure with Co2MnAl

2. Electronic structure and strongly correlated electron systems including superconductivity

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The author has chosen not to publicise the abstract.

Field 5

Field 6

O15 - Magnon excitations and quantum critical behavior of the ferromagnet U4Ru7Ge6

2. Electronic structure and strongly correlated electron systems including superconductivity

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We present an extensive study of the ferromagnetic heavy fermion compound $U_4Ru_7Ge_6$. Measurements of electrical resistivity, specific heat and magnetic properties show that this material orders ferromagnetically at ambient pressure with a Curie temperature TC = 6.8 ± 0.3 K. The low temperature magnetic behavior of this soft ferromagnet is dominated by the excitation of gapless spin-wave modes. Our results on the electrical resistivity of $U_4Ru_7Ge_6$ under pressures up to 2.49 GPa suggest that this system has a putative ferromagnetic quantum critical point (QCP) at $P_c \approx 1.7 \pm 0.02$ GPa. In the ordered phase, ferromagnetic magnons scatter the conduction electrons and give rise to a well defined power law temperature dependence in the resistivity. The coefficient of this term is related to the spin-wave stiffness and measurements of the very low temperature resistivity allow to accompany the behavior of this quantity as the the ferromagnetic QCP is approached. We find that the spin-wave stiffness decreases with increasing pressure implying that the transition to the non-magnetic Fermi liquid state is driven by the softening of the magnons. The observed quantum critical behavior of the magnetic stiffness is consistent with the influence of disorder in our system. At quantum criticality ($P = P_c$), the resistivity shows the behavior expected for an itinerant metallic system near a ferromagnetic QCP.

O16 - Pressure effects on the magnetic superconductor Eu(Fe0.88Ir0.12)2As2

2. Electronic structure and strongly correlated electron systems including superconductivity

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The observation of high-Tc superconductivity in FeAs based 122-type compounds (AFe_2As_2) in 2008 has triggered an enormous scientific interest in the last decade [1-5]. Here, we investigate the rich playground among the electronic, magnetic and structural properties of the $Eu(Fe_{0.88}Ir_{0.12})_2As_2$ compound using x-ray absorption spectroscopy and single crystal diffraction techniques under high pressure and at room and low temperatures. The aforementioned Eu-based material orders ferromagnetic (FM) below $T_C \sim 17$ K at ambient pressure, where a small or complete absence of magnetic moments are observed at the Fe and Ir sites. Therefore the magnetism is dominated by the Eu^{2+} ions (J=7/2). In addition, macroscopic measurements surprisingly display a bulk superconductivity emerging below 22 K [3] in which magnetism and superconductivity coexist at low temperatures.

Our X-ray absorption spectroscopy (XAS) measurements reveal that the Eu^{2+} ions have the magnetic state diminished followed by an enhancement of the amount of the non-magnetic Eu^{3+} ions (J = 0) [Fig. 1(a)-(b)]. The collapse of the magnetic state starts arising around 3-5 GPa in which it can be seen as a delocalization of the $4f^7$ shell electrons. Consequently a charge transfer between the Eu magnetic ions and the dense orbital environment can be expected. However, no evidence of magnetism was found at the Fe ions under pressure which contradicts band structure calculations performed for Co doped materials [6]. In addition, we observe that around 15 GPa the x-ray magnetic circular dichroism (XMCD) is reduced drastically to 20 % in which the average oxidation state for the Eu ions is approximately +2.3.

To probe the lattice, high-pressure single crystal x-ray diffraction measurements were performed at room and at low temperatures. As observed in the XAS measurements, around 3-5 GPa a first transition from tetragonal (T) to collapsed-tetragonal (CT) is observed, that is temperature-independent [Fig. 1(c)]. This isostructural transition is mainly stimulated by the compression of the Eu ions since the Eu^{3+} ions have a small volume compared with the Eu2+. However, the CT phase is rapidly suppressed in which above 8-12 GPa the system transits to an orthorhombic (Or) phase with a strong temperature dependence as observed for data collected at room and low temperatures. In this range of pressure and above, the Eu oxidation seems to be very close to the saturation value which makes the As-Fe/Ir-As and As-Eu-As layer distances play important role in the properties of the system. Consequently, the layer distance might directly affect the superconductivity and the magnetism in the system.

These results open up new possibilities for exploring how the structural, electronic and magnetic properties can be coupled to superconductivity in the 122 family.

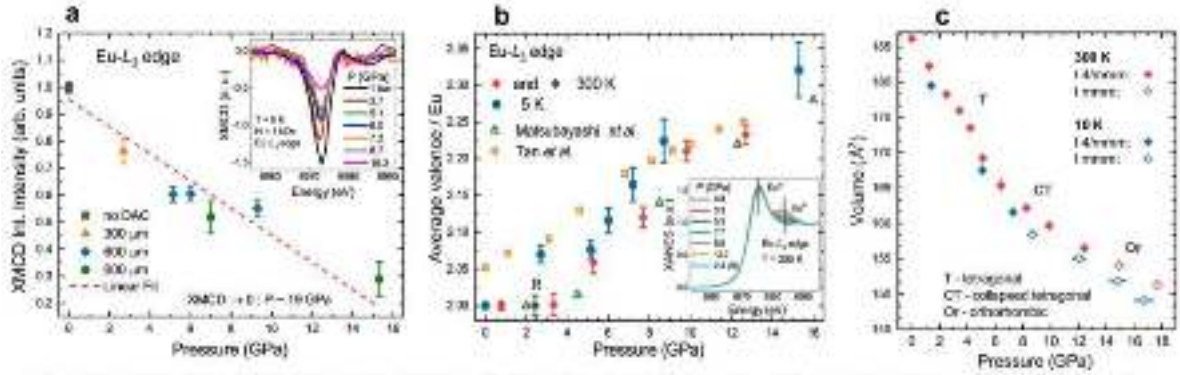

Fig. 1: Pressure dependence obtained at different temperatures on $Eu(Fe_{0.88}Ir_{0.12})_2As_2$ single crystals and powder samples. Panels (a)-(b) show the XMCD and XANES data collected at the Eu L_2 edge, respectively and (c) the unit cell volume.

O17 - Reemerging magnetism in TiPO4 at high pressure

2. Electronic structure and strongly correlated electron systems including superconductivity

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Titanium phosphate shows several interesting features as pressure and temperature is varied, e.g. spin-Peierls transition and incommensurately modulated phases. In this work we have investigated the magnetic properties of $TiPO_4$ at high pressure and the effect of electron correlations on the structural and electronic properties of $TiPO_4$.

At ambient pressure $TiPO_4$ feature edge-sharing TiO_6 octahedra that form chains in the c-direction (phase I). At low temperatures these chains are antiferromagnetically ordered. As pressure is increased the chains begin to dimerise, leading to an incommensurately modulated crystal structure (phase II). Eventually the dimerisation of these chains locks in, leading to a dimerised phase III.

We find that as pressure is further increased the local magnetic moments of the Ti atoms and the band gap decrease. In connection with metallization, there is a phase transition into two recently discovered crystallographic phases.
In these high pressure phases, the band gap is restored.
In an addition, one of the phases also shows a large local magnetic moment of the Ti atoms.

O18 - The Quasi-one-dimensional Metallic Antiferromagnet NaV2O4 Studied by Neutrons, Muons and Photons

2. Electronic structure and strongly correlated electron systems including superconductivity

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The microscopic magnetic nature of NaV_2O_4, in which the V ions form quasi-1D (Q1D) zigzag chains along the **b**-axis, was initially investigated by positive muon-spin spectroscopy (μSR) **[1]**. Powder samples were studied down to $T = 1.8$ K and a static antiferromagnetic (AF) order appears below $T_N = 140$ K. In order to clarify the reason for the coexistence of long-range AF order and metallic conductivity in NaV_2O_4, neutron powder diffraction experiments were performed. The analysis of the magnetic Bragg peaks below $T_N = 140$ K demonstrated the formation of an incommensurate spin density wave order (IC-SDW) **[2]** with **k** = (0, 0.191, 0), the ordered moment was estimated to be (0, 0, 0.77 μ_B) at T = 20 K. Further, from synchrotron radiation x-ray diffraction, we found no indication of structural phase transitions down to $T = 100$ K. Hence, the IC-SDW order is thought to be caused by an intrinsic instability of the V_2O_4 zigzag chain system at low T. Recently, we found details in our μSR data, indicating the presence of a helical magnetic order in this compound **[3]**, which was further supported, by NMR and bulk measurements **[4]**. Finally, the electronic structure of single crystal NaV_2O_4 was investigated using angle-resolved photoelectron spectroscopy (ARPES). The spectra show two dispersing bands crossing the Fermi level and a 1D Fermi surface strongly nested along the **b**-axis **[5-6]**. The nesting vector is found as **k** = (0, 0.195, 0), perfectly matching our neutron diffraction data.

This research is funded by Swedish Foundation for Strategic Research (SSF) within the Swedish national graduate school in neutron scattering (SwedNess), a Marie Skłodowska-Curie Action, International Career Grant through the European Commission and Swedish Research Council, VR (INCA, Dnr. 2014-6426), a VR neutron project grant (BIFROST, Dnr. 2016-06955), a VR Starting Grant (Dnr. 2017-05078) as well as Carl Tryggers Foundation for Scientific Research (CTS-18:272).

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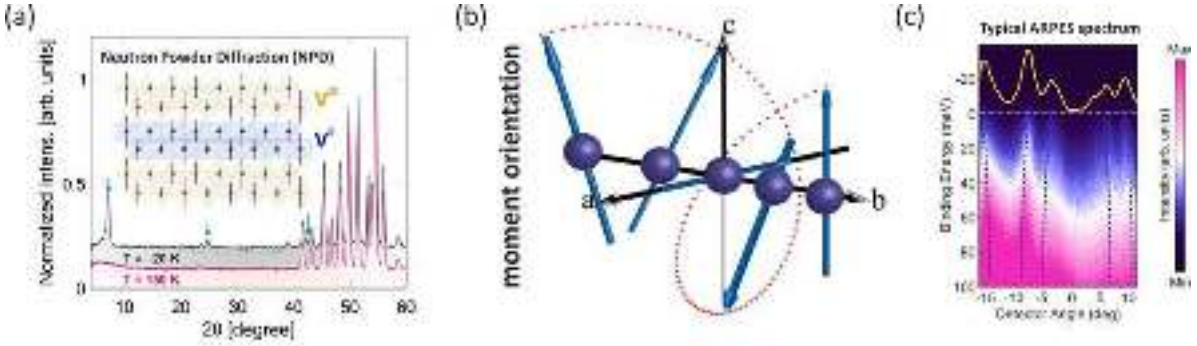

Figure 1: **(a)** Neutron Powder Diffraction (NPD) pattern above and below T_N. **(b)** μ+SR measurements reveal that the magnetic order is of a helical nature. **(c)** ARPES data show clear nesting of the Fermi surface.

O19 - UCu2P2 and high Curie temperatures at U-based ferromagnets

2. Electronic structure and strongly correlated electron systems including superconductivity

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Very strong spin-orbit interaction of the 5f states involved in metallic bonding has a great potential for information storage, magnet technologies, or spintronics. A drawback is low ordering temperatures, remaining below the room temparture for all U-based ferromagnets. Alloying with 3d metals, the route working well for enhancing the T_C value in rare-earth compounds, leads to the mutual 5f-3d hybridization, detrimental for both 3d and 5f magnetism in the actinides case. How else can be the 5f magnetism tuned? A hint has been provided by uranium hydrides. Short U-U distances, being as low as 330 pm in beta-UH_3, prevent the localization of the 5f states. Following the systematics, the hydrides should be actually non-magnetic. In reality they are robust ferromagnets with T_C = 165 K, equal for both UH_3 structure modifications. This fact brought us to explore the reasons, as they may hint to a more general route of the T_C enhancement. They could be identified when comparing partial densities of states of U metal and UH_3. The H bonding affects mostly the U-6d states, normally bringing the 5f-6d hybridization, contributing to the 5f band broadening. In the hydrides, the 6d states are withdrawn from the hybridization with the 5f states. One part is hybridized with the H-1s states in the range 5-7 eV below the Fermi level, another part shifts above the Fermi level. The 5f-6d hybridization is therefore mostly inhibited, the very narrow 5f band stays around the Fermi level, leading to a modified band magnetism with strongly correlated features, indeed observed by electron spectroscopies. The total negative charge on H increases, mostly due to the 6d transfer, while the 5f occupancy remains practically unchanged [1].

Exploring other possible U-based materials, a similar situation can be expected in pnictides. Binary and ternary compounds including a pnictogen (As, Sb, Bi) exhibit magnetic ordering at rather high temperatures. Among ferromagnets, UCu_2P_2 is the record holder with T_C = 216 K [2]. Unlike hydrides, the U-U spacing is considerably larger, reaching almost 400 pm, which can be actually too high for optimum T_C. To test it we undertook an experiment of exposure of a UCu_2P_2 single crystal to hydrostatic pressure p while monitoring the T_C variations. Indeed, T_C strongly increases, reaching almost 270 K in a broad maximum around p = 6 GPa. The experiment is complemented by ab-initio fully relativistic spin- and orbital-polarized calculations, revealing the changes of populations of individual type of states. It is shown that the total moment 1.9 μ_B/f.u. consists of spin μ_S = -2.0 μ_B and orbit μ_L = 3.9 μ_B. The calculations correctly reproduced the easy magnetization direction, which is the *c*-axis of the hexagonal structure. The anisotropy energy is 8.2 meV/U atom, i.e 131 K. DLM calculations give the T_C = 282 K. The case demonstrates that the 5f ferromagnetism at room temperature is possible.

This work was supported by the Czech Science Foundation under the grant No. 18-02344S.

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P22 - Interfacial FM Coupling and Spontaneous Positive Exchange Bias in SrFeO3-x/La0.7Sr0.3MnO3 bilayer

2. Electronic structure and strongly correlated electron systems including superconductivity

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Negative exchange bias (NEB) is usually discovered in ferromagnetic (FM)/antiferromagnetic(AFM) or FM/FM heterostructures after field cooling (FC). [1,2] Relatively, positive exchange bias (PEB) is a rarely observed phenomenon. So far, almost all of models for PEB whether undergo FC or zero-field-cooled (ZFC) have been explained by an interaction of strong AFM coupling at the interface.[3-5] In this work, high-quality $SrFeO_{3-x}$ 20 u.c/LSMO 13 u.c bilayers were successfully fabricated on the STO (001) substrate by pulsed laser deposition system. The interfacial flatness of the film was observed by high-angle annular dark-field scanning transmission electron microscopy (HAADF-STEM) instrument, certifying the layer-by-layer growth nature. X-ray diffraction (XRD) technique confirmed the bilayers were fully textured along the (00*l*) orientation of the substrate. Magnetic properties were determined by vibrating sample magnetometer in PPMS (PPMS-VSM) with a in-plane applied magnetic field, and First-principles calculations were carried out with density functional theory and using the projector augmented wave method as implemented in the Vienna *Ab initio* Simulation Package (VASP). The result reveals that a novel PEB effect were obtained after ZFC the bilayer, of which the shift directions are unfixable and dependent on initial magnetization direction. Through an in-plane induced field to control the remanence (M_r) direction of LSMO at room temperature (RT), followed by cooling below the T_N of $SrFeO_{3-x}$ without any magnetic field treatments, the shift direction can be locked only toward the induced field. Combine with experimental results and first-principles calculations**,** we propose that the above phenomena are explained as field-induced AFM phase of $SrFeO_{3-x}$ transform into FM phase at a FM coupling bilayer interface. Thus, our conclusions not only provide an appealing way to realize and tune the zero-field-cooled PEB with FM coupling heterogeneous systems but also promote the application of low energy consumption EB-based spintronics without magnetic field cooling.

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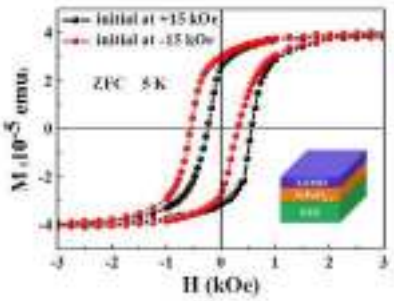

Fig. 1. M-H loops of $SrFeO_{3-x}$ 20 u.c/LSMO 13u.c bilayer after ZFC at 5 K, the black and red loops represent the measurements from initial magnetization field of +15 kOe and -15 kOe respectively, the inset shows the stack order of the sample.

3. Frustrated and disordered magnetism, artificial spin ice

O20 - Dipolar Spin Ice Under Uniaxial Pressure

3. Frustrated and disordered magnetism, artificial spin ice

Richard Edberg[1] , *Lise Ørduk Sandberg[2], Ingrid Marie Bergh Bakke[3], Morten Lunn Haubro[2], Lucile Mangin-Thro[4], Andrew Wildes[4], Malcolm Guthrie[5, 6], Alexander Holmes[5], Magnus Sørby[7], Kim Lefmann[2], Helmer Fjellvåg[3], Pascale Petronella Deen[2, 5], Patrik Henelius[1, 8]*

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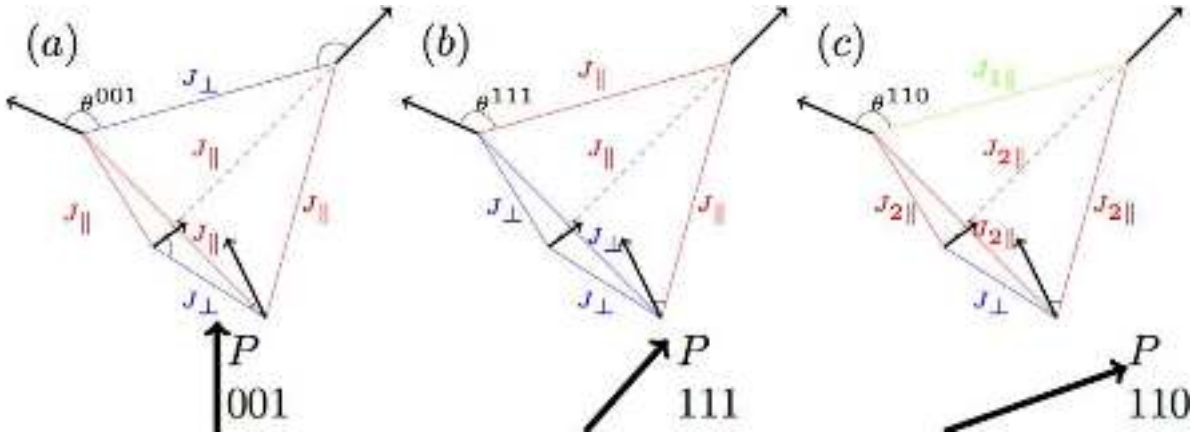
The magnetically frustrated spin ice family of materials is host to numerous exotic phenomena such as magnetic monopole excitations and macroscopic residual entropy extending to low temperature. A finite-temperature ordering transition in the absence of applied fields has not been experimentally observed in the classical spin ice materials $Dy2Ti_2O_7$ and $Ho_2Ti_2O_7$. Such a transition could be induced by the application of pressure, and in this work we consider the effects of uniaxial pressure on classical spin ice. Theoretically we find that the pressure induced ordering transition in $Dy_2Ti_2O_7$ is strongly affected by the dipolar interation. We also report measurements on the neutron structure factor of $Ho_2Ti_2O_7$ under pressure, and compare the experimental results with the predictions from our theoretical model.



O21 - Elementary excitations of fluctuating-stripe state in quantum spin chain

3. Frustrated and disordered magnetism, artificial spin ice

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Elementary excitations are a basic concept essential for describing dynamical processes in condensed matter. Their variety is vast; ranging from established phonons and magnons to exotic magnetic monopoles [1] and Majorna fermions [2]. Yet, when order parameters intertwine, identification of elementary excitations is extremely difficult. For instance, the elusive excitations in high-temperature superconductors that propel fluctuating-charge-stripe, i.e., electronic nematic, phases [3] are still unidentified.

Here we report on a new type of elementary excitations in a spin-stripe state that is a bound state of two phason excitations, corresponding to two perpendicular amplitude-modulated magnetic components with different modulation periods. Exploring the frustrated zigzag spin-1/2 chain compound beta-$TeVO_4$ [4,5] by muon-spin relaxation, neutron diffraction and dielectric spectroscopy, we find that the spin-orbit coupling introduces sizable anisotropic- and fourth-order-exchange interactions, which stabilize the spin-stripe phase and set the energy scale of underlying excitations. beta-$TeVO_4$ offers a unique perspective on the stripe physics that avoid the problem of intertwining degrees of freedom, which hinders high-temperature superconductors.

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O22 - Energy barrier reduction in square artificial spin ice due to collective excitation modes

3. Frustrated and disordered magnetism, artificial spin ice

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In contrast to the geometrical frustration arising from a disorder in the structure, a new emerging topic of research is to make use of topologically well-ordered systems consisting of ferromagnetic nanoislands arranged in planar arrays to create the geometrical frustrations. The systems, where the geometrical frustration arises from the dipolar interactions among the magnetic islands, are called artificial spin ices (ASIs)[1]. In square ASI, different magnetizations of the four islands arranged in a vertex lead either to excited or stable states. The possible configurations are separated by energy barriers (ΔE), which can be reduced to zero by either applying an external field forcing the macrospins to a rearrangement or overcome due to thermal fluctuations. To be able to control these structures it is necessary to fully understand the reversal mechanism between distinct states.

We investigate the thermal relaxation and therefore, the reversal mechanism in square ASI by performing micromagnetic simulations. We consider an excited state (two Type III vertices) as the initial state. By reversing the magnetization of the central island, we obtain one stable state (two Type II vertices), see Fig.1-b. We find that the interactions of the central island with its nearest neighbors are crucial to understanding the reversal mechanism between two state types. In order to analyze the temperature dependence of ΔE, we perform the simulations reducing the saturation magnetization defined as $M_S(T)=M_0(1-T/T_c)^{0.54}$, where M_0 is the saturation magnetization at zero temperature, T the temperature and T_C is the Curie-temperature. By applying the “string method”[2], we find the minimum energy path (MEP) for the reversal mechanism between Type III and Type II vertices. The MEP yields the energy barrier necessary to switch between different types. Furthermore, with the obtained ASI configurations we analyze the changes in ΔE arising from the MEPs for the two possible rotation directions of the magnetization of the central nanoisland.

We will show that it is essential that the collective magnetization excitations during the reversal of the central element are taken into account. We consider two different scenarios for the neighbors. First, ΔE is computed thus that the magnetization of the neighboring islands are relaxed and hold constant during the rotation process. We apply the interaction fields as an external field on the central island. In the second case, we relax the magnetization of the neighboring islands for each intermediate state, as usual in the improved string method[2], see Fig. 1. We show that the magnetization of the central island affects the interaction fields during the rotation process. For the second approach, we obtain a different and energetically more convenient MEP (Fig.1-a). Hence the energy barrier is reduced by 20 % with respect to one isolated nanoisland. Furthermore, the Néel relaxation time of the central island decreases from $\tau=9.4\cdot10^{17}$(s) to $\tau=2.1\cdot10^{12}$(s) for $\nu_0=0.5\cdot10^{12}$ (s^{-1}) and T=350(K)[3].

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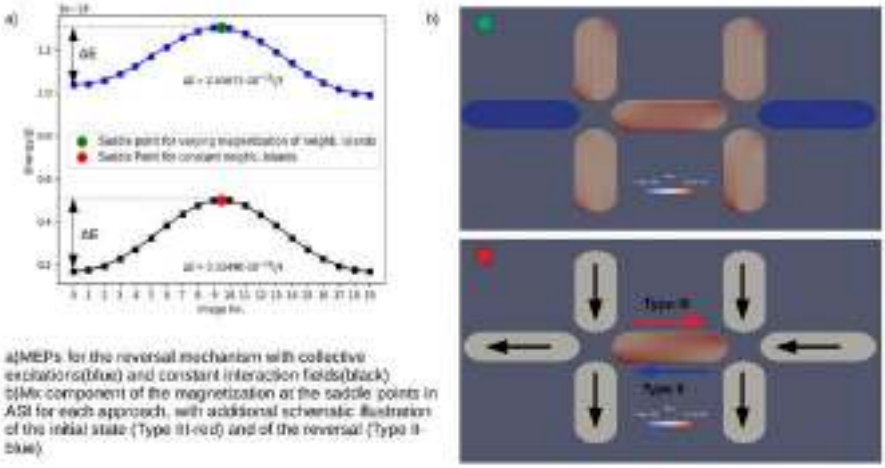

a)MEPs for the reversal mechanism with collective excitations(blue) and constant interaction fields(black) b)Mx component of the magnetization at the saddle points in ASI for each approach, with additional schematic illustration of the initial state (Type III-red) and of the reversal (Type II-blue)

O23 - Exploring Magnetic Disorder at the Nanoscale

3. Frustrated and disordered magnetism, artificial spin ice

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Magnetic nanoparticles (MNPs) show many interesting phenomena due to their unusual physical properties strongly correlated with their size and morphology. Among the relevant features of the size reduction of MNPs, the occurrence of surface magnetic disorder deserves a special attention as it strongly modifies the magnetic properties of the materials. In the case of magnetic nanoparticles with surface to volume ratio (S/V) higher than 1 (i.e. for spherical nanoparticle with diameter below 5 nm) the fraction of spins lying at/or near the surface produces a great enhancement of surface anisotropy and magnetic frustration due to the spin disorder. In this frame, this communication will present two kinds of nanoparticle systems with high S/V ratio, highlighting the effect molecular coating and peculiar magnetic structure in hollow nanoparticles with R > 1. We investigated the effect of coating 5 nm $CoFe_2O_4$ particles by diethylene glycol (DEG) and oleic acid (OA). An unexpected increase of the saturation magnetization and the blocking temperature, and a decrease of the coercive field was observed DEG coated $CoFe_2O_4$ nanoparticles with respect to nanoparticles coated by OA. This can be attributed to the larger atomic magnetic moments and to the lower magnetocrystalline anisotropy of the DEG sample as was demonstrated by DFT calculations[1]. Starting from these results and having in mind the exploration of “the no man’s land” of system with very high value of R > 1 hollow iron oxide nanoparticles with external diameter ~9.4 nm has been investigated. High-resolution transmission electron microscopy images confirmed the crystalline structure and the presence of an ultrathin shell thickness of ~1.4 nm, implying, to the best of our knowledge, the highest value of R observed in the literature (R ≈ 1.5). These hollow nanoparticles have been investigated by AC/DC magnetization measurements and using zero-field/in-field ^{57}Fe Mössbauer spectrometry. The in-field hyperfine structure suggests presence of a complex magnetic structure that can be fairly described as due to two opposite pseudo speromagnetic sublattices attributed to octahedral and tetrahedral iron sites. Such an unusual feature, observed for the first time in crystalline materials.[2]

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This work was partially supported by the FET-Proactive MAGENTA Project (Contract N. 731976).

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O24 - Interaction modifiers in artificial spin ices

3. Frustrated and disordered magnetism, artificial spin ice

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We present a generic solution to continuously alter the effective coupling between mesoscopically sized islands of a ferro-magnetic material in a fully planar geometry [1]. The approach involves mixing nano-magnetic objects of distinctly different mesospin dimensionality. In our example we use both elongated islands, spin dimensionality one, and discs, spin dimensionality two, to create a new type of square artificial spin ice (SASI) system dubbed modified SASI (mSASI) where a disc is placed in each vertex. The disc acts as an interaction modifier and alters the effective coupling strengths between the elongated islands. In this way we can not only recover the degeneracy between T_I and T_{II} vertices, which is lost in SASI [2]**,** but also promote an emergent magnetic order when the energy landscape is reversed, see Fig. 1**.**

In order to study spatial correlations we use the magnetic spin structure factor (SSF). As G is decreased, and the effective coupling increased, the magnetic SSF goes from having well defined bragg peaks (D=0) as expected when having large T_I domains, to resemble the characteristic intensity distribution for a square-ice model spin liquid (G=30), associated with an emergent Coulomb phase with slow decaying spin correlations [3,4,5]. Furthermore at the smallest G=15 the T_I and T_{II} population is reversed. Here the abundance of T_{II} vertices gives rise to an emergent flux lattice on the next length scale dictating the order of the spin system. The synergy and cooperative behaviour between the two different mesospins provides a route for designing new types of magnetic metamaterials with rich magnetic phase diagrams and thermodynamics.

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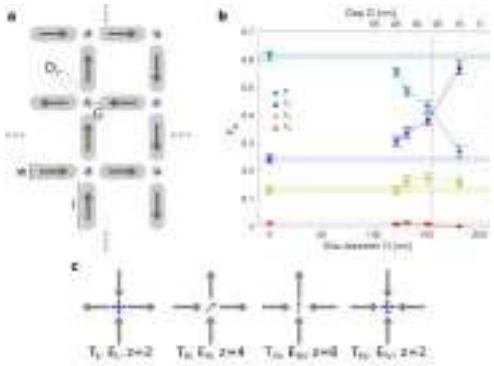

Figure 1: **a** Schematic illustration of the mSASI lattice with a disc in the middle of each vertex. The gap, G, depends on the disc diameter, D, the island length, l, and the island width, w. **b** Degeneracy corrected fraction of vertex population with changing D in thermally equilibrated magnetic states. l and w are kept constant. **c** The four vertex types, T, with their respective energies, E, and degeneracy, z.

O25 - Kondo Screening in a Quantum Spin Liquid

3. Frustrated and disordered magnetism, artificial spin ice

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The Kondo effect, traditionally arising from exchange scattering of conduction electrons on a magnetic impurity in a metal, is an eminent manifestation of many-body physics in condensed matter [1, 2]. The resulting screening of the impurity's local moment by the electron Fermi sea is characterized by a Kondo temperature below which the system enters a strongly-coupled, non-perturbative regime (Fig. 1). In recent years, this effect has found its realizations beyond the bulk-metal paradigm in many other conduction-electron systems, such as in quantum point contacts, graphene, topological insulators, quantum dots in semiconductor heterostructures and nanomaterials, and was also predicted for three-dimensional Dirac and Weyl semimetals.

We have recently demonstrated the first experimental realization of Kondo screening by charge-neutral quasiparticles [3]. The observed effect occurs in Zn-brochantite, $ZnCu_3(OH)_6SO_4$ [4-7], a charge-insulating quantum kagome antiferromagnet in which strong frustration coupled with quantum fluctuations suppresses any long-range magnetic order, giving rise to a long-range-entangled disordered state called a quantum spin liquid instead. The general properties of this state are still hotly debated [8] but in Zn-brochantite the observable behaviour is dominated by neutral-yet-spinful spinon excitations that form an extended Fermi surface. These take the role of conduction electrons in screening the magnetic moments of inherently-present impurities in the sample. The observed impurity behaviour therefore bears a striking resemblance to the conventional case of a magnetic impurity in a metal, albeit with some subtle but noticeable deviations due to the presence of emergent gauge fields that are present in quantum spin liquids but not in metals.

The discovered spinon-based Kondo effect provides a prominent platform for characterising quantum spin liquids, in the general context of utilizing impurities as *in situ* probes of their host states, and also offers a unique way of manipulating these enigmatic and elusive states.

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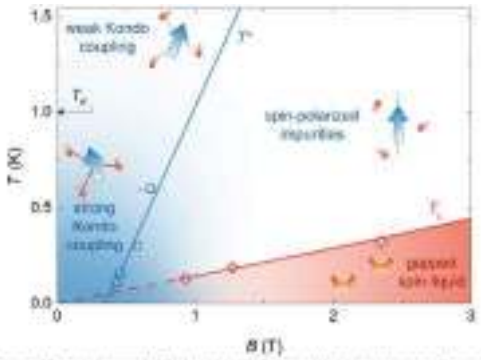

Figure 1. Phase diagram of Zn-brochantite showing Kondo screening of impurity spins (large arrows) by spinons (small arrows) in the gapless spin-liquid state of Zn-brochantite. The Kondo temperature T_K separates the weak- and strong-coupling Kondo regimes, while the $T^*(B)$ line corresponds to experimentally-determined Kondo-resonance-splitting fields (squares) above which impurities strongly polarize. At elevated fields and temperatures below T_c (diamonds) Zn-brochantite undergoes a separate, intrinsic spinon-pairing transition into a gapped spin-liquid state.

O26 - Magnetic Force Microscopy of Intermediate Angle Pinwheel Artificial Spin Ice

3. Frustrated and disordered magnetism, artificial spin ice

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Square artificial spin ice (ASI) are systems of bistable coupled single-domain nanomagnets arranged in a square lattice, with four adjacent magnets aligned head-on at each vertex point. The magnets are dipolar-coupled so that the macrospins at each vertex point obey ice rules, minimizing the magnetic charge. The square ASI systems have been extensively studied and found to exhibit stable demagnetized antiferromagnetic ordering [1]. By rotating each nanomagnet some angle α around its center the pinwheel ASI variant is created. Recent studies have shown a new phase of stable ferromagnetic ordering for pinwheel ASI where α is near 45° [2]. Theoretical considerations of these pinwheel ASI conclude that they exhibit regions of net magnetization, arranged to minimize the overall stray magnetic field.

Preliminary simulations show that a regime with co-existing ferro-/antiferromagnetic order can be found at intermediate rotation angles (α-values around 30°-35°). In this study we use magnetic force microscopy to investigate pinwheel ASI with intermediate α between 0°-45°. The investigated ASI are made of elements of about 220 nm by 80 nm. Additionally, the dipolar coupling of the magnets is controlled by varying the pitch of the lattice, effectively tuning the packing density and spacing between magnets. See SEM image of fabricated 45° pinwheel structure with magnet spacing of about 16 nm and corresponding MFM image below.

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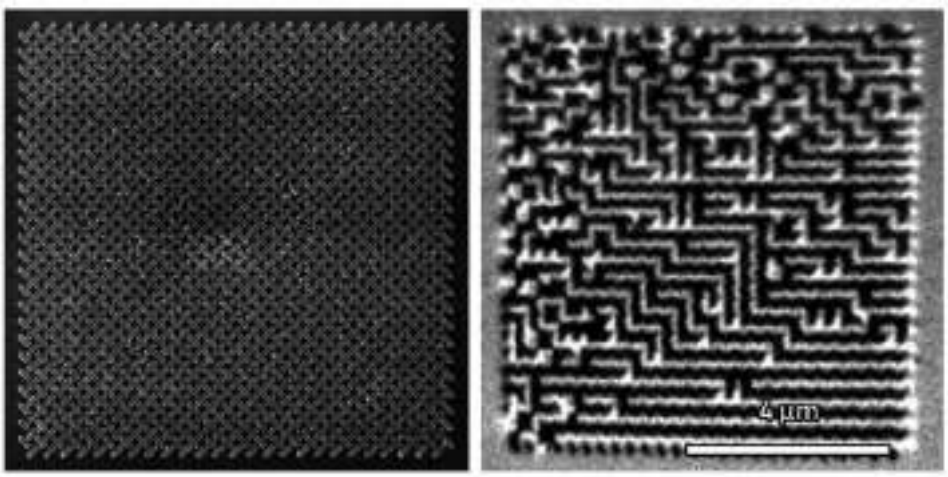

O27 - Magnetic properties of the transition-metal chalcogenide LiCrSe2

3. Frustrated and disordered magnetism, artificial spin ice

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For compounds having a two-dimensional triangular lattice (2DTL), on which each corner is occupied by a magnetic moment, when the interaction between the two neighboring moments is antiferromagnetic (AF), it is impossible to satisfy all AF interactions. As a result, such geometrical frustration often leads to exotic magnetic transitions. Chromium compounds $ACrX_2$ with a triangular lattice are widely studied as a geometrically frustrated Heisenberg spin system with S = 3/2. Among them, chromium selenides and tellurides ($ACrSe_2$ and $ACrTe_2$) **[1,2]**, where Cr ions create the 2DTL connecting edge-sharing CrX_6 octahedra, are the less studied, probably due to the difficult synthesis. In this work we present the results of the very first neutron diffraction experiment performed on the novel compound $LiCrSe_2$, obtained by Li+ ion insertion in the crystal structure of $CrSe_2$, previously characterized within our collaboration **[3]**. Our interest around $LiCrSe_2$ is double:

- From a magnetic point of view, the occurrence of a competition between the antiferromagnetic in-plane metal-metal direct exchange interaction and the ferromagnetic interlayer super-exchange interaction, leads to a spin structure very different with respect to the one observed in the parent compound $CrSe_2$. Preliminary magnetic susceptibility measurements show that $LiCrSe_2$ displays an antiferromagnetic transition at T_N = 33. Moreover, from in-house XRD, $LiCrSe_2$ shows a first-order-like phase transition from a trigonal phase to lower symmetry phase at T_N.
- From the applied science point of view, the layered crystal structure of $LiCrSe_2$, with the Li-ion planes sandwiched between the CrO_2 planes, makes it suitable for possible battery applications. Such structure is indeed similar to well established battery cathode materials e.g. $LiCoO_2$ **[5]**, and $NaCoO_2$ **[6]**.

The neutron powder diffraction experiment on $LiCrSe_2$ confirmed the room temperature crystal structure as well as the first-order nature of the structural transition observed in the XRD experiment. From the comparison with the results of our previous μ^+SR characterization, also the magnetic transition is shown to display a first-order like behavior. The occurrence of magnetic and structural transition at the same critical temperature is explained by the presence of magnetoelastic coupling between the ordered magnetic moments of the chromium atoms, which induces the lattice distortion. The conjecture formulated after the preliminary in-house XRD experiment for the low temperature crystal structure is monoclinic C2/m, nevertheless the attempts of magnetic structure refinement with the neutron data, starting from a C2/m crystal structure, could not lead to any solution for the spin structure. This is an indication of the fact that the conjecture is probably wrong, however the occurrence of magnetoelastic coupling greatly complicates the neutron analysis, a further synchrotron XRD experiment is therefore foreseen to complete the picture.

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O28 - Micromagnetic simulations of artificial spin ice lattices and vertices

3. Frustrated and disordered magnetism, artificial spin ice

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Research into geometrical frustration over the past two decades has revealed fundamentally new exotic behavior [1]. The magnetic interactions of the structure, coupled with the specific geometry causes frustration in the system, referred to as artificial spin ices. Several geometries exist, but for the purpose of this research, the kagome and square moment arrangements were used. In general, the geometry of these frustrated systems follows the ice rule, that being two interacting moments point in while two point out. The kagome however follows the modified ice rule of two moments pointing in while one points out or vice versa. These systems appear as 2D analogues to the 3D structure and it is the lattice configuration along with the specific frustration created that causes these exotic behaviors. Presented here are the magnetoresistances obtained for kagome and square magnetically frustrated systems in a single vertex and lattice format. Both geometries are compared in a magnetically connected format and a magnetically disconnected format in order to observe the exchange and dipolar energies. These structures were simulated as permalloy, using OOMMF [2], with dimensions of 1µm long, 100nm wide and 10nm thick, with the aim being to evaluate the magneto resistance. These calculations were done in post processing, assuming the current density aligns with the long axis and a basic resistor network. By comparing the simulated data for the connected and disconnected lattices with the measurements taken previously, a greater understanding of the effect of the disconnected versus connected structures can be achieved. Measurements of the kagome lattice showed that the disconnected lattice had a change in magnetoresistance that was 2~3 times greater than the connected lattice. The subtle difference in the geometries of the connected and disconnected lattices aids in the explanation of the effects and interplay of both the spin structures and the current density.
This work demonstrates the potential for using simulations to expose magnetic interactions in a lattice type structure and other interesting geometries, along with the enhanced magnetoresistance.

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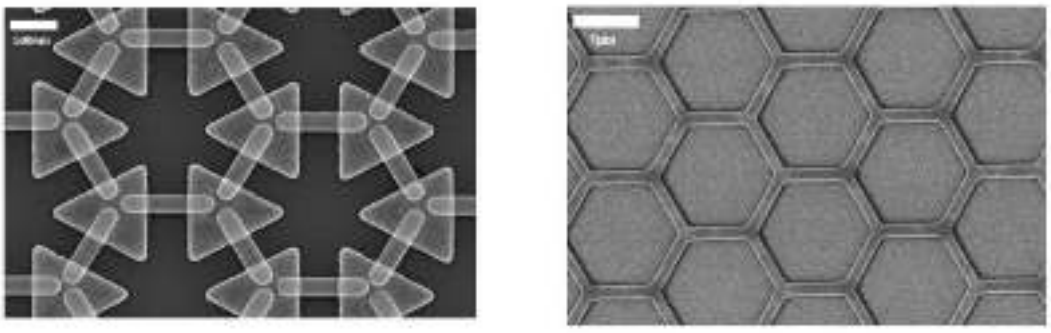

Figure 1. SEM images of an electrically connected but magnetically disconnected (hybrid) lattice (left). Also shown is the standard honeycomb lattice for comparison.

O29 - Neutron diffraction study of NaMn2O4 with two-leg zigzag ladders

3. Frustrated and disordered magnetism, artificial spin ice

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The interest for low dimensional and frustrated spin systems is attracting attention in both the experimental, as well as theoretical research communities (*1*, *2*). The reason is that these materials display a variety of fascinating phenomena, such as exotic magnetic ground states, superconductivity and quantum effects. Often, such the physics behind these phenomena arises from crystal and magnetic structure, e.g. well-separated chains (1D) or planes (2D), triangular-based, the Kagome and honeycomb lattices.
The compounds with Calcium-ferrite $CaFe_2O_4$ (CFO) structure have been extensively studied in the last decade because of their complexity of competing interactions on a magnetic arrangement, as they exhibit an original geometrically frustrated lattice, based on a honeycomblike mesh of triangular or zigzag ladders of magnetic atoms (*3*, *4*).
Within this CFO system, $NaMn_2O_4$ was first reported by Awaka et al. (*5*, *6*), who synthesized it under high-pressure of 4.5 GPa. The crystal structure at room-temperature is reported as an orthorhombic having a *Pnam* with a~8.87Å, b~11.2Å and c~2.85Å. In this structure, Mn_2O_4 double zigzag chains are formed by a network of edge-sharing MnO_6 octahedra aligned along the *c*-axis so as to make irregular hexagonal 1D channels. The most characteristic feature in the present $NaMn_2O_4$ structure is the manganese charge and orbital ordering (Jahn-Teller effect) in the Mn^{3+}/Mn^{4+}sites, which might give strong influences to spin ordering (Figure 1a,b). In fact, our muon spin rotation spectroscopy study investigated the signature of the complex magnetic structure of $NaMn_2O_4$ (*7*).

The fact that the magnetic structure of $NaMn_2O_4$ was not determined in these earlier works motivated us to revisit its crystal and magnetic structures, along with the physical properties. To this end, neutron powder diffraction (HRPT and DMC@PSI, Switzerland), were performed on this compound.
High-resolution neutron powder diffraction data recorded at 200 and 1.5K show the absence of any modification of the crystal structure, which remains *Pnam* down to 1.5K. A broad asymmetric feature is observed on the neutron diffraction data below 75K. This diffuse scattering signal decreases and the first magnetic peaks appear at 32K, which all indexed with a propagation vector k = (0.5 -0.5 0.5). For below 6K, a few extra magnetic peaks are observed on top of commensurate magnetic phase, which can be indexed with an incommensurate propagation vector (Figure 1c).
The investigation of magnetic structures is currently carrying out by Rietveld refinement using symmetry-adapted modes derived from representation analysis. There are four irreducible representations of the little group which all indicate antiferromagnetic couplings along edge-sharing octahedra (*c*-axis). This result is in good agreement with the prediction based on direct exchange interaction and super-exchange interaction between Mn sites (*3*, *8*).

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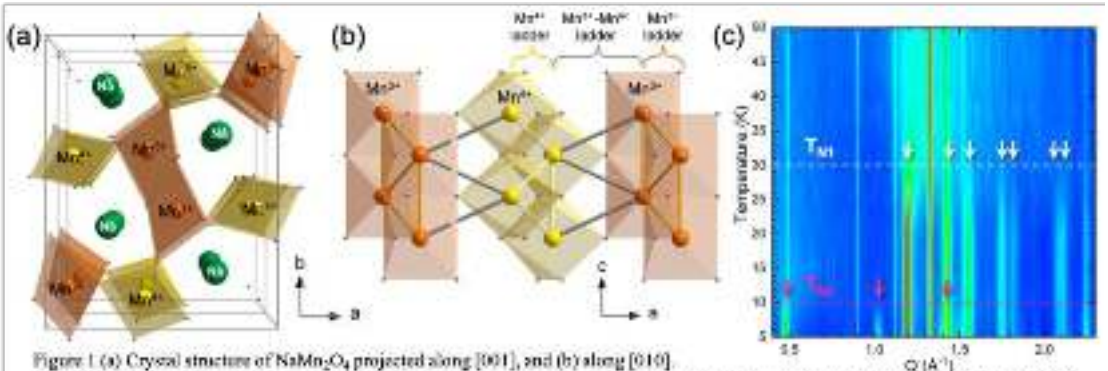

Figure 1 (a) Crystal structure of $NaMn_2O_4$ projected along [001], and (b) along [010]. The Mn^{3+} and Mn^{4+} sites are octahedrally coordinated by oxygen atoms, are shown in orange and yellow polyhedra, respectively. The thick grey bonds show the ladders rungs between adjacent chains on nonequivalent sites. (c) Evolution with temperature of the neutron diffractograms (DMC) of $NaMn_2O_4$. T_{N1} and T_{N2} refer to the temperatures of commensurate and incommensurate magnetic transitions. Arrows indicate magnetic Bragg peaks.

O30 - Phase transitions, topological defects and manifold restoration in 2-D artificial spin ices

3. Frustrated and disordered magnetism, artificial spin ice

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Artificial Spin Ices (ASIs) are arrays of strongly correlated nanoscale magnetic islands that prove an excellent physical playground in which to study the role of topology on critical phenomena. In this work [1, 2], we highlight an ASI system in which the magnetic order can be tuned through changes to the lattice topology. In particular, we morph from the canonical square ice to the recently studied pinwheel geometry [3, 4] by rotating each island about an angle. The angle then acts as a proxy for controlling inter-island interactions. Using Lorentz transmission electron microscopy on thermally annealed Co arrays, we experimentally observe a change in magnetic order from antiferromagnetic (AFM) to ferromagnetic (FM) across this class of geometries and study the dynamics as the blocking temperature is traversed in the two phases. The change in ordering leads to a change in the nature of the defects supported: from one dimensional strings in the AFM phase to two-dimensional vortices in the FM phase, consistent with the Kibble-Zurek mechanism [5]. Our results show how magnetic order in ASIs can be tuned by changes in geometry so that a truly frustrated ice-rule phase is possible in 2-D systems, and demonstrate this system as a testbed to investigate out-of-equilibrium dynamics across phases.

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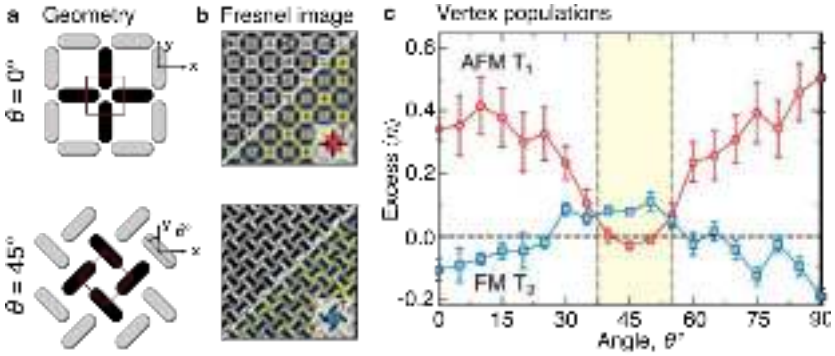

Figure 1. a. The square ice tiling (upper panel) is deformed into the pinwheel tiling on rotation of each island through $\theta = 45°$. **b.** Corresponding Fresnel images (raw in greyscale; Fourier-filtered in colour) are analysed to extract the macrospin orientation. **c.** Repeating this process for arrays with rotation angles in the range [0°, 90°] shows separate regions for which AFM and FM ordering among spins is preferred.

O31 - Quantum origin of the 2/3 plateau in the new frustrated isolated spin-triangle compound BHAP-Ni3.

3. Frustrated and disordered magnetism, artificial spin ice

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We report exotic magnetic properties of the new frustrated quantum magnet [2-[Bis(2-hydroxybenzyl)aminomethyl]pyridine]Ni(II)-trimer (BHAP-Ni_3) synthesized in single-crystalline form. BHAP-Ni_3 provides an ideal opportunity to study the magnetism of a frustrated spin-triangle unit as it is comprised of spin-1 triangles where each triangle is essentially magnetically isolated from the others. Calculations based on density functional theory reveal the presence of all-antiferromagnetic type intra-triangle exchange interactions in this system reflecting the frustrated character of the magnetism involved. Our combined experimental results and theoretical model calculations reveal the existence of an exotic spin state that stabilizes a robust 2/3 magnetization plateau between 7 and 20 T in an external magnetic field at 360 mK. AC-susceptibility data show the absence of any magnetic order/glassy state down to 60 mK. The magnetic ground state is found to be disordered and specific-heat measurements show a gapped nature of spin excitations. Our theoretical modelling suggests that the experimentally observed 2/3 plateau originates from the interplay between Heisenberg and biquadratic spin-spin interactions within a nearly isolated spin $S = 1$ triangle.

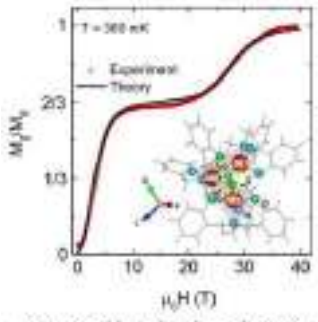

FIGURE: *Field (H) dependence of magnetization (M) measured at 360 mK in pulsed magnetic field up to 40 T along with the theoretical magnetization curve showing the 2/3-magnetization plateau. Inset: A perspective view of the Ni^{2+} (red spheres) spin triangle along with the intra-triangle exchange interactions (yellow lines) in BHAP-Ni_3.*

O32 - Quantum spins on a hyperkagome lattice

3. Frustrated and disordered magnetism, artificial spin ice

Lise Ørduk Sandberg[1, 2] , *Richard Edberg*[3], *Ingrid Marie Bergh Bakke*[4], *Magnus Sørby*[5], *Monica Ciomaga-Hatnean*[6], *Geetha Balakrishnan*[6], *Georg Ehlers*[7], *Gabriele Sala*[7], *Bjorn Fåk*[8], *Lucile Mangin-Thro*[8], *Andrew Wildes*[8], *Kim Lefmann*[2], *Helmer Fjellvåg*[4], *Patrik Henelius*[9], *Pascale Petronella Deen*[1]

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Quantum spin liquid (QSL) states are exotic states of matter that feature strong quantum fluctuations. The signatures of QSL are a disordered ground state at zero temperatures with emergent quasiparticles that exhibit fractionalised excitations. Quantum fluctuations are strongly enhanced in crystalline structures (a) that reveal crystalline symmetry with geometric frustration (b) that are comprised of low spin magnetic ions (S = 1/2) and (c) in which the total spin is entangled with orbital angular momenta. We show that Yb$_{3}$Ga$_{5}$O$_{12}$ (YbGG) realises all of the above parameters and is thus a candidate for a QSL ground state.

The magnetic Yb ions in YbGG realise a lattice of two interpenetrating hyperkagome structures with Yb creating 3D networks of corner sharing triangles. The local crystal field environment, as determined using inelastic neutron scattering, splits the ground state degeneracy J = 7/2 into a Γ_{7} doublet ground state separated from the first excited levels by 64.6 meV (= 746.78 K) such that, at temperatures much lower than the crystal field gap, the magnetic properties are fully described by an effective S=1/2 local moment. Magnetisation measurements determine a Curie-Weiss temperature θ_{CW} = -118 K, indicative of strong net antiferromagnetic exchange, with no indication of long range order down to T_{N} = 54 mK [1], resulting in an unusually high frustration index of θ_{CW}/T_N $\sim$ 2100. Specific heat measurements determined the development of short range magnetic correlations below 0.5 K and a lambda-transition at 54 mK while 170-Yb M\"{o}ssbauer spectroscopy, determined no static magnetic order at temperatures below the lambda-transition. Indeed, the specific heat measurements indicate that only 20\% of entropy is frozen at the lambda point [1,2].

It has recently been possible to synthesise a YbGG single crystal suitable for neutron scattering studies, thereby accessing the detailed magnetic structure and spin dynamics relevant for these low energy phenomena. Neutron scattering results confirm the short range nature of the spin-spin correlations with unusual diffuse scattering features in both the elastic and inelastic channels. Unusually, the short ranged ordered state in the quantum spin YbGG is reminiscent of the directorate state found in the isostructural classical spin compound (S = 7/2) Gd$_{3}$Ga$_{5}$O$_{12}$ (GGG). The directorate state in GGG is a long range multipolar state formed by 10 ion spin loops, locally disordered with antiferromagnetic exchange, yet perturbed by anisotropy to create a non-symmetry breaking state [3]. Interestingly, the local spin configuration for YbGG, derived from Reverse Monte Carlo simulations on 2D single crystal magnetic structure factor data, also reveals a long range directorate state. An overview of the magnetic properties of YbGG are presented and considered in the light of a phenomena that crosses the boundary between classical and quantum spin states.

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O33 - Return Point Memory in Square Artificial Spin Systems

3. Frustrated and disordered magnetism, artificial spin ice

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Many hysteretic systems exhibit an effect referred to as return point memory (RPM) where the system cycles through exactly the same microstates upon subsequent minor field loops. This has been shown in a diverse set of physical systems, from superfluid Helium condensation in capillaries [1] to the domain structure in magnetic thin films [2]. However, in these systems RPM is inferred from macroscopic measurements. Artificial spin ice (ASI) is an array of frustrated magnetic nanoislands which allows for observation of the precise microstate throughout the minor loop. In previous studies ASI has been shown to exhibit RPM [3, 4]. Using magnetic force microscopy and dipolar needle simulations we examine the behaviour of square ASI in response to minor field loops for a range of quenched disorder and interaction strengths. For specific quenched disorder and interaction strengths we show ASI will no longer return to the same microstate after a single minor loop but instead exhibit higher order periodic behaviour. Here we explore the specific structural and magnetic features that give rise to the higher order behaviour.

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O34 - Spin-glass ground-state in Er2Zr2O7: the case of magnetic correlations on diluted fcc lattice

3. Frustrated and disordered magnetism, artificial spin ice

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Cubic $A_2B_2O_7$ oxides with A standing for a rare-earth element and B for a transition or main block metal have been systematically studied for their frequently exotic crystallographic and electronic properties. Diverse ground states, magnetic structures and predicted exciting electronic, magnetic and even topological properties originating from a competition between electron-electron correlations and spin-orbit coupling have been reported [1 and references therein]. The geometrical frustration of magnetic moments residing on the A and/or B crystallographic positions offer a playground for scientific investigations as well.

$A_2B_2O_7$ compounds in general crystallize either in a pyrochlore structure (*F d -3 m,* 227), defect-fluorite structure (*F m -3 m*, 225) or a low-symmetry monoclinic structure (*P 1 1 2_1*, 2 [2]) at ambient pressure. The pyrochlore structure represents one of the canonical examples for a structure where a unique ground state is difficult to achieve for a system of magnetically coupled moments as demonstrated on a number of compounds [1,3,4 and references therein]. The fluorite structure is another example of a geometrically frustrated lattice, due to the fcc lattice of cations. However, the rare-earth/transition metal octahedra are edge-, not vertex-sharing leading to a different exchange pathway type and thus different magnetic exchanges. Moreover, the diluted magnetic lattice (complete A/B disorder on the *4a* position) is bound to have a great impact on the ground state of $A_2B_2O_7$ compounds as well.

We present our recent results on $Er_2Zr_2O_7$ crystallizing in latter structure type. An $Er_2Zr_2O_7$ single crystal was prepared for the first time, being concurrently the first single crystal in the $A_2Zr_2O_7$ family adopting the defect-fluorite type of cubic structure. The single crystal was characterized by x-ray and neutron diffraction methods and studied by means of magnetization, AC-susceptibility and specific heat [5]. The obtained results are dominated by a pronounced low-temperature anomaly of magnetic origin in all types of measurements. Several scenarios to explain the presence of the anomaly are introduced, leaving a spin-glass state in $Er_2Zr_2O_7$ as the most probable explanation. Further, we investigated powdered $Er_2Zr_2O_7$ employing low-temperature (0.3 K) neutron diffraction experiment (E6, HZB). Measured diffraction patterns contain except nuclear (reflections) peaks also a magnetic feature at around 20 degrees in 2θ. The temperature evolution of magnetic signal is well in agreement with a development of the anomaly in magnetization and specific heat data. The results are discussed in broader context of $A_2B_2O_7$ oxides crystallizing both in defect-fluorite and pyrochlore structure.

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O35 - Tuning short-range order through competing interactions in a compensated artifical spin system

3. Frustrated and disordered magnetism, artificial spin ice

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Domains in ferroic systems define their functional properties. By controlling the domain size and shape these properties can be modified. For magnets with a zero macroscopic net moment though, such a control is non-trivial: Due to a vanishing demagnetizing field, there is no energetic contribution limiting the domain size. The absence of an external field which couples to a microscopic spin leaves the temperature as the only controlling handle for domain manipulation - quenching the magnet fast enough through its phase transition forces the system out of equilibrium and consequently prevents the formation of a single-domain state in the ordered phase.

Here, we link the role of short-range ordering mediated by competing interactions to the domain morphology of an antiferromagnet. Tuning this short-range order requires precise adjustment of the competing interactions. Thus, we choose an artificial spin system based on a two-dimensional lattice of dipolar-coupled Ising-like nanomagnetic islands placed on the edge of a square, as shown in the figure. The balance of interactions between parallel and orthogonal islands can be tuned by the inter-island distances. The single-domain ground state of this system is independent of the strength of the two interactions. It is characterised by flux-closed magnetic vortices within the unit cell (caused by the interaction between orthogonal islands), with the handedness of neighbouring cells aligning (stabilised by the coupling between parallel islands)[1]. Equilibrium Monte-Carlo simulations, however, reveal a crossover between different short-range orderings emerging above the critical temperature when varying the interaction ratio.

We use a combination of magnetic force microscopy on as-grown samples and out-of-equilibrium kinetic Monte-Carlo simulation to investigate the formation of short-range order and its effect on the domain morphology. We find that, by crossing in between the different short-range orderings, we can continuously tune the domain size, the preferred domain-wall orientation as well as intrinsic properties of magnetic domain walls. Our findings may therefore provide a pathway for manipulation of domain patterns in otherwise difficult to access compensated magnets.

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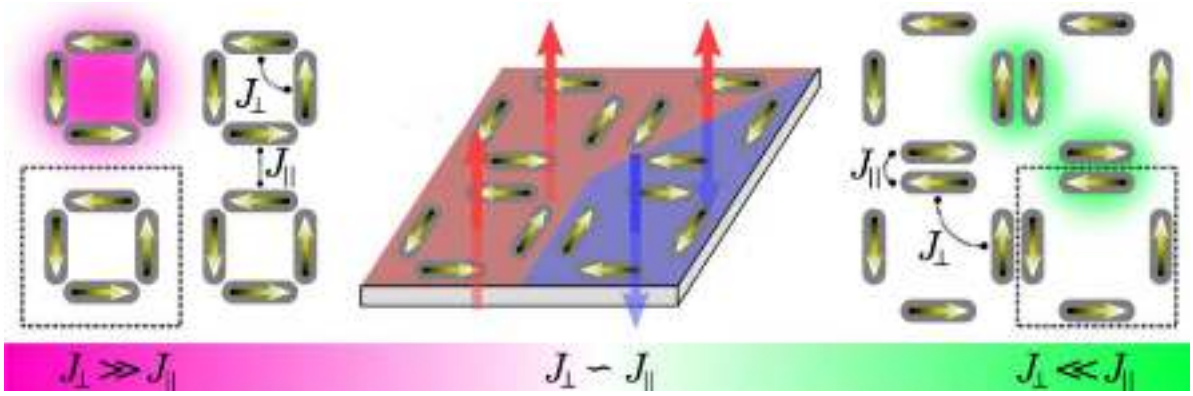
$J_\perp$
$J_\parallel$
$J_\parallel$
$J_\perp$
$J_\perp \gg J_\parallel$
$J_\perp \sim J_\parallel$
$J_\perp \ll J_\parallel$

4. Magnetism in carbon-based and organic materials

O36 - Cobalt phtalocyanine-induced magnetic switching in Ni/Cu(110)-(2x1)O thin films

4. Magnetism in carbon-based and organic materials

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The latest advances in the field of molecular spintronics have shown that the adsorption of organic thin films can modify important properties of ferromagnetic thin films, like its spin polarization, density of states and magnetization [1]. Moreover, a large variety of ferromagnetic thin film systems are known to have a spin reorientation transition (SRT), which can be driven by the film thickness, temperature, strain or adsorbates [2]. In the case of Ni thin films grown on the oxygen (2x1) reconstructed Cu(110)-(2x1)O surface, a sharp SRT of the magnetic easy axis from in-plane to out-of-plane orientation was found for at a critical thickness of 9 ML [3].

In this work we demonstrate the switching of the magnetization in a thin nickel film deposited on a Cu(110)-(2x1)O surface from out-of-plane to in-plane through the deposition of cobalt (II) phthalocyanine (CoPc) thin layers above 2.7 ML. The evolution of the magnetic properties of the CoPc/Ni system has been monitored by in-situ magneto-optical spectroscopy, allowing us to follow not only the magnetic switching in real-time during deposition, but also the evolution of the optical properties of the CoPc as a function of coverage on the ferromagnetic Ni film. The observed magnetic switching is attributed to the modification of the surface magnetic anisotropy of the Ni thin film due to the adsorbed CoPc molecules [4]. Our results show that through the deposition of CoPc on a ferromagnetic surface, the optical and magnetic properties of the organic/inorganic system can be tuned by the organic thin film thickness, encouraging the use of this relevant organic dye for molecular spintronics.

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O37 - Effects of a Molecular C60 Interface on the Spin-dependent scattering of YIG/Pt

4. Magnetism in carbon-based and organic materials

SATAM ALOTIBI[1]

[1] S. Alotibi

We have studied the Spin Hall magnetoresistance in YIG/Pt interfaces with and without a C_{60} overlayer. The SHMR is generated by a current flow in thin (~nm) heavy metal layers with a large spin orbit coupling (SOC) deposited on a magnetic insulators. A spin current Js is generated in the metallic layer, perpendicular to the electronic current. When the direction of the magnetisation M in the ferrimagnet is parallel to Js, the spin current is reflected from the interface and back into the metal due to the inverse spin Hall Effect. However, if the direction of the magnetisation M and spin polarisation are perpendicular, the spin current propagates into the insulator as spin waves. Thus, the SHMR can be observed by rotating the magnetisation vector. This effect has generated a large interest and it is critical in the study of the spin Hall angle and its applications, e.g. for devices such as spin torque MRAM [1, 2]. Nevertheless, the applied field should not exceed the out-of-plane saturation field of YIG, or other mechanisms such as ordinary MR, localisation and the Hanle effect may contribute to the results, in particular at low temperatures see figure (a).

At metallo-molecular interfaces, the electronic properties of both materials are changed due to charge transfer and hybridisation. Previously, it has been shown that this can lead to the emergence of spin ordering.[3]. This interfacial effect is also critical in spin filtering and spin transport effects.[4]. Here, we have studied the effect of C_{60} interfaces on the SHMR generated in YIG/Pt. We find that the conducting interface formed between C_{60} and Pt layers results in a better residual resistivity and lower resistance by 40-60%. The SHMR of Pt layers between 1.5 and 5 nm is enhanced by up to a factor 5 with C_{60}. Thus, the spin Hall angle ΘSH is bigger for Pt/C60 than Pt, which we attribute to an enhancement of the spin orbit coupling (SOC) by the C_{60} -see figure (b,c). This SOC enhancement is corroborated via anomalous Hall effect measurements [5]. Furthermore, there are other SOC effects that are affected by the C_{60}, such as the presence of a low field AMR that we attribute to emergent/proximity magnetism in Pt and the formation of domain walls at the hybrid interface (figure d).

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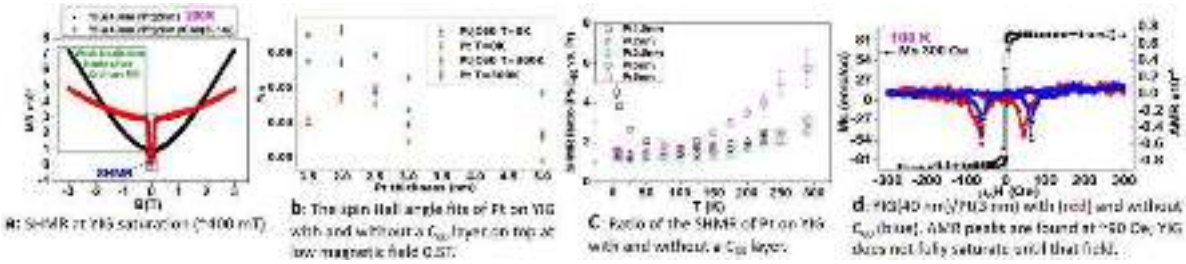

O38 - Europium cyclooctatetraene nanowire carpets: a low-dimensional, organometallic ferromagnet

4. Magnetism in carbon-based and organic materials

Heiko Wende[1] , *Felix Huttmann[2], Nico Rothenbach[1], Stefan Kraus[2], Katharina Ollefs[1], Lucas M. Arruda[3], Matthias Bernien[3], Danny Thonig[4], Anna Delin[4, 5, 6], Jonas Fransson[4], Kurt Kummer[7], Nicholas B. Brookes[7], Olle Eriksson[4, 8], Wolfgang Kuch[3], Thomas Michely[2]*

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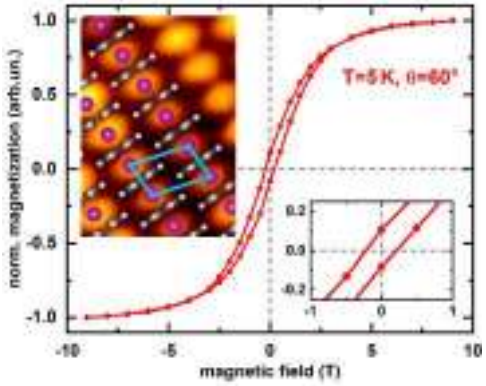
Sandwich molecular wires are a particular 1D class of organometallic structures. They consist of a periodic sequence of 4f rare-earth metal cations, predominantly ionically bound and eight-fold coordinated to planar aromatic anions, based on the cyclooctatetraene (C_8H_8 (Cot)) molecule as a ligand. Because of organometallic hybridization between the metal atomic states and the extended π orbitals of the Cot, the metal ions in the wire were proposed to couple magnetically [1]. Here we investigate the magnetic and electronic properties of europium cyclooctatetraene (EuCot) nanowires by means of low-temperature X-ray magnetic circular dichroism (XMCD) and scanning tunneling microscopy (STM) and spectroscopy (STS) [2]. The EuCot nanowires are prepared in situ on a graphene surface. STS measurements identify EuCot as an insulator with a minority band gap of 2.3 eV. By means of Eu $M_{5,4}$ edge XMCD, orbital and spin magnetic moments of $(-0.1 \pm 0.3)\mu_B$ and $(+7.0 \pm 0.6)\mu_B$, respectively, were determined. Field-dependent measurements of the XMCD signal at the Eu M_5 edge show hysteresis for grazing X-ray incidence at 5 K, thus confirming EuCot as a ferromagnetic material (see figure). Our density functional theory calculations reproduce the experimentally observed minority band gap. Modeling the experimental results theoretically, we find that the effective interatomic exchange interaction between Eu atoms is on the order of millielectronvolts, that magnetocrystalline anisotropy energy is roughly half as big, and that dipolar energy is approximately ten times lower. We are confident that the finding of ferromagnetic ordering in an experimentally well-accessible, surface-supported, organometallic system will provide new inspiration for the field of molecular spintronics.

This work is supported by Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) through projects WE 2623/17-1 and MI 581/23-1 and DFG Projektnummer 278162697 - SFB 1242, eSSENCE, the Swedish Research Council, the KAW foundation (projects 2013.0020 and 2012.0031), and the Foundation for Strategic Research. Further financial support through the Institutional Strategy of the University of Cologne within the German Excellence Initiative, BMBF (no. 05K13KEA “VEKMAG”) and CAPES (no. 9469/13-3) is acknowledged.

[1] N. Atodiresei et al., Phys. Rev. Lett. 2008, 100, 117207.
[2] F. Huttmann et al., J. Phys. Chem. Lett. 2019, 10, 911.


T=5 K, θ=60°
norm. magnetization (arb.un.)
magnetic field (T)
1.0
0.5
0.0
-0.5
-1.0
-10
-5
0
5
10
0.2
0.0
-0.2
-1
0
1

O39 - Importance of organic ligands and substrates in 2D metal-organic coordination network magnetism

4. Magnetism in carbon-based and organic materials

Maria Blanco-Rey[1, 2] , *Ane Sarasola*[1, 2], *Corneliu Nistor*[3], *Luca Persichetti*[3], *Christian Stamm*[3], *Cinthia Piamonteze*[4], *Pietro Gambardella*[3], *Sebastian Stepanow*[3], *Mikhail M. Otrokov*[2, 5, 6, 7], *Vitaly Golovach*[1, 2, 5, 6], *Andres Arnau*[1, 2, 5]

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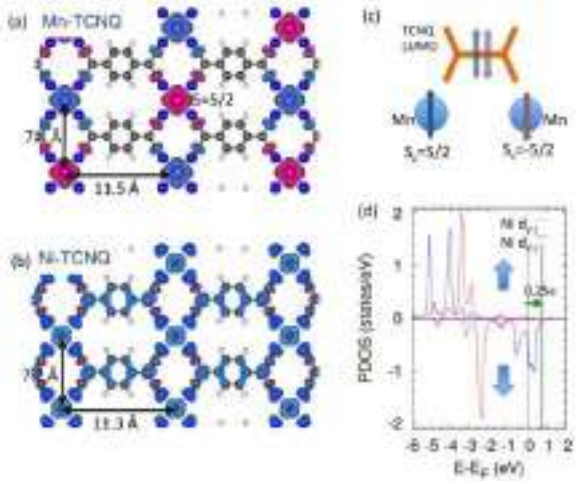
The magnetic properties of two-dimensional metal-organic coordination networks consisting of TCNQ molecules linked by Mn and Ni atoms deposited on a Au(111) metal substrate have been characterised, using X-ray magnetic circular dichroism (XMCD) at low-temperature (T=2.5K), density-functional theory (DFT) and model Hamiltonian calculations. In the DFT calculations, the electronic structure effects associated with the substrate are introduced by varying the charge of the two-dimensional model networks.

A Weiss-theory analysis of the XMCD magnetization curves permits arriving at the conclusion that in Mn-TCNQ the Mn atoms have rather large spins (close to S=5/2) that are antiferromagnetically (AFM) coupled, while in Ni-TCNQ the spin of the Ni atoms is lower (close to S=1/2) and they are ferromagnetically (FM) coupled (spin densities are shown in Fig. a-b). The AFM coupling in the Mn-TCNQ network is of the Anderson's superexchange kind, mediated by hopping terms between Mn(d) and the localised TCNQ-LUMO orbitals, which are doubly occupied in the network (see sketch in Fig. c). By contrast, in the Ni-TCNQ case, the LUMO is partially occupied and strongly hybridised with the Ni(d) electrons; the ferromagnetic coupling follows from a RKKY-like exchange interaction via the itinerant electrons in this hybrid band of about 100 meV width. Our DFT calculations predict the AFM/FM couplings in the Mn/Ni systems, including a fingerprint of frustration in the Mn case, although they yield overall larger exchange coupling constants than the Weiss fit of the data [1,2].

XMCD measurements at normal and grazing incidence, together with the Weiss analysis, provide information on the magnetocrystalline anisotropy (MCA). Mn-TCNQ is weakly anisotropic with in-plane magnetization, while anisotropy is negligible for Ni–TCNQ, in line with the S=1/2 ion picture. In the former system, DFT explains the behaviour as a spin-density distribution anisotropy. In the latter, the scenario is more complex and the aforementioned strongly hybrid Ni(d)-TCNQ states dominate the MCA, but it can not be described by single-ion spin models. Additional DFT calculations that include spin-orbit interaction effects self-consistently yield for Ni-TCNQ an out-of-plane magnetization with MCA energies in the 0.44-1.90 meV range with a strong azimuthal dependence The reason is an electronic structure symmetry breaking that affects the hybrid states near the Fermi level. However, the observed MCA behaviour can be explained by two substrate effects of different nature: (i) a structural distortion of the network to ensure lattice commensurability, which reduces the Ni atom coordination, and (ii) an electron transfer of 0.25e from Au (projected densities of states on relevant d-orbitals are shown in Fig. d). Both mechanisms would bring the system closer to a S=1/2 behaviour and, consequently, reduce the magnetic anisotropy [2].

[1] M. Faraggi et al, J. Phys. Chem. C 2015, 119, 547–555; doi: 10.1021/jp512019w
[2] M. Blanco-Rey et al, Molecules 2018, 23, 964; doi:10.3390/molecules23040964


(a) Mn-TCNQ
S=5/2
7.5 Å
11.5 Å
(b) Ni-TCNQ
7.5 Å
11.3 Å
(c)
TCNQ
LUMO
Mn
Mn
S_z=5/2
S_z=-5/2
(d)
Ni d_{z^2}
Ni d_{x^2}
0.25eV
PDOS (states/eV)
2
1
0
-1
-2
-6 -5 -4 -3 -2 -1 0 1 2
E-E$_F$ (eV)

O41 - Room-temperature proximity induced spin Hall effect in graphene/MoS2 van der Waals heterostructures

4. Magnetism in carbon-based and organic materials

Safeer Chenattukuzhiyil[1] , *Josep Ingla-Aynés[1], Franz Herling[1], José H Garcia[2], Marc Vila[2, 3], Nerea Ontoso[1], Reyes M Calvo[1, 4], Stephan Roche[2, 5], Luis E. Hueso[1, 4], Fèlix Casanova[1, 4]*

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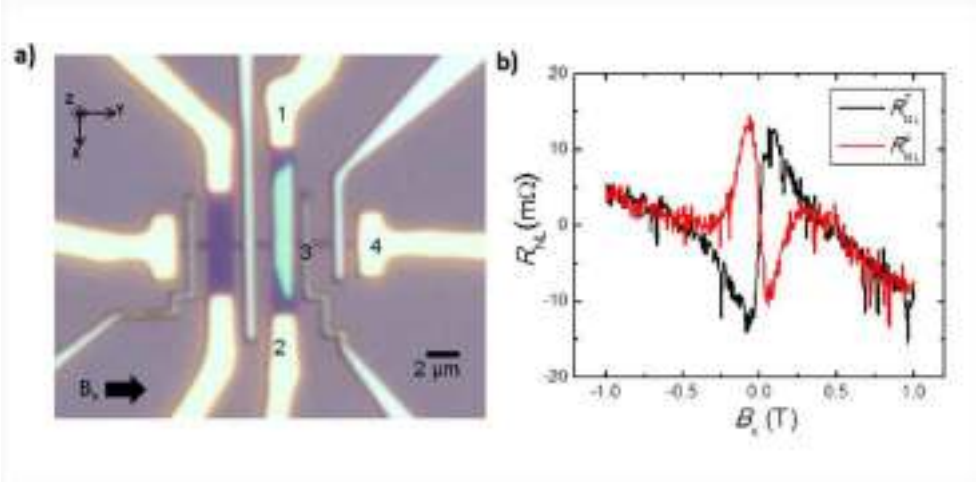
Graphene is an excellent material for long distance spin transport but allows little spin manipulation. Transition metal dichalcogenides imprint their strong spin-orbit coupling into graphene via proximity effect, and it has been predicted that efficient spin-to-charge conversion due to spin Hall and Rashba-Edelstein effects could be achieved [1]. Here, by combining Hall probes with ferromagnetic electrodes, we unambiguously demonstrate experimentally spin Hall effect in graphene induced by MoS_2 proximity and for varying temperature up to room temperature [2].

To study and quantify the proximity-induced spin Hall effect in graphene, we fabricated devices as the one shown in Fig. 1a. The device contains exfoliated few-layer graphene shaped into a narrow channel with double Hall bars. A multilayer MoS_2 flake lies on top of one of the graphene Hall bars. Ferromagnetic Co electrodes are placed on the graphene channel forming lateral spin valves. Nonlocal spin-to-charge conversion curves (Fig. 1b) are obtained by applying a charge current between Co electrode (terminal 3) and graphene (terminal 4) and measuring the voltage across the graphene/MoS_2 stripe (terminals 1 and 2), with the magnetic field applied along the in-plane hard axis direction (see the configuration in Fig. 1a). As the initial spin polarization and applied field are orthogonal, the spins precess around the field. This process results in an antisymmetric Hanle signal exhibiting either a maximum or minimum at certain values of the magnetic field, when the spins reaching the graphene/MoS_2 region point out-of-plane. The antisymmetric Hanle curve is also reversed when the initial magnetization direction is switched since the injected spins are opposite (red vs black line in Fig. 1b). By fitting the antisymmetric Hanle signal to the solution of the Bloch equation, we calculate the spin Hall angle to be -0.3% at room temperature, increasing up to -4.8% at 10 K [2].

The fact that spin transport and spin Hall effect occur in different parts of the same material gives rise to a hitherto unreported efficiency for the spin-to-charge voltage output, at least 20 times larger than in the Pt/graphene system [3]. Our findings pave the way towards the combination of spin information transport and spin-to-charge conversion in two-dimensional materials, opening exciting opportunities in a variety of future spintronic applications.

1. J. H. Garcia, et al. *Nano Letters,* **17,** 5078 (2017).
2. C. K. Safeer, et al. *Nano Letters,* **19**, 1074 (2019).
3. W. Yan, et al. *Nature Communications*, **8**, 661 (2017).


a)
1
2
3
4
2 µm
b)
20
10
0
-10
-20
-1.0
-0.5
0.0
0.5
1.0
B_x (T)
R_{NL} (mΩ)

5. Magnetorecording media, magnetic memories and magnetic sensors

O42 - A multifunctional standardized MTJ stack embedding sensor, memory and oscillator functionalities

5. Magnetorecording media, magnetic memories and magnetic sensors

Antoine Chavent[1] , *Vadym Iurchuk[1], Luc Tillie[1], Yoann Bel[1], Nathalie Lamard[1], Laurent Vila[1], Ursula Ebels[1], Ricardo C. Sousa[1], Bernard Dieny[1], Gregory Di Pendina[1], Guillaume Prenat[1], Juergen Langer[2], Jerzy Wrona[2], Ioan Lucian Prejbeanu[1]*

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For monolithic heterogeneous integration, fast yet low-power processing and storage, and high integration density, the objective of this study is to co-integrate multiple digital and analog functions together within CMOS by adapting the Magnetic Tunneling Junctions (MTJs) into a single baseline technology enabling logic, memory, and analog functions, particularly for Internet of Things (IoT) platforms. This will lead to a unique STT-MTJ cell technology called Multifunctional Standardized Stack (MSS). This paper presents the progress in the project regarding the three functionalities targeted for the technology, which are memory oscillator and sensor. We show that the same magnetic stack can be used to have on the same wafer these three functionalities.

For the memory function, the critical spin transfer torque (STT) switching phase diagrams (Voltage vs. Field) were measured for a MTJ layer stack having a 1.4nm thick FeCoB free layer, for different dot diameters. The STT switching phase diagrams are well defined. The evaluation of the phase diagrams gave a minimum stability of $40k_BT$ with a write voltage distribution of 0.2V around 0.8V. A second functionality of the MSS layer stack is to act as magnetic field sensor. The sensing approach is based on orthogonal reference and sensing magnetic layers. In this operation mode, the device provides an analog sensor signal, by monitoring the resistance variation under applied field. In a multifunctional cell having perpendicular anisotropy this has been realized by applying an in-plane bias field thanks to integrated magnets. We observed two different sensing scenarios depending on the in-plane bias amplitude. In one, the sensibility is essentially due to the storage layer while in the other, it is due to some part of the reference layer. The magnetoresistance sensibility can reach 4%/mT. Finally, we describe the possibility to use pMTJ-based spin transfer torque nano-oscillators (STNOs) for basic RF functions such as signal generation, injection locking, frequency modulation and signal detection. We have shown STT-induced microwave signal generation in pMTJ with the free-running frequencies ranging from 2 to 6 GHz depending on the external magnetic field and the value of dc current passing through the STNO. The minimum linewidth of ~20 MHz and the integrated power up to ~20 nW are observed at moderate I_{dc} values corresponding to half of the estimated breakdown voltage of the MTJ. We also confirm current-induced frequency modulation for several amplitudes and frequencies of the modulating current, allowing the data transfer via so-called frequency shift keying technique. Spin-torque ferromagnetic resonance (ST-FMR) measurements were conducted to explore the possibility of rf-to-dc conversion in pMTJ-based STNOs. The rectified signal in the mV range was observed for both passive (no dc current) and active (with dc current) regimes indicating microwave signal rectification of both thermal and steady-state precession modes.

The authors acknowledge the funding support from the GREAT project (EU Horizon 2020 research and innovation program under grant agreement No. 687973)

O43 - Flexible interconnections for magnetoresistive-based multipoint tactile sensors

5. Magnetorecording media, magnetic memories and magnetic sensors

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The development of tactile sensors is a key technology to provide robots with the ability to grasp and manipulate objects, critical for robots to become more useful in human-like environments. The development tactile sensor has been prolific but the works that are able to include all the development steps, from the manufacturing to the integration are few.

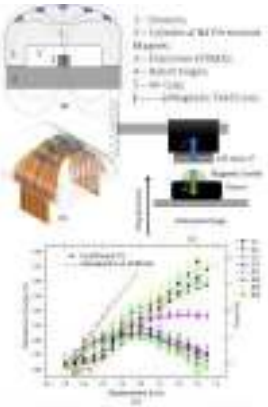
We are proposing a magnetic tactile sensor to provide multi-contact point and contact area information, vital for correct object grasping and manipulation. To provide this we have developed a manufacturing process as well as integrated into a part of the robotic finger.

Jamone et al. [1] propose to attach a 3D hall effect sensor on the robot finger and a permanent magnet (PM) in an elastomeric part. The design principle is based on the Hall Sensor signal detected due to the magnetic field variation generated by the PM displacement. This approach has been found to be unreliable in contact point determination as well as unable to detect the contact area [2]. To overcome this limitation, we propose a solution where a cylindrical Nd PM (1×1 mm) (Fig1.a)(1)) is fixed on the robot finger (Fig1.a)(3)) while a flexible sensor matrix (FSM) (Fig1.a)(4)) is positioned at the surface of the elastomer (Fig1.a)(3)). The FSM is composed by Si chips (1.5×0.8 mm^2) containing six microfabricated magnetoresistive spin valve sensors [3] (1.5×40 μm^2) connected in series (Fig1c)). The sensors show R = 1.6 kOhm, the linear range of + - 4 mT), and the 300nm thick AlSiCu pads (dimensions 0.4x0.8mm^2) were bonded onto to the 9µm thick copper lines of a polyimide (25µm) flexible printed circuit board (FPC) using a conductive epoxy. Due to geometrical constraints the finger surface fits 8 chips with sensors on the surface left side (L1, L2, L3, and L4) and the right side (R1, R2, R3 and R4) see Fig1.b).

An experimental setup was prepared in which the magnetic tactile sensor was fixed to a 3 degree-of-freedom Cartesian motorized stage (Thorlabs DDS220) and 6-degree force sensor (ATI nano 17) was fixed to an aluminum rod. The stage is used to align and press the sensors against each other retrieving the action-reaction pair of the system see Fig1.c).

Fig1.d) shows the resistance variation of each sensor submitted to each displacement as well as the force in the Z direction measured by the ATI nano 17. The sensors on the left show a negative resistance change while the right side provides a positive resistance change. Since all the sensors have the same magnetotransport relationship the field is increasing for the right side while the left side is decreasing, which is to be expected given the central position of the contact and the placement of PM. To improve understanding of the system COMSOL simulations have also been performed.

[1] L. Jamone,et al.,IEEE Sensors Journal, Vol. 15, No. 8, pp. 4226-4233. DOI: 10.1109/JSEN.2015.2417759
[2] T. Paulino,et al, ICRA Conference, 2017. DOI: 10.1109/ICRA.2017.7989118
[3] V. Gehanno,et al, IEEE Trans.Magn. (35), 5, 4361-4367, 1999. DOI: 10.1109/20.799086



O44 - Magnetic Property of Co-Tb alloy based Bit Patterned Media

5. Magnetorecording media, magnetic memories and magnetic sensors

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Recently, bit patterned media (BPM) has been demonstrated as novel recording media used to increase the storage density of hard disk drive (HDD). In such bit patterned media, each artificially fabricated magnetic nanostructure is capable of storing an individual bit rather than using hundreds of naturally formed small grains to store single bit as in conventional media. We developed a novel non-lithographic method to fabricate perpendicularly magnetized BPM system [Appl. Phys. Lett. 101, 013110 (2012)] and we studied Co/Pt bit pattern media [Physical Review B 89 (2014) 174421].

In present work, we fabricated and studied Co-Tb alloys based ferromagnetic nano-dots, so-called nano-bumps. These nano-bumps were fabricated by depositing $Co_{1-x}Tb_x$ (x=0.10, 0.12, 0.13 and 0.15) alloys onto the barrier layer of hexagonally close-packed auto assembled anodic alumina template with 100 nm periods using DC magnetron sputtering. We used vibrating sample magnetometer (VSM) to characterize the magnetic property of these nano-bumps. From room temperature M-H loops, an increase of coercivity with squareness of the films was observed with increase of Tb content. A change of magnetic isotropy to magnetic anisotropy behavior with the increase of Tb composition was observed i.e. $Co_{0.85}Tb_{0.15}$ and $Co_{0.88}Tb_{0.12}$ was found to exhibit perpendicular magnetic anisotropy. The measurement of temperature variation of magnetization indicates that these films exhibit ferrimagnetisms with Curie temperature (T_C) are 542^{o}C for x=0.15 and 545^{o}C for x=0.12 respectively. These materials can be promising candidates for magnetic recording media.

O45 - Optimization of xMR technologies for highly accurate magnetic based positioning systems

5. Magnetorecording media, magnetic memories and magnetic sensors

Fernando Franco[1, 2] , *Marilia Silva*[1, 2], *Ricardo Ferreira*[3], *Torsten Becker*[4], *Susana Cardoso*[1, 2], *Paulo P. Freitas*[1, 3]

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Magnetoresistive (MR) sensors are a high-performance magnetic sensing technology widely spread over non-recording applications driven by its sensitivity, detectivity, dimension, cost and power consumption. Indeed, the recent developments on xMR technologies provide a competitive and reliable solution for biomedical tools, flexible electronics, non-destructive evaluation, navigation and positioning systems being expandable to portable devices or the internet of things.

Encoded positioning systems for linear or rotary motion rely mainly on optical based encoders due to a high resolution and accuracy. However, their performance is drastically affected in harsh industrial environments demanding sealed packages to avoid contaminations whereas the device cost and size are compromised. Meanwhile, magnetic based encoders emerged as a cheaper alternative with a high operating temperature range and immune to dust, fluids and humidity. Currently, MR sensors based on AMR and GMR effects are a maturated technology in series production for position, angular or speed measurements encoded by linear measuring scales and pole rings (active scales) or ferromagnetic gear tooth structures (passive scale) limited to a pole pitch size of 0.5 mm and a reading distance up to 1x the pole pitch size. However, the implementation of optimized xMR sensing devices combined with the downsize of the pole pitch can push the magnetic positioning technology towards more critical applications reaching the performance of low-level optical encoders.

The optimization of such devices relies on the tuning of the xMR technology, its dimension and measuring scheme. Wheatstone bridge architectures are a common resistive measuring scheme highly compatible with standard signal processing chains. When powered in a voltage mode, each bridge arm is under a constant current and the bridge output is given by $V_{cc}.H.S/R_0$, wherein V_{cc} is the bias voltage, R_0 the bridge resistance in the absence of a magnetic field H and S is the sensitivity of a resistive sensing group.

An approach to achieve a high-performance sensing device is proposed by dimensioning it according to its sensitivity-resistance ratio while a high breakdown voltage must be ensured by a series of sensing elements to handle a higher V_{cc}. Among different xMR technologies (i) spinvalve (SV), (ii) SV with nano-oxide-layer, (iii) AlOx based magnetic tunnel junction (MTJ) and (iv) MgO based MTJ combined with a soft pinned sensing layer, it was observed that the sensor technology and the dimension (length and height) can drastically influence the output [Figure 1 (a)] while the mean magnetic field over the sensor area is directly compromised by the ratio between the sensor length and the pole pitch size [Figure 1 (b)]. Consequently, upon an optimized sensing geometry combined with the xMR technology that revealed the highest sensitivity-resistance ratio (MgO based MTJ with soft pinned sensing layer), different prototypes were designed according to common specifications of commercial sin/cos interpolators targeting pole pitch sizes below 500 µm down to less than 100 µm. With enhanced performance, each device was successfully tested as a sensing technology for magnetic based encoders highlighting an improved reading distance above 2x the pole pitch size.

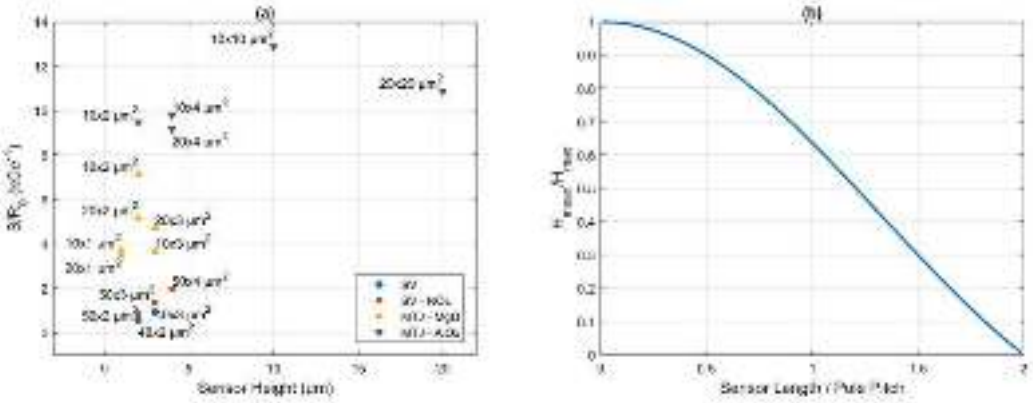

Figure 1: (a) Sensitivity resistance ratio for different xMR technologies as a function of the sensor dimension. (b). Mean magnetic field attenuation as a function of the sensor length with respect to the pole pitch size.

O46 - SAF-based perpendicular magnetized GMR spin-valves on flexible substrates

5. Magnetorecording media, magnetic memories and magnetic sensors

Sara Laureti[1] , *Gaspare Varvaro[1], Mariam Hassan[1, 2], Christian Rinaldi[3], Sara Varotto[3], Gianni Barucca[2], Olga Lik[4], Nataliia Safonova[4], Manfred Albrecht[4]*

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Flexible electronics has received a great deal of attention over the past decades owing to its outstanding potential in many technological fields including energy, optics, sensors and information storage, among others [1,2]. The ability to bend and adjust the shape of a device and owing both lower weight and costs make flexible devices more advantageous than their conventional counterparts on rigid substrates. Aiming to widen the domain of flexible electronics, a significant effort has been recently pursuit to develop spin-related electronic devices on flexible substrates [2]. In this work, we investigated the possibility to obtain high-quality GMR heterostructures with perpendicular magnetic anisotropy on large-area flexible substrates by exploiting a versatile *transfer-and-bond* approach where the heterostructure is first deposited on a rigid substrate covered with a weakly-adhering layer, and then transferred on an adhesive and flexible substrate by a simple mechanical peel-off step. For this purpose, a 10-nm Au layer was first deposited by DC-sputtering onto a thermally oxidized Si substrate in order to exploit the low adhesion coefficient of Au on such a substrate. On top of the Au layer, $[Co/Pd]_4/Ru/[Co/Pd]_4/Cu(x\ nm)/[Co/Pd]_2$ GMR stacks (x = 2, 3 and 5 nm) with a fully compensated $[Co/Pd]_4/Ru/[Co/Pd]_4$ synthetic antiferromagnetic reference layer were deposited at room temperature. The magnetic and magneto-resistive properties were investigated as a function of the Cu spacer thickness (t_{Cu}). The same GMR stacks were also directly deposited on thermally oxidized Si substrates as reference. All the samples present a clear perpendicular anisotropy as confirmed by the behavior of out-of-plane and in-plane magnetization loops. The Au-free reference samples show the expected field-dependent magnetization response, the GMR ratio (DR/R_{low}) increasing from 2.5 % (t_{Cu} = 5 nm) to 4.5 % (t_{Cu} = 2, 3 nm) in line with the results reported in the literature for similar systems. When the stack is deposited on Au, the overall magnetic properties are maintained down to a Cu spacer of 3 nm and a GMR ratio of about 1.7 % is achieved. The slight worsening of the magnetic and magneto-resistive properties can be attributed to a larger Au surface roughness, which leads to an increase intermixing at the interfaces or to other coupling contributions, such as orange peel coupling. Centimeter-scaled spin valve stacks were successfully transferred on an adhesive 3M polyester tape without affecting their magnetic and magneto-resistive properties (figure 1), thus confirming that the proposed Au-mediated transfer-and-bond approach can be pursuit to obtain complex spintronic heterostructures on flexible substrates.

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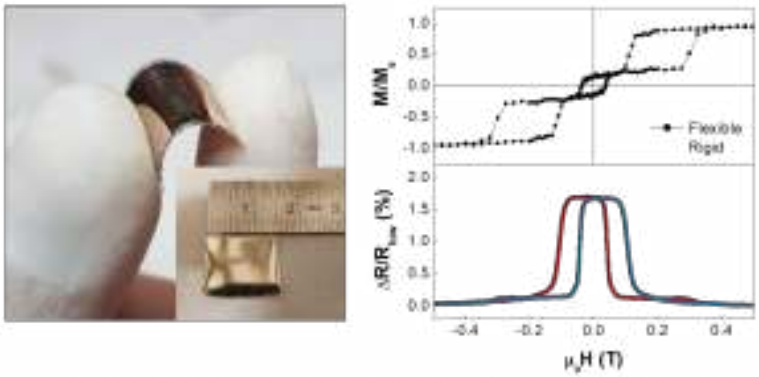

Figure 1. (Left) Optical photograph of the transferred $[Co/Pd]_4/Ru/[Co/Pd]_6/Cu(3\ nm)/[Co/Pd]_3$ GMR stacks. (Right) Corresponding out-of-plane room temperature field-dependent magnetization loop and magneto-resistance measurements.

O47 - The Superior Role of Damping on the Signal-to-Noise Ratio in Heat-Assisted Magnetic Recording

5. Magnetorecording media, magnetic memories and magnetic sensors

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The next generation recording technology to increase the areal storage density of hard disk drives beyond 1.5 Tb/in^2 is heat-assisted magnetic recording (HAMR). HAMR uses a heat pulse to locally enhance the temperature of the high anisotropy recording medium beyond the Curie temperature. Due to the heating, the coercivity of the grain drops and it can be written with the available head fields. After the grain is written, the medium is cooled and the information is safely stored. A good indicator for the quality of the written bits is the so-called signal-to-noise ratio (SNR) which gives the power of the signal over the power of the noise. To achieve high areal storage densities, recording materials that yield high SNR values even at small grain sizes are needed. However, a priori it is not clear which write head parameters and which material parameters have the strongest influence on the SNR. Thus, it is of great interest to understand the role of each parameter. In this work, HAMR simulations with the atomistic simulation program VAMPIRE [1] are performed for cylindrical recording grains with a diameter d=5nm and a height h=8nm. The material parameters of FePt like hard magnetic recording media according to the Advanced Storage Technology Consortium (ASTC) [2] are used. In each simulation, one recording parameter is varied and the SNR is determined with the help of an SNR reader provided by SEAGATE. The simulations show that the write head parameters improve the SNR only if the bitlength is changed due to a higher head velocity or a longer field duration. However, the simulations also show that most of the parameters have a minor relevance compared to the influence of the damping. Thus, further simulations with varying damping constants for two different grain diameters d1=5nm and d2=7nm are performed. The damping constant was varied between α=0.01 and α=0.5. The results (see Figure 1) show that for d1=5nm damping constants larger or equal than 0.1 lead to the best SNR values. For d2=7nm α=0.05 already leads to good results. Enhancing the damping constant beyond 0.3 does not show any further improvement, the SNR saturates.

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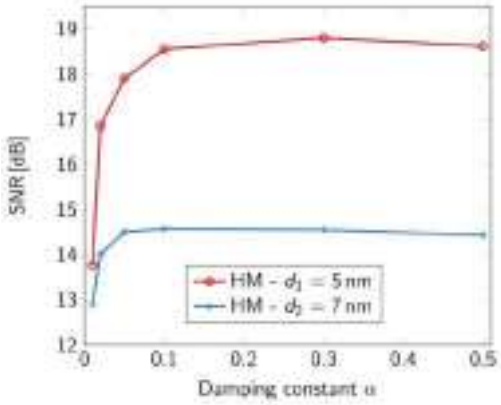

Figure 1: Resulting SNR curves for different damping constants α for the grain sizes d1=5nm and d2=7nm.

O48 - Towards Chirality-encoded Domain Wall Logic Devices

5. Magnetorecording media, magnetic memories and magnetic sensors

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As CMOS reaches the limits of its scaling potential, there is a need to develop new technologies that will allow continued growth in the power and functionality of computer hardware. While the maturity of CMOS makes it unlikely that, in the short term, a single technology will out-perform it in all areas, new approaches are likely to offer distinct advantages for specific applications. For example, the non-volatility of nanomagnetic systems will offer substantial advantages in terms of power consumption if they can be harnessed to perform logical operations.

Most proposals for nanomagnetic logic devices have focused on using simple, uniformly magnetised states, of either individual nano-islands [1,2] or domains in nanowires [3], to represent data. However, nanomagnetic features with more complex spin configurations, such as geometrically confined domain walls (DWs), also contain internals degrees in freedom that can also be used to directly encode information. Here, we present progress towards creating a fully-functioning logic architecture where data is encoded using the internal chirality of vortex DWs in $Ni_{80}Fe_{20}$ nanowires [4,5].

Initially, we will present micromagnetic simulations demonstrating how carefully designed nanowire segments can perform a full range of logic operations, including NOT, NAND, AND, NOR and OR on the chirality of vortex DWs (Figure 1(a)). We will then present Magnetic soft X-ray Transmission Microscopy (MTXM) measurements that demonstrate how the chiralities of DWs can be rectified by sharp nanowire corners, and thus the basic feasibility of using geometrical features to reliably manipulate DW chirality (Figure 1(b)). Finally, we will present further MTXM measurements that demonstrate the critical functions of each of the logic gates designs described above. Together our results experimentally indicate the feasibility of a fully functioning chirality-based DW logic architecture.

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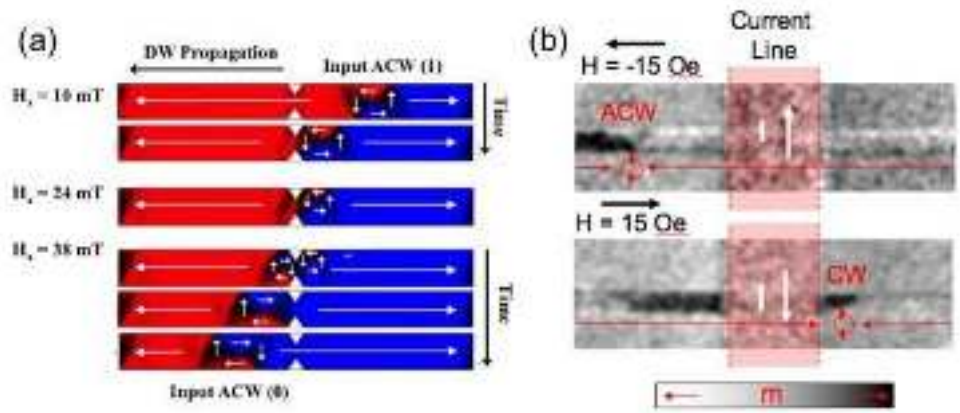
Figure 1: (a) Micromagnetic simulation showing the operation of a chirality-encoded NOT gate. (b) MTXM images showing the equivalent operation performed in a fabricated nanowire device.


(a)
DW Propagation
Input ACW (1)
H_x = 16 mT
H_x = 24 mT
H_x = 38 mT
Time
Time
Input ACW (0)
(b)
Current Line
H = -15 Oe
ACW
H = 15 Oe
CW
m

6. Magnetic thin films, multilayers, surface and interfaces

O50 - A ferromagnetic insulator with low magnetic damping: magnetism and structure of NiZnAl - ferrite

6. Magnetic thin films, multilayers, surface and interfaces

Julia Lumetzberger[1] , *Martin Buchner[1], Verena Ney[1], Andreas Ney[1]*
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In spintronics one aims to obtain pure spin currents as an additional degree of freedom in logic circuits aside from electric charges. By means of spin pumping it is feasible to induce a spin current from ferromagnetic materials into adjacent non-magnetic layers. To ensure pure spin currents and exclude charge currents, ferromagnetic insulators are the material of choice. However, ferromagnetic insulators with low intrinsic damping are sparse. The most commonly used material for magnetoelectric devices is yttrium iron garnet (YIG)[1]. YIG has two major drawbacks, namely the complex garnet structure, which is almost exclusively grown on Gadolinium Gallium Garnet (GGG) substrates and its weak magnetoelastic response. It could be replaced by cubic NiZnAl – ferrite thin films grown on $MgAl_2O_4$, which were reported to have similar magnetic properties[2]: ferromagnetic at room temperature, low intrinsic damping, and additionally a strong magnetoelastic coupling. Since the NiZnAl-ferrite has also insulating properties it can be used as source for pure spin currents in devices. In this contribution we use reactive magnetron sputtering as a preparation method to optimise the magnetic properties by the variation of growth parameters like argon:oxygen ratio, temperature and annealing time. All samples are analysed with X-ray diffractometry for their crystallographic properties. To evidence the desired low magnetic damping room temperature multifrequency ferromagnetic resonance (FMR) with a short-circuited set-up is performed[3]. From the frequency dependence of the resonance line-width the homogeneous and inhomogeneous contributions to the damping of the system can be extracted. The results so far show a strong correlation between the c/a ratio and the damping in NiZnAl-ferrites. Additionally, transmission electron microscopy is performed to investigate the interface on an atomic scale and the chemical composition by means of EDX. The latter is especially important, since the doping percentage of Al reportedly has a significant influence on the magnetic anisotropy[4]. Furthermore, the angular and frequency dependence of the resonance position is measured to quantify the strain-induced magnetic anisotropy contributions. In a last step XMCD and XMCD (H) at the $L_{3,2}$ edge of Ni and Fe are performed to complement the integral SQUID magnetometry measurements and evidence their magnetic contributions to the hysteresis separately. The different oxidation states as well as occupied lattice sites of Ni and Fe are of special interest since a strong influence on the intrinsic damping was reported[2].

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O51 - ALD growth of Co thin films on the topological insulator Sb2Te3

6. Magnetic thin films, multilayers, surface and interfaces

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[2] Università degli Studi di Milano-Bicocca, Dipartimento di Scienze dei Materiali, Milano, Italy

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[4] Istituto Officina dei Materiali del CNR (CNR-IOM), Sede Secondaria di Perugia, c/o Dipartimento di Fisica e Geologia, Università di Perugia, I-06123 Perugia, Italy

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The coupling between ferromagnetic thin films (FM) and topological insulators (TI) is attracting huge interest in the context of spintronics.[1,2] Indeed, the presence of Dirac-like dispersed surface states in the TI, jointly with the presence of a large spin-orbit coupling, is expected to favour a super-efficient magnetization manipulation of the FM through a large *spin orbit torque* (SOT).[3] In this work, we present the first attempt of employing a pure atomic layer deposition (ALD) process to grow Co thin films in direct contact with the Sb_2Te_3 TI, grown by Metal Organic Chemical Vapor Deposition (MOCVD).[4,5] ALD allows a large-scale deposition process with highly-controllable, self-limited and conformal growth, although so far scarcely employed for.[6-9] Being the role of the interface between Co and TI fundamentally important in driving the SOT functionalities, the advantages of ALD are exceptionally appealing.

The ALD growth of few-to-tens nm of Co is successfully conducted on top of MOCVD-grown granular Sb_2Te_3 films (whose surface roughness is 2-5 nm) and on top of Pt layers produced by magnetron sputtering.[10] Pt is conventionally used as SOT material[11], thus providing an excellent benchmark material to evaluate the Sb_2Te_3 properties. The thorough chemical-structural characterization of the Co/Sb_2Te_3 and Co/Pt heterostructures is performed by X-Ray Diffraction and Reflectivity (XRD/XRR) and Scanning Electron Microscopy (SEM). The results demonstrate the formation of uniform and high structural-quality Co thin films, characterized by a stable and sharp interface with the Sb_2Te_3 substrate (*Figure 1*). Interestingly, XRD showed different Co phases depending on the underlying material: Co layers show an hexagonal crystalline structure on Sb_2Te_3, while they grow in the cubic phase on Pt. Broadband Ferromagnetic Resonance (BFMR) experiments are used to measure the damping (α) and the magnetic anisotropy constants (K_1 and K_2) of the Co/Pt and the Co/Sb_2Te_3 heterostructures (*Fig.1(b)*), highlighting the differences between the two systems in terms of magnetic properties. Complementary information is obtained by Magnetic Force Microscopy, Vibrating Sample Magnetometry and Brillouin Light Scattering spectroscopy will also be presented. Noteworthy, on the basis of this study, the combined use of ALD and MOCVD could open interesting possibilities to scale up the manufacture of large-scale devices based on the FM/TI heterostructures.

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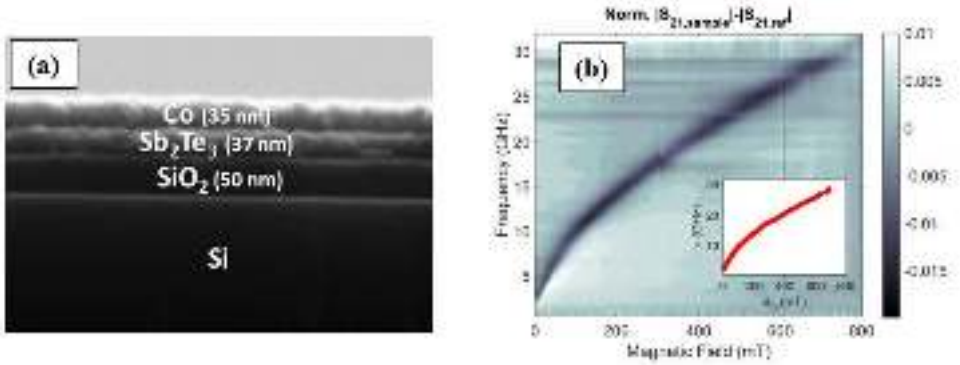

Figure 1. (a) SEM cross sectional view of a Co/Sb_2Te_3 heterostructure deposited on a SiO_2/Si substrate, (b) FMR collected data for a Co(60 nm)/Sb_2Te_3(37 nm)/SiO_2 sample. On the x and y axis are shown respectively the quasi-static magnetic field and the microwave frequency applied to the sample. In the inset of (b) the extracted resonant magnetic field values (B_r) versus frequency are reported.

O52 - Anisotropic magnetoresistance of topological-insulator surface states in an in-plane magnetic field

6. Magnetic thin films, multilayers, surface and interfaces

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The influence of external perturbations on the surface-state (SS) transport properties of topological insulators (TI) is presently the subject of intense investigation. We report on a theoretical analysis of the influence of an in-plane magnetic field on SS properties. For 2D electron systems confined to semiconductor quantum wells, in-plane magnetic fields yield transport anisotropy that can be traced to an enhancement in quasiparticle mass for motion in the in-plane direction perpendicular to the field. To verify the existence of a similar anisotropy in the TI SS system, we consider a long-wavelength four-band model of SSs that is relevant for several TIs with the Bi2Se3 crystal structure. An in-plane field influences the orbital motion, but leaves the SS momenta as good quantum numbers. Assuming a plane-wave solution, we solve the resulting energy eigenvalue equation leading to chiral linearly dispersed as well as non-chiral parabolic modes. We find that the magnetic field introduces an in-plane anisotropy in the energy dispersion of Dirac's states which affects the conductivity. We compare the size of the anisotropic orbital magnetoresistance with the anisotropy originating from Zeeman coupling. The results of this approximate continuum model are compared with the predictions of a realistic tight-binding model for Bi2Se3 thin films.

O53 - Aperiodic quantum oscillations in the two-dimensional electron gas at the complex oxide interfaces

6. Magnetic thin films, multilayers, surface and interfaces

Rubi Km[1] , *Julien Gosteau*[2], *Raphaël Serra*[2], *Rémi Arras*[2], *Benedicte Warot-Fonrose*[2], *Shengwei Zeng*[3], *Ariando Ariando*[3], *Michel Goiran*[4], *Walter Escoffier*[4]

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The discovery of the two-dimensional electron gas (2DEG) at the $LaAlO_3/SrTiO_3$ (LAO/STO) interface has not only enhanced the potentials in oxide electronics, but has also brought new opportunity to study the novel physics of the 2DEG with unmapped parameters. Several exciting phenomena including coexistence of ferromagnetic and superconductivity, Rashba spin-orbit coupling have been explored both experimentally and theoretically for the past decade. The quantum oscillations for this interface have been studied several times, however, the analysis of these oscillations delivered distinctive interpretation with respect to different experimental conditions [1]. We have investigated the magneto-transport of a gate tunable high mobility 2DEG at the LAO/STO interface in high pulsed field (55 T) and at low temperature (1.6 K) [2]. The longitudinal resistivity exhibits large amplitude Shubnikov-de Haas (SdH) oscillations despite of a linear Hall effect.
Interestingly, the SDH oscillations are non 1/B-periodic in full field range and produce a non-linear Landau plot (Landau level index versus 1/B). Among several possible scenarios, the Roth-Gao-Niu model [3] provides new insights on these aperiodic oscillations and brings evidence for non-trivial dispersion relations at the Fermi energy. The prolonged issue regarding the large mismatch in the carrier density extracted from SDH oscillations and Hall effect for complex oxide interfaces will be discussed in light of high-resolution scanning transmission electron microscopy analysis as well as calculations from density functional theory.

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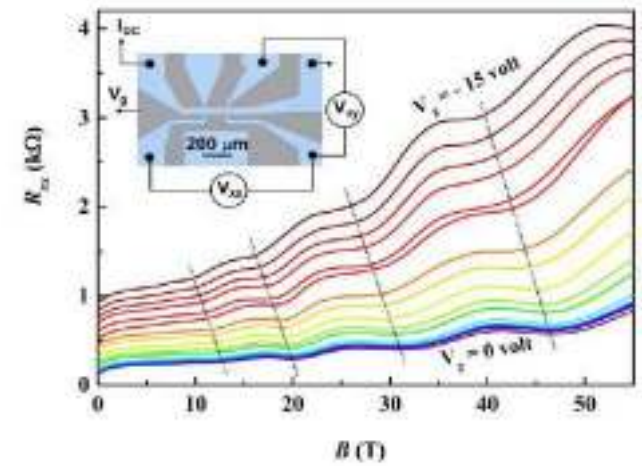

O54 - Cation-specific magnetic depth profiles in ultrathin Fe3O4 films obtained by XRMR

6. Magnetic thin films, multilayers, surface and interfaces

Tobias Pohlmann[1] , *Karsten Küpper[1], Timo Kuschel[2], Kevin Ruwisch[1], Jari Rodewald[1], Jannis Thien[1], Joachim Wollschläger[1]*

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Fe_3O_4 is a frequently studied magnetic oxide growing in the inverse spinel structure, whose ferrimagnetism stems from the interplay of its three cation species due to super exchange and double exchange depending on site and oxidation state: Octahedrally coordinated Fe^{2+} and Fe^{3+} ions, and tetrahedrally coordinated Fe^{3+} ions. The coupling among octahedral sites is ferromagnetic, while tetrahedral and octahedral sites couple antiferromagnetically. One of the most successful ways to discriminate between the magnetic contributions of these cations are X-Ray Magnetic Circular Dichroism (XMCD) experiments at the Fe $L_{2,3}$ edge, making use of a slight difference of their L edge energies and the easily resolvable antiferromagnetic coupling between the tetrahedral and the octahedral sites.

For ultrathin Fe_3O_4 films, there have been different reports on an increasing magnetic saturation moment per atom for decreasing film thicknesses, exceeding the 4 μ_B /f.u. known from the bulk [1,2]. One possible explanation for this behaviour could be an enhanced magnetisation of the near-surface region, having an higher impact with decreasing film thickness [1]. We are testing this hypothesis by employing X-Ray Magnetic Reflectometry (XRMR), a technique combining the depth resolution of X-Ray Reflectrometry and the element- and magnetism-sensitivity of XMCD. By this, we are able to obtain the magnetisation profile of the three cations separately. In figure a), the asymmetry ratios obtained from XRMR measurements are shown for all three cation species together with reflectometry fits which use the magnetic profiles shown in figure b) [3].
It is revealed that in fact both Fe^{3+}-cations show an enhanced magnetisation layer of about 6 Å close to the surface, while the Fe^{2+} cations provide an homogeneous magnetisation profile. We discuss this finding in context with the enhanced magnetisation of thin Fe_3O_4 films.

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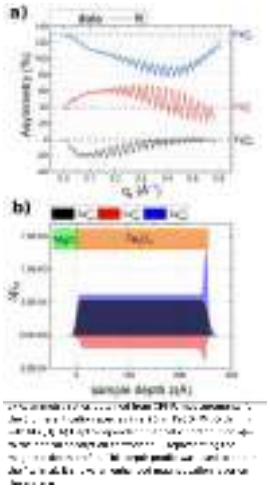

O55 - Chiral domain walls in perpendicularly magnetized epitaxial Ni films

6. Magnetic thin films, multilayers, surface and interfaces

Benedikt Boehm[1] , *Andreas Bischof*[1], *Oliver Reich*[1], ***Rolf Allenspach***[1]
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The Dzyaloshinskii-Moriya interaction (DMI) has been found to strongly influence the domain wall type in perpendicularly magnetized thin films. Achiral Bloch walls acquire a magnetization component transverse to the wall plane or are even entirely replaced by chiral Néel walls, depending on the DMI strength. By resolving the three magnetization components within a wall profile by spin-polarized scanning electron microscopy, the sign and strength of the DMI can be directly determined. We investigate perpendicularly magnetized epitaxial Ni/Cu(001) and compare with earlier results on the Ni/Fe/Cu(001) system, in which an appreciable DMI has been found [1]. Since the perpendicular magnetization is maintained beyond the ultrathin film limit, we can follow the evolution of the wall type up to thicknesses of 10 nm. At these thicknesses, the interfacial DMI is expected to be negligible and epitaxial strain is largely relaxed. We compare structural and magnetic characterization of Ni films grown on Cu(001) and on Cu(001)/Si(001) and discuss domain walls and their chirality in these systems.

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O56 - Colossal Electric Field Control of Magnetic Anisotropy at Ferromagnetic Interfaces

6. Magnetic thin films, multilayers, surface and interfaces

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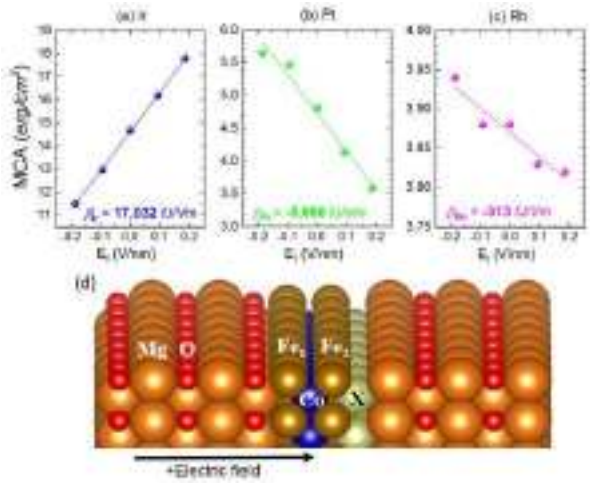
Voltage-induced magnetization switching can lead to a new paradigm enabling ultralow-power and high density instant-on nonvolatile magnetoelectric random access memory (MeRAM) devices. Two major challenges for future MeRAM devices are to achieve large perpendicular magnetic anisotropy (PMA) (> 2 mJ/m^2) and high voltage-controlled magnetic anisotropy (VCMA) efficiency (> 1,000 fJ/(Vm)) to scale both with the size and write energy. Thus, there is an urgent need to search for novel heavy metal and architectures to enhance both the PMA by a factor of two-three and the VCMA efficiency by one to two orders of magnitude. Ab initio electronic structure calculations reveal that ultrathin 5d heavy metal films in MgO/X/FeCo/MgO heterostructures (X = Ir and Pt) can induce *both* large PMA and colossal VCMA efficiency which is two orders of magnitude (17,000 fJ/(Vm)) than those reported today. The underlying mechanism is the synergistic effects of (1) the emergence of X local moments under biaxial tensile strain, (2) the large X spin orbit coupling (SOC), and (3) the giant modulation of the PMA at the X/MgO interface. These results provide useful guiding rules in the design of the next-generation of ultralow energy MeRAM memory devices.

The work is supported by NSF ERC-Translational Ap-plications of Nanoscale Multiferroic Systems (TANMS)-Grant No. 1160504, and by NSF-Partnership in Research and Education in Materials (PREM) Grant Nos. DMR- 1205734 and DMR-1828019.



O57 - Controlled individual skyrmion nucleation at artificial defects formed by ion irradiation

6. Magnetic thin films, multilayers, surface and interfaces

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Skyrmions are the subject of intense current interest with those supported in magnetic multilayer systems most likely to realise potential for memory and logic applications. We report on a new method of nucleating Neel type skyrmions at nanoscale defect sites, created in a controlled manner with focused ion beam (FIB) irradiation, in polycrystalline magnetic multilayer samples with interfacial exchange. Using the FIB method we are able to nucleate compact individual skyrmions local to the point-like artificial defect sites and, for specific ion doses, these remain stable both at room temperature and in zero applied magnetic field. The size of the skyrmion nucleated by this method matches that supported by the unmodified material system where the skyrmions appear at random positions during reversal. The skymrion size in the systems studied range between 100 and 200 nm. The physical, compositional and magntic structure of the defects and skyrmions are characterised using a range of transmission electron microscopy (TEM) techniques. This provides a correlation of the effect on dose on the nature of the defect and its influence on the behaviour of the skyrmions. Results are presented from two different film systems with doses varying over 3 orders of magnitude which will show the best conditions for the controlled skyrmion nucleation and their region of stability.

O58 - Deterministic switching of configurational dynamic magnetic properties in punctured thin films

6. Magnetic thin films, multilayers, surface and interfaces

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A challenge in tunable magnetic microwave devices lies in achieving an energy efficient way to tune the ferromagnetic resonance in a reversible and reproducible way. Using artificially generated magnetic domains and domain wall configurations, the magnetodynamic response of magnetic films is altered. By switching between two dissimilar remanent states of magnetization, we achieve deterministic swapping of effective dynamic magnetic properties. The symmetry breaking of the domain state is attained by patterning an amorphous FeCoSiB thin film with a spatially widely distributed low-density array of diamond-shaped antidots, leading to a deterministically changeable magnetic domain wall network. Aligning the uniaxial anisotropy relative to the edges of diamond-shaped antidots leads to bi-stable domain configurations. In particular, we switch the domain configuration from overlapping to non-overlapping Néel spikes and create varying local effective field at zero external magnetic field.

Quasi-static and dynamic magneto-optical Kerr imaging with picosecond time resolution proof that the different periodic remanent magnetic domain configurations are responsible for the dynamic magnetic bi-stability. Specifically, the effective ferromagnetic resonance frequency can be altered repeatable between 1.3 GHz and 2.3 GHz for the same material system (see Fig.). Time-resolved magneto-optical domain imaging at the FMR frequencies [1,2] show that local configurational ferromagnetic resonances lead to the intended magnetodynamic behavior. Due to the spatially distributed local effective fields of the domain configurations, different inductive permeability spectra are obtained at zero field.

The configurational patterning utilized switching of high-frequency magnetodynamic properties without the necessity of a constantly applied magnetic field. No change in the materials structure and anisotropy is needed for the non-volatile altering dynamic characteristics of the film. The described fundamental mechanism could help building new reconfigurable microwave devices, utilizing switching between zero-field domain arrangements.

We thank the DFG for support through grant MC9/10-2.

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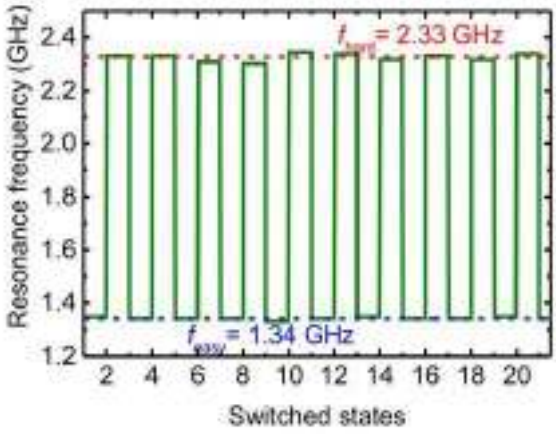
Resonance frequency (GHz)
2.4
2.2
2.0
1.8
1.6
1.4
1.2
f_{high} = 2.33 GHz
f_{low} = 1.34 GHz
2 4 6 8 10 12 14 16 18 20
Switched states

O60 - Effect of magnetic field sweeping rate on transitions in CoFeB/M/CoFeB and Pt/Co/M/Co/Pt spin valves

6. Magnetic thin films, multilayers, surface and interfaces

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Engineering of new spintronic devices used in magnetic memory and data storage devices requires synthetic antiferromagnets with perpendicular anisotropy. The domain wall (DW) dynamics in multilayered antiferromagnetic systems with perpendicular magnetic anisotropy is very unusual due to interlayer DW interactions [1]. The synthetic ferrimagnets, namely MgO/CoFeB/Ta/CoFeB/MgO/GaAs and Pt/Co/Ir/Co/Pt/Ta/SiO_2, have been investigated. We have demonstrated in previous studies [2, 3] the presence of four stable magnetic states P+, P–, AP+ and AP–. Magnetic relaxation affects the magnetization switching dynamics. The timescales of these relaxations varies from a few seconds to several hours. The evolution of the switching field between four stable states as a function of the magnetic field sweep rate (MFSR) has been studied. If the loop recording time is comparable to the magnetic relaxation time, then the MFSR greatly affects the shape of the hysteresis loop and the switching field between the parallel and antiparallel states of synthetic antiferromagnets. Three independent techniques (SQUID magnetometry, MOKE microscopy and microwave ESR spectrometry) were used to provide a wide range of the magnetic field sweep rate 0.1 – 10^4 Oe/s.

This work is aimed at the experimental analysis of the effect of magnetic field sweeping rate on switching field between stable states of the synthetic ferrimagnet with perpendicular anisotropy as well as the comparison of these data with the results obtained in single ferromagnetic films.

The effect of the MFSR on the inversion of interstate transitions sequence will be discussed in the work.

The competition of the mechanisms for the nucleation of the magnetization reversal phase and propagation of the domain walls leads to a nonlinear dependence of the switching fields on the MFSR in MgO/CoFeB/Ta/CoFeB/MgO/GaAs synthetic ferrimagnets.

The sequence of the transitions between stable states can be changed by controlling the sweeping rate of the magnetic field in a Pt/Co/Ir/Co/Pt heterostructure (Figure 1). Simultaneous presence of the AP+ → AP– and AP+ → P– transitions is due to the different height of the activation barriers of transitions and the presence of interlayer DW interactions.

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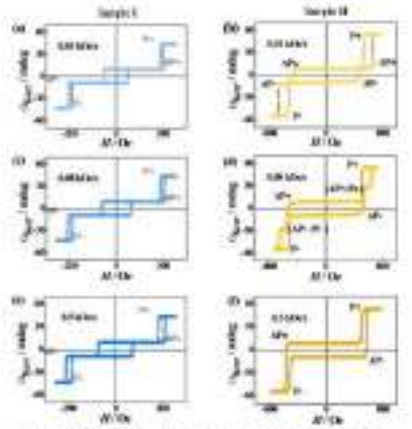

O61 - Electron correlation and exchange interaction at the nanoscale probed by APECS: size vs bias effects

6. Magnetic thin films, multilayers, surface and interfaces

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Even though DMFT and DFT-LDA calculations allow to properly predict the itinerant-like electronic properties of transition metals and their oxides, as well as ferromagnetic (FM) and antiferromagnetic (AFM) magnetic moments, the interplay between band structure, magnetism and many-body correlations is still intriguing and debated [1]. In particular, the relevance of the on-site Coulomb interaction in the *d* orbitals (Hubbard U_{eff}) as compared to the non-local exchange interaction is far from being clarified in depth even at the experimental level [2]. Furthermore, not an adequate consideration is devoted to the role played by the size of the modeled systems and by the electron-electron interaction in the early stages of magnetic thin films/nanostructures synthesis and to their coupling.
Core-valence-valence (CVV) Auger decays have the unique potential to probe intimately the electron-electron interaction in the valence band but most of the time Auger spectra are featureless, often leading to the conclusion that the behavior of some of the major magnetic materials, like Fe, is band-like due to an U_{eff} small as compared to the band-width.
We thus resorted on Angle Resolved Auger-PhotoElectron Coincidence Spectroscopy (AR-APECS), which is capable to unravel the otherwise blurred multiplet structure in Auger spectra. It gives access with unprecedented accuracy to the spin coupling of the two valence hole final state, hence yielding a direct measure of Coulomb and exchange interactions for each individual multiplet component [3].
We report on a full experimental campaign carried out on FM (Fe and Ni), AFM (CoO and NiO) materials and FM/AFM (Fe/CoO) and FM/diamagnetic (Fe/Ag) interfaces that highlight new aspects of the role of the electronic correlation in magnetic systems. The major results are summarized in the following:

- U_{eff}, usually defined for the Auger decay as the on-site Coulomb repulsion, is found to go beyond its established meaning to fully include the exchange interaction;
- in the case of Fe a full set of values of U_{eff} has been found concerning all the possible combinations of orbitals in the two-hole final state (majority and minority spin, t_{2g} and e_g symmetry)
- unexpected large values of U_{eff} have been measured for FM systems and their values strongly depends on the magnetic state;
- a giant size effect has been found on U_{eff} for FM systems;
- a systematic increase of U_{eff} values has been found at the FM/AFM interfaces, the result leading to the conclusion that the orbital symmetry plays a relevant role in setting up the bias effects;
- the dramatic change in the spin resolved Auger lineshape found in AFM transition metal oxides, when crossing the Neèl temperature, is not yet explained.

The elusive objective of measuring the pure Fe CVV Auger lineshape with unprecedented discrimination of the different components has been achieved, thus definitively unmasking the conviction that Auger spectra of Fe are simple self convolutions of DOSs.

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O62 - Exchange coupling between ferromagnetic and ferrimagnetic multilayers

6. Magnetic thin films, multilayers, surface and interfaces

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Nowadays, a great interest of ferrimagnetic (FI) materials is related to their unique properties, eg., easy manipulation of magnetization and anisotropy, tuning the Curie and compensation temperature. In particular, this applies to FI amorphous alloys or multilayers (MLs) consisting of a Rare Earths-Transition Metal (RE-TM), which are characterized by perpendicular magnetic anisotropy (PMA).

Here, we investigated the coupling between ferromagnetic (F) = $(Au/Co)_3$ MLs and FI = $(Tb/Co)_6$ MLs at room temperature conditions. Each Tb sublayers was a form of a wedge, which allows us to study magnetic properties of the system as a function of Tb sublayer thickness (t_{Tb}) or equivalent atomic concentration of Tb (c_{Tb}). This approach is very useful for RE/TM systems because a slight change of $c_{Tb}(t_{Tb})$ in the vicinity of the compensation point/thickness (t_{comp}) have a strong impact on their magnetic properties.

In Fig. 1a, we present results of magnetic measurements for a $(Au\text{-}1nm/Co\text{-}0.8nm)_3$/(Tb-wedge-0-2nm/Co-0.66nm)$_6$ ML system. For Tb thickness $t_{Tb} \geq 0.26$ nm ($c_{Tb} \geq 10.2$ at.%) the shape of the hysteresis loop indicates that both F and FI MLs exhibit a PMA. The compensation point in our systems takes place at $t_{comp} = t_{Tb} = 1.08$ nm ($c_{Tb} = 32.0$ at.%). For $t_{Tb} < t_{comp}$ (TM+ range) the magnetization reversal of F and FI MLs occurs simultaneously and for $t_{Tb} > t_{comp}$ (RE+ range) we observed sequentially switching of F layer followed by switching of FI layer. In the case when $t_{Tb} > 1.45$ nm magnetization reversal process starts from FI layer after which the F layer is switched. This behavior is related to the strong reduction of saturation magnetization (M_S) for high c_{Tb}. From minor loop shift (H_{mls} parameter) in RE+ range, we were able to determine the exchange coupling strength (J) between F and FI structures (Fig. 1b). We found that if t_{Tb} approach to t_{comp} the J increase up to 140 merg/cm^2. Due to that strong exchange interaction the switching field of the ferromagnetic layer (H_S^F) reach high values and can be modified from -8 kOe up to +8 kOe. This show that a proper choice of Tb sublayer thickness (concentration of Tb) open a way to control the absolute value of the switching field and exchange coupling in the wide range, which is very promising for applications in spintronic devices.

The work was financed by the National Science Centre Poland under SONATA BIS funding UMO-2015/18/E/ST3/00557

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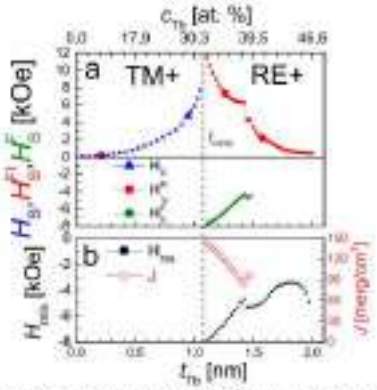

(a) Switching fields of the entire system (H_S), ferrimagnetic (H_S^{ip}) and ferromagnetic (H_S^{oop}) multilayers of the $(Au/Co)_3/(Tb/Co)_n$ system and (b) minor loop shift (H_{ms}) and corresponding exchange constant (J) as a function of t_{Tb}, c_{Tb}. The dashed line represents t_{comp} which divides the TM+ and RE+ ranges.

O64 - First-principles approach to novel 2D ferromagnets

6. Magnetic thin films, multilayers, surface and interfaces

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There is currently an increasing enthusiasm towards long-range magnetic order in two-dimensional materials (such as CrI_3 and $Cr_2Ge_2Te_6$), from the fundamental and from the applicative point of view, from theory and from experiments. In this work, we carry out an extensive investigation based on density functional theory on an extended class of such materials, starting from the database of exfoliable materials reported in N. Mounet *et al.*, *Nature Nano.* 13, 26 (2018). In the aim of optimizing the properties of 2D-ferromagnets and increasing the Curie temperature, our analysis focuses on tri- and di- halides (with formula M-$(VII)_3$ and M-$(VII)_2$, where M is a transition metal and VII = Cl, Br, I). In addition to structural and electronic properties, we analyse magnetic properties, in terms of magnetic moments, Heisenberg exchange coupling constants and magnetic anisotropy energy. Some of the considered materials show exchange coupling constants significantly larger than the prototypical CrI_3, so they might be promising candidates for larger transition temperatures.

O65 - Flexible amorphous nanostructures with tunable magnetic properties

6. Magnetic thin films, multilayers, surface and interfaces

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Flexible magnetic materials are used in e.g. flexible electronics, sensors, and strain-mediated magnetoelectric devices combining magnetoelastic and piezoelectric materials in composite structures [1]–[3]. Magnetic metallic glasses are in this respect very interesting since they can be as elastic as polymers, with excellent soft magnetic properties and metallic conduction. The fast cooling rates obtained using physical vapor deposition techniques make it possible to produce amorphous thin metallic films in a wide range of compositions. In addition, the anisotropy of the films can be tuned during deposition by e.g. an applied magnetic field, depositing compositionally graded films, or by straining the substrate during the deposition [4].

In this work, we investigate how to tune the magnetic properties of magnetic amorphous thin films post-deposition by strain or by creating purely magnetic non-topographic nanostructures. Due to the magnetoelastic coupling (the inverse magnetostriction effect), strain induces magnetic anisotropy. The uniaxial anisotropy of flexible thin CoFeZr films, subjected to tensile and compressive strain, have been investigated using magneto-optical Kerr effect (MOKE) magnetometry. Magnetic non-topographic nanostructures have been created by taking advantage of the physical properties of metallic glasses being extremely sensitive to small changes in the local chemical composition. The local chemical composition was modified by ion implantation through a Cr-mask. The mask was removed after ion implantation leaving a flat film with embedded magnetic nanostructures for which the magnetic anisotropy is tunable by the shape and symmetry of the implanted regions. Choosing the matrix to be paramagnetic at room temperature and the implanted parts to be ferromagnetic, properties similar to those of ordinary topographic nanostructures have been observed in paramagnetic FeZr films with ferromagnetic FeZrB structures using MOKE microscopy and magnetometry [5].

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O66 - Imaging and Manipulating Antiferromagnetic Domains in BiFeO3 Epitaxial Layers

6. Magnetic thin films, multilayers, surface and interfaces

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Antiferromagnetic materials are promising candidates for beyond Moore's electronics. Due to antiparallel alignment of their spins, their long range stray field is null, enabling a high domain density for data storage and huge robustness against external magnetic perturbations. Their intrinsic magnetic order and their abundance among oxides make them perfectly compatible with most spintronic devices, including insulators, opening the way to Joule effect free data manipulation. Nonetheless, the most promising asset concerns their dynamics. Indeed, most antiferromagnets have their magnetic resonances in the teraHertz range. They could both accelerate spintronics dynamics by several order of magnitude, and provide emitters and detectors to fill the so-called "THz Gap" with its possible countless applications.

This work investigates antiferromagnetic domain walls dynamics in an epitaxial layer of bismuth ferrite – a prototypical magneto-electric antiferromagnet – using time-resolved second harmonic generation (SHG). Our sub-micron spatial resolution within a pump-probe frame enables probing sub-picosecond phenomena occurring after an intense optical excitation of about one hundred femtoseconds. Due to ultrafast internal rectified electrical polarization and magneto-electric coupling, one can expect to see direct occurrences of ultrafast magnetic dynamics in the teraHertz range.

Preliminary results show that dynamical effects are present but not necessarily of pure magnetic nature. More selective sources of excitation are then considered.

O68 - In-field δM plots: simple yet efficient manner to assess interactions in exchange bias systems

6. Magnetic thin films, multilayers, surface and interfaces

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In 1958, Wohlfarth identified a relation [1] between the principal remanence curves of systems with symmetric major loops, which should be valid no matter whether the magnetization, M, reversal occurs via domain nucleation followed by domain wall-motion or coherent rotation when the magnetic field, H, is varied. Since then, the interaction studies have mostly been based on this relation through remanence $\delta M(H)$ plots. Recently, a relation analogous to that of Wohlfarth but between in-field magnetization (and not remanence) curves has been derived [2], leading to introduction of a novel, $\delta M_R(H)$ plot. The latter is obtained from the major loop and one recoil curve only. This plot does not demand demagnetization, which significantly simplifies the measurements.

In exchange bias, EB, systems, characterized by shifted and often asymmetric major hysteresis loops, remanence δM plots cannot be used in their classical forms. Although this technique has been adapted and extended to EB systems [3], it still requires attaining a demagnetized state and measuring of a great number of minor loops.

Here we present assessment of magnetic interactions in EB systems using an in-field magnetization plot [4] which is more general than that introduced for symmetric loops [2] in 2018. All one needs to construct a general δM_R plot is a recoil loop and the values of the shifts (if such exist) along the axes of the respective major hysteresis loop. An asymmetric EB major loop has one of its branches steeper than the other. This leads to (i) an essentially nonzero δM_R data generated from the major loop (this plot revealed to be a very precise quantitative measure of the asymmetry), and (ii) two distinct δM_R plots obtained from recoil loops having the same recoil field (e.g., the coercive field) but traced along different, the descending and ascending, magnetic field paths; the cross-examination of these plots might provide valuable information on the magnetization reversal mechanism.

In particular, we discuss results of application of the method on a Co/IrMn thin film sample. It turns out that the δM_R technique is a tool able to reveal particularly valuable information. It might, e.g., allow distinguishing effects coming from magnetic coupling into the ferromagnet from those stemming from interactions in its interface with the antiferromagnet.

We also provide a free software (www.if.ufrgs.br/pes/lam/dMr.html) which generates δM_R plots.

This work has been financed by CNPq (grants 305796/2016-0 and 422740/2018-7) and CAPES.

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O69 - Investigating RF magnetic properties and Interlayer exchange coupling in magnetic films using FMR

6. Magnetic thin films, multilayers, surface and interfaces

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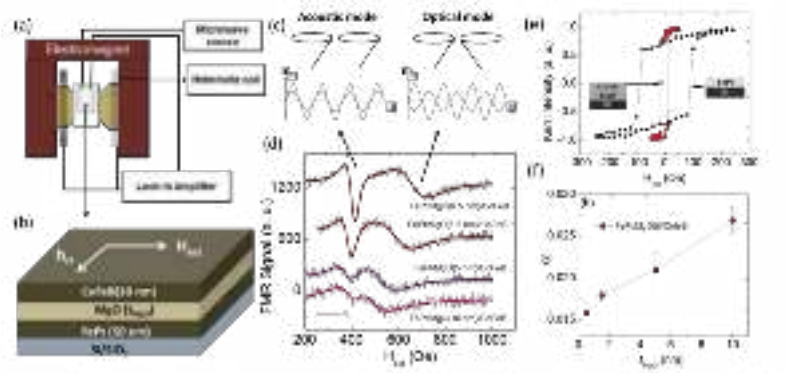
Two ferromagnetic (FM) layers separated by a non-magnetic spacer have attracted ample interest as they act as a key component of modern technology. FM_1/Insulator/FM_2 structures provide unlimited opportunities for rf magnetic and various spintronics devices due to their application in magnetic recording media, magnetic microactuators, and magnetic tunnel junctions etc. Recently, exchange system consisting of soft FM coupled to hard FM have been proposed to increase the rf properties of soft FM due to their similarity to antiferromagnetic(AFM)/ferromagnetic(FM) system. However, in contrast to AFM/FM which requires field cooling, hard/soft FM systems shows a room temperature exchange coupling effect due to the interplay between exchange coupling at interface. These systems are studies using FMR technique which is a powerful method for studying interlayer exchange coupling (IEC) in sandwiched multilayers. FMR spectra are strongly influenced by the IEC. A set of four films with Si_{sub}/FePt(50nm)/MgO(t)/ CoFeB(10nm) have been prepared with thickness of the MgO, t= 0.5, 1.5, 5, and 10 nm. Here, the bottom FePt alloy films of composition 46% and 54% respectively were prepared separately on Si substrate by co-sputtering of pre-calibrated Fe and Pt targets using dc magnetron sputtering. Rest of the structure MgO(t)/CoFeB has been grown on FePt layer using ion beam sputtering technique at the base pressure of $\sim 2 \acute{} 10^{-7}$ mbar. Structural and magnetic characterizations of the film were done using XRR, X-ray fluorescence and MOKE. MOKE measurement showed that the coercively of FePt layer is significantly higher than that of CoFeB layer, which acts as the hard layer and is coupled to the CoFeB soft layer.

We systematically evaluated the rf magnetic properties and IEC on thin films sandwich structure. FMR measurements were carried out at excitation frequencies from 4-10 GHz using field modulation technique to maximize the signal to noise ratio for accurate measurements[**1**]. Two resonance modes were achieved, is basically due to the difference in saturation magnetization of two FM layers[**1-2**]. We evaluated Gilbert damping constant (α), linewidths and the IEC constant (J_{int}) from the FMR absorption signal. We found α varies from 0.016 to 0.027 with increasing t_{MgO} is likely due to IEC. Our analysis shows a strong absorption peak (designated as acoustic mode) around H_{ext} = 400 Oe and weak absorption peak (designated as optical mode) around H_{ext} = 630 Oe, indicates AFC type of exchange coupling in our samples and is confirmed from the exchange field calculation and values obtained from the fits of FMR absorption signals[**3-6**]. AFC, J_{int}, decreases with increase in t_{MgO}. Thus, our results suggest that we can use the IEC between the FM layers to tune optical mode resonance that can provide an increase in operation frequency at reduced H_{ext} in microwave based devices. Our results also suggest that hard/soft FM layers can act as a good candidate of rf device applications, which require soft magnetic films along with high saturation magnetization. Further, IEC can act as an additional means to optimize the magnetic relaxation and anisotropy properties in magnetic structures, which is important for applications in rf microwave devices.



O70 - Ion-induced defects at the interfaces correlating with enhanced perpendicular magnetic anisotropy

6. Magnetic thin films, multilayers, surface and interfaces

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Perpendicular magnetic anisotropy (PMA) of thin magnetic films can be enhanced by ion irradiation in Pt/Co/Pt heterostructure[1,2]. Recently, Pt/Co system shows considerable interest for the scientific community, in the context of the Dzyaloshinskii-Moriya (DMI) interactions and chiral magnetic structures[3,4], including structural inversion symmetrical Pt/Co/Pt layers[5] and defects presence[6]. So it seems that the precise control of the interfacial defects could have a huge impact whenever enhanced PMA and sufficiently large DMI is needed.

Symmetrical covers of Pt, induce in Pt/Co/Pt strong PMA, orienting out-of-plane magnetization up to Co layer critical thickness $\mathbf{d_{SRT}}$. While decreasing cobalt thickness, $\mathbf{d_{Co}}$ below $\mathbf{d_{SRT}}$ (ca. 1.9nm), a spin reorientation transition (SRT) from in-plane to out-of-plane magnetization alignment takes place. Initial works on ion irradiation of Pt/Co/Pt reported a decrease in PMA[7] upon treatment. However, an opposite modification enhancing the PMA is also possible[1,2] where under ion irradiation, a sequential increase of the PMA with the ion fluence, **F** increases.

Recently, we reported[1] the possibility to induce PMA in ultrathin Co by Ar^+ ions bombardment instead of Ga^+ ions [3]. We selected Ar^+ ions of energy 1.2, 5 and 30 keV enabling studies of precise nanostructure modifications on different depth in relation to magnetic layer position. We establish a correlation between the magnetic and structural changes of Pt/Co/Pt ultra-thin layered structure induced by irradiation with Ar^+ ions. Our work discusses particularly structural factors related to crystal lattice defects and strain, created and modified by irradiation, co-responsible for the increase in PMA. We investigate the magnetic properties as a function of $\mathbf{d_{Co}}$ and **F** and the evolution of the structure under irradiation. Finally, the unique properties of positron interaction with the thin film surface region have been utilized, in positron annihilation spectroscopy (PAS)[8] for the defect spectroscopy of the ion irradiated samples. Our work opens the interpretation where defects creation alloy formation, strain generation can be correlated to observed magneto-optical properties and the PMA.

Acknowledgements

This work was supported by the Foundation for Polish Science (FNP)and co-financed by the EU European Regional Development Fund, [TEAM SYMPHONY OPIE 07-13, and REINTEGRATION 2017 OPIE 14-20]. The MePS facility has partly been funded by the Federal Ministry of Education and Research (BMBF) with the grant PosiAnalyse (05K2013). The support of the ELBE team at HZDR is greatly acknowledged.

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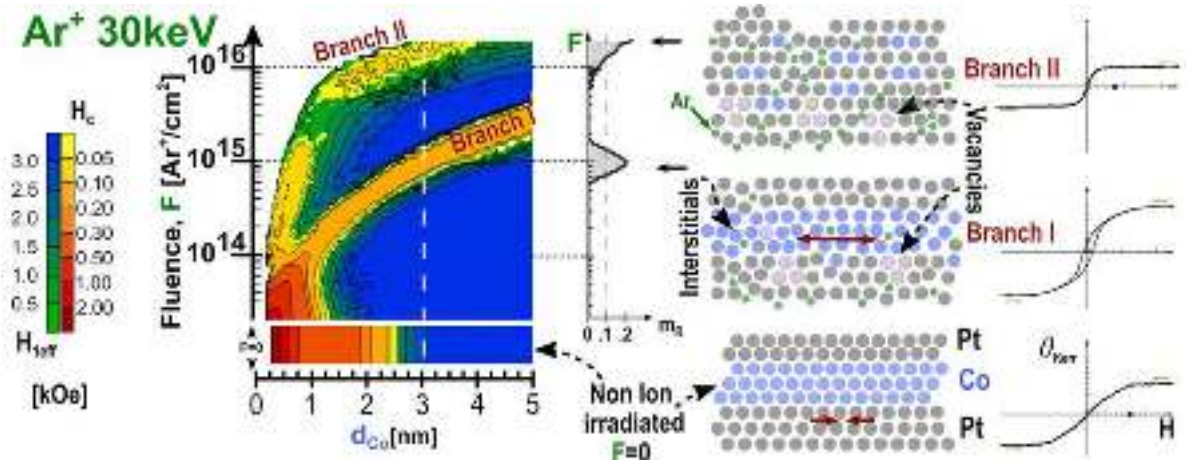
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H1nT
[kOe]
Fluence, F [Ar+/cm2]
10^16
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10^14
Branch II
Branch I
0 1 2 3 4 5
dCo[nm]
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Non Ion+ irradiated
F=0
Ar+
Interstitials
Vacancies
Branch II
Branch I
Pt
Co
Pt
H

O71 - L10-ordered ferrimagnetic Fe(1-x)Cr(x)Pt (001) thin films

6. Magnetic thin films, multilayers, surface and interfaces

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New magnetic materials designed for ultrafast all-optical switching (AOS) of magnetization are of high interest from a fundamental as well as technological point of view because AOS could be exploited as a future recording concept [1, 2]. One of the interesting materials in this regard is chemically ordered $L1_0$ FePt alloy thin films exhibiting large perpendicular magnetic anisotropy (PMA) of up to 7 MJ/m^3 [3], which have been recently implemented as ultra-high density magnetic storage medium for applications in heat-assisted magnetic recording (HAMR) [4]. Recently, AOS with assistance of additional external magnetic field on FePtAgC granular medium was demonstrated [5]. Furthermore, it has been shown experimentally for TbFe films, that the remanent magnetization (M_r) [6] or domain size [7] could be the factor which limits the AOS capability.
In this regard, a series of $(Fe_{(100-x)}Cr_{(x)})_{50}Pt_{50}$ alloy thin films with a thickness of about 10 nm were prepared by epitaxial growth on MgO(100) substrates at 800°C. The Cr content x was varied in the range of 0 – 100 at.% for continuous tuning of the remanent magnetization. All samples in the series reveal pronounced $L1_0$ chemical ordering, where *c* lattice parameter in growth direction is steadily changing from $L1_0$-FePt (c = 0.372 nm) to the bulk value of $L1_0$-CrPt (c = 0.381 nm). With substitution of Fe by Cr in the $L1_0$ lattice up to 20 at.% strong PMA is observed at 300 K (Fig. 1). However, with addition of 45 at.% Cr, PMA gets strongly reduced. With further addition of Cr, the film turns into an antiferromagnetic system. Also the coercivity in out-of-plane direction decreases from 42.94 kOe to 10.82 kOe with addition of 20 at.% Cr, which is in fact attributed to a strong alteration of the film morphology changing from island-like to a more continuous film structure. Furthermore, x-ray magnetic circular dichroism studies at the Fe and Cr $L_{3,2}$ edges revealed a strong antiferromagnetic coupling between Fe and Cr, which supports the reduction in net magnetization of the film (Fig. 1).

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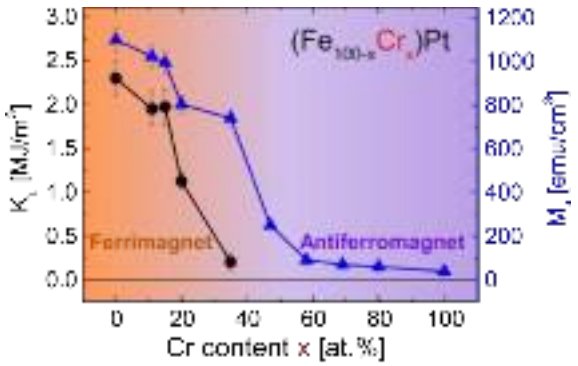

Figure 1. Dependence of the uniaxial magnetic anisotropy (blackdots) and saturation magnetization (blue triangles) on the Cr content, obtained at 300 K.

O72 - Magnetic imaging of epitaxial Co thin films with C2v symmetry and Dzyaloshinskii-Moriya interaction

6. Magnetic thin films, multilayers, surface and interfaces

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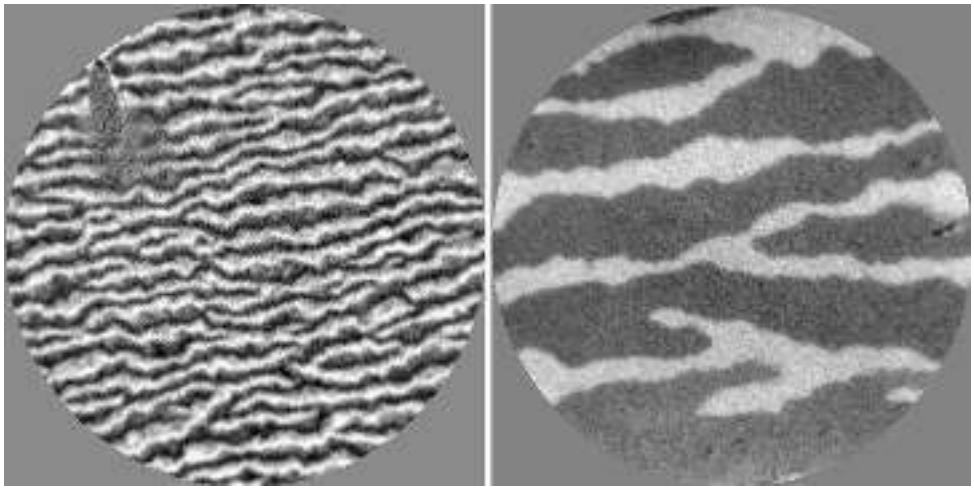
Symmetry plays an important role in magnetism, since the structural symmetry of a crystal also determines the symmetry of the magnetic interactions. In this work, we have studied the magnetic properties of thin Co films with C_{2v}-symmetry, epitaxially grown on bcc-W(110). In particular, we have used Photo Emission Electron Microscopy combined with X-ray Magnetic Circular Dichroism (XMCD-PEEM) to observe the domain structure and domain wall configurations in bcc-W(110)/hcp-Co(0001)/fcc-$Pt_{33}Au_{67}$ (111) for different Co thicknesses. For Co thicknesses between 2 and 5 ML (0.5 – 1.0 nm), this system shows a perpendicular magnetization, with an additional in-plane anisotropy along the W [-110] direction due to magnetoelastic anisotropy. Moreover, the structural inversion asymmetry and the presence of Pt at one of the interfaces also leads to an isotropic strong interfacial Dzyaloshinskii-Moriya interaction, estimated as 0.75 pJ/m using Brillouin Light Scattering spectroscopy. The XMCD-PEEM images show a stripe domain structure for Co thickness between 0.6 and 1.0 nm with the stripes aligned along the W[-110] direction, the in-plane easy axis of magnetization. The domain walls between the stripe domains show a clear, chiral Néel component due to the DMI. The domain period decreases with increasing Co thickness, giving rise to a configuration close to a magnetic spiral for the thickest Co layer (about 5 ML). Upon application of a magnetic field perpendicular to the film plane, elongated skyrmion bubbles were observed.
The Figure shows the domain structure at zero magnetic field for ~4.5 ML (left) and ~3.5 ML (right) of Co, measured with XMCD-PEEM. The field of view of the images is 5 µm. The W[-110] direction is the horizontal axis in the images.



O73 - Magnetic Properties in Double Perovskite La2Ni1–xMn1+xO6 Insulating Thin Films

6. Magnetic thin films, multilayers, surface and interfaces

Monica Bernal-Salamanca[1] , ***Zorica Konstantinovic***[2], *Lluis Balcells*[1], *Carlos Frontera*[1], *Elisa Pannunzio-Miner*[3], *Alberto Pomar*[1], *Benjamin Martinez*[1]

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Double perovskite La2NiMnO6 (LNMO) is one of few ferromagnetic materials with semiconducting character and as such, a good candidate for magnetically active insulating barrier in spin filters. In this work epitaxial thin films have been prepared on (001) oriented SrTiO3 substrates by RF magnetron sputtering using a stoichiometric La_2NiMnO_6 target. The effects of the oxygen pressure (PO_2) and growth temperatures on the microstructure, magnetic and transport properties have been investigated. Irrespective to the growth conditions, films grow fully strained showing insulating behavior. However, microstructure (Ni/Mn ratio) and magnetic properties strongly depend on oxygen pressure conditions. High oxygen pressures promotes the growth of stoichiometric films, with Ni:Mn = 1, but poor magnetic properties. Most interestingly, films grown at low oxygen pressure exhibit Ni/Mn ratios below 1 indicating a deviation from the ideal double perovskite structure, but ferromagnetic properties closed to optimal ones. The valence balance between Ni and Mn ions in nonstoichiometric sample has been studied by X-ray absorption spectroscopy. These results indicate that Ni deficiency plays an important role in the unexpected insulating ferromagnetic behavior of nonstoichiometric LNMO thin films.

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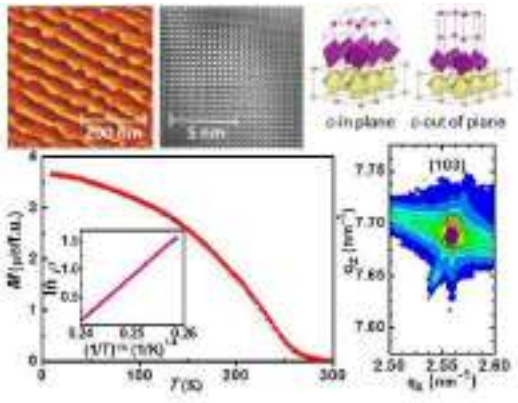

O74 - Magnetic soft X-ray transmission tomography: a tool to reveal complex magnetic textures

6. Magnetic thin films, multilayers, surface and interfaces

Aurelio Hierro-Rodriguez[1] , *Carlos Quiros*[2, 3], *Andrea Sorrentino*[4], *Luis Manuel Alvarez-Prado*[2, 3], *Jose Ignacio Martin*[2, 3], *Jose Maria Alameda*[2, 3], *Stephen McVitie*[1], *Eva Pereiro*[4], *Maria Velez*[2, 3], *Salvador Ferrer*[4]

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Traditionally, magnetism has been linked to the imaging and study of magnetic domains within ferromagnets as their behavior is critical to understand the magnetic properties of the systems under investigation [1]. Nowadays, with the increased complexity of the magnetic textures to be used in Spintronics [2] and at the beginning of the novel field of 3D Nanomagnetism [3], magnetic imaging techniques face the challenge of moving from the characterization of magnetization textures in planar systems to the study of complex 3D magnetic configurations within heterostructures and 3D nanomagnets. In this framework, magnetic X-ray transmission tomography allows the user to reconstruct the full magnetization configuration within the volume of the sample with high spatial resolution [4,5].

In this work we have experimentally demonstrated the potential of soft X-ray magnetic tomography by reconstructing the complex magnetization configuration of a $Ni_{80}Fe_{20}/NdCo_5/Ni_{80}Fe_{20}$ heterostructure. Soft X ray transmission tomography permits to reveal the 3D magnetization of a ferromagnetic material thanks to the angular sensitivity of the magnetic dichroism. Several interesting magnetic singularities appear as a result of the weak perpendicular magnetic anisotropy character of the $NdCo_5$ magnetic layer [6,7]. The experiment was carried out at the Mistral beamline of the ALBA Synchrotron. The heterostructure consisted on 80nm $Ni_{80}Fe_{20}$/80nm $NdCo_5$/80nm $Ni_{80}Fe_{20.}$ Two different tilt series were recorded from the same sample area in order to be sensitive to the three components of the magnetization vector. Each projection was recorded with positive and negative circular polarized photons at the Fe L_3 absorption edge energy. As described in ref. 5, by using this approach the pure XMCD signal can be extracted forming the magnetic tomogram to be reconstructed. The reconstructed configuration experimentally confirms the reversal topological rules described in ref. 7. Moreover, a Bloch point and a Meron-like texture have been identified within the central layer due to the magnetization behavior close to the interfaces in the $Ni_{80}Fe_{20}$. The results show the potential of the technique as a unique tool for the magnetic 3D characterization of arbitrary systems and heterostructures which is of great interest for Spintronics and 3D Nanomagnetism.

Authors acknowledge the support from Generalitat de Catalunya (Spain), Spanish MINECO (FIS2016-76058) and Spanish Ministry of Science and Innovation. A. Hierro-Rodriguez and S. McVitie acknowledge the support from the European Commission under the Marie-Slklodowska-Curie Actions H2020-MSCA-IF-2016-746958.

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O75 - Magnetism of Fe doped ZrO2 thin films studied by synchrotron measurements and ab initio simulations

6. Magnetic thin films, multilayers, surface and interfaces

Alberto Debernardi[1] , *Roberta Ciprian*[2], *Alessio Lamperti*[1], *Luca Capasso*[2], *Elena Cianci*[1], *Eugene Weschke*[3]

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Diluted magnetic oxides are driving increasing interest in solid state physics and materials science communities for their potential applications in spintronic devices where they allow to reduce power consumption and to store and manipulate non-volatile data beyond room temperature, as requested in nano-electronics. Among oxides, zirconia (ZrO_2) is a promising candidate with a high dielectric constant and ionic conductivity which has recently been integrated in ultra-scaled devices. Fe is substitutional dopant that stabilizes the tetragonal phase of Zirconia [1,2]. Exploiting x-ray absorption near edge spectroscopy (XANES) in high magnetic fields, we investigated the magnetic properties of thin films grown by atomic layer deposition (ALD) of zirconia doped with magnetic impurities. The spectra were acquired at Fe-$L_{2,3}$, and O-K edges of iron-doped zirconia ($Zr_{1-x}Fe_xO_{2-y}$) for different Fe dopant concentrations x, ranging from diluted (x ~1-2 at. %) up to high (x ~25 at. %) concentration. By x-ray magnetic circular dichroism (XMCD), we carefully analyzed the temperature dependence of the magnetic moments of this dilute magnetic oxides from low (T=5 K) up to room-temperature, for different Fe concentrations studying the best dopant concentration range maximizing the magnetic signal. The results underline a relation between the Fe^{3+} /Fe^{2+} ratio and the amount of oxygen vacancies responsible for the temperature dependence behavior of the magnetization and the degradation of magnetic properties at high dopant regime. In particular, the measured magnetic signal decreases as the Fe concentration increases. To enlighten this surprising behavior, we performed first principles simulations of Fe doped zirconia, by using the super-cell method and plane-wave pseudopotential techniques within the framework of density functional theory. On the basis of our ab initio results we propose that the microscopic mechanisms responsible of the peculiar magnetic properties of this compound can be explained by oxygen mediated super-exchange mechanism between the Fe dopant and the complex formed of Fe atom and O vacancies, producing, at high dopant concentration, an antiferromagnetic coupling between two Fe atoms.

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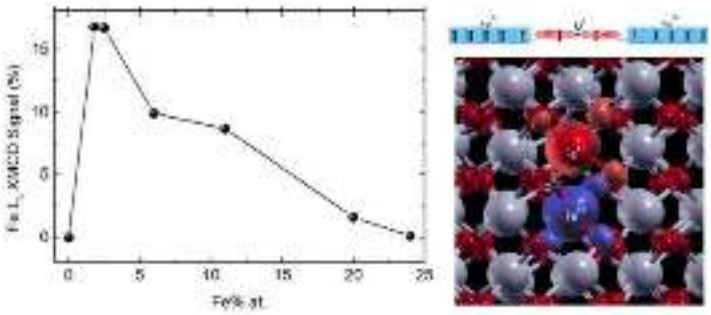

Figure. Left Panel: Fe L_3 XMCD signal as a function of Fe dopant concentration. Right Panel: Antiferromagnetic coupling between two Fe atoms induced on O bridge atom by means of super-exchange mechanism. Top Right: scheme of O- induced super-exchange. Bottom Right: stick and ball model of one of the atomic configurations studied (in the atomically relaxed structure displayed, two Fe atoms substitutional to Zr are in the nearest-neighbors of the Zr lattice sites)

O76 - Magneto-Crystalline Anisotropy of Fe, Co and Ni slabs: A benchmark from DFT and Tight-Binding models

6. Magnetic thin films, multilayers, surface and interfaces

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I will report magneto-crystalline anisotropy (MCA) calculation of Fe, Co and Ni slabs of various thicknesses and crystalline orientations from two Density Functional Theory codes based on a plane wave (Quantum Espresso [1]) and a local atomic basis set (Quantum ATK [2]) expansion as well as a magnetic tight-binding method [3].
I will analyse the evolution of the MCA with the number of layers of the slabs (N=1, ..15). The decomposition of the total MCA into contributions of atomic sites performed via the application of the Force Theorem [4] helps understanding the oscillatory behaviour of the MCA with the slab thickness and highlights the role of quantum well states. I will also identify some specific systems with enhanced MCA.
MCA is a quantity that depends sensitively on many parameters. It will be illustrated by a k-space (see figure)- as well as the strain-analysis showing very rich features that could eventually be used to tailor systems with enhanced magnetic properties. Finally, this work can serve as a benchmark for MCA calculations and setting the limit of electronic structure methods.

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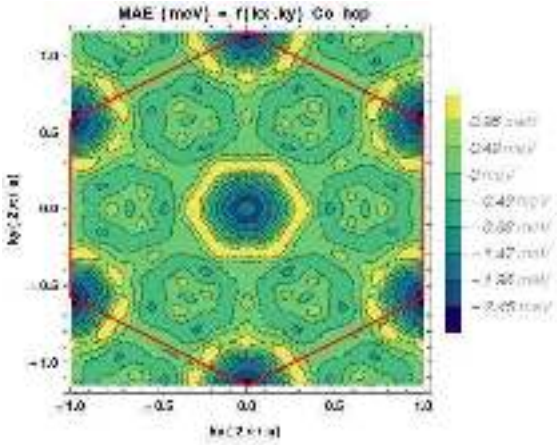

K-space resolved MCA in Co hcp

O77 - Magnetostriction Behavior of Fe-Co(001) Single-Crystal Films Formed on VN Underlayers

6. Magnetic thin films, multilayers, surface and interfaces

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Magnetic thin films with large magnetostriction coefficients have been studied for microelectromechanical-system applications such as actuators, sensors, and vibration energy harvesting devices. Fe-Co alloys with bcc structure are typical soft magnetic materials and have recently attracted much attention as one of magnetostrictive materials, since they show large magnetostriction coefficients of 10^{-4} [1–3]. In our previous study [4], bcc-$Fe_{100-x}Co_x$(001) single-crystal films (x = 0–50 at. %) were prepared on MgO(001) substrates at 300 °C. The magnetostriction coefficients of λ_{100} and λ_{111} respectively increased from $+10^{-5}$ to $+10^{-4}$ and from -10^{-5} to $+10^{-5}$, with increasing the x value.

A higher growth temperature may improve the crystallographic and the magnetostrictive properties. However, an elevated substrate temperature generally enhances the film surface roughness, which makes it difficult to measure the magnetostriction property. In order to suppress the roughness, it is useful to employ an underlayer material whose surface energy is higher than that of Fe-Co alloy. Vanadium nitride (VN) has NaCl-type crystal structure with the length parameter of 0.42 nm, similar to the case of MgO. On the contrary, the surface energy of VN crystal is much higher than that of MgO crystal. Therefore, VN seems suitable as underlayer material for Fe-Co film. In the present study, $Fe_{50}Co_{50}$ alloy films are prepared on VN(001) single-crystal underlayers hetero-epitaxially grown on MgO substrates by varying the substrate temperature from room temperature (RT) to 600 °C. The influence of growth temperature on the structure and the magnetostrictive properties is investigated.

$Fe_{50}Co_{50}$ films grow epitaxially on VN(001) underlayers for all the investigated substrate temperatures. The crystal structure and the orientation relationship with respect to VN underlayer are determined by RHEED and XRD as bcc-$Fe_{50}Co_{50}$(001)[110] || VN(001)[100]. The lattice strain decreases with increasing the growth temperature. The surface morphology is observed by AFM. Flat film surfaces are realized for all the films, even when elevated substrate temperatures are used. The magnetostriction behavior is observed by using a cantilever method under rotating magnetic fields of 0–1.2 kOe. The bending is measured by using a laser displacement meter. Figures 1(a) and (b) summarize the magnetostriction coefficients of λ_{100} and λ_{111}, respectively. As the growth temperature increases from RT to 600 °C, the λ_{100} and the λ_{111} values increase from $+261\times10^{-6}$ to $+299\times10^{-6}$ and from -16×10^{-6} to $+117\times10^{-6}$, respectively. The present study shows that an introduction of VN underlayer and an employment of high growth temperature are useful to enhance the magnetostriction of Fe-Co film.

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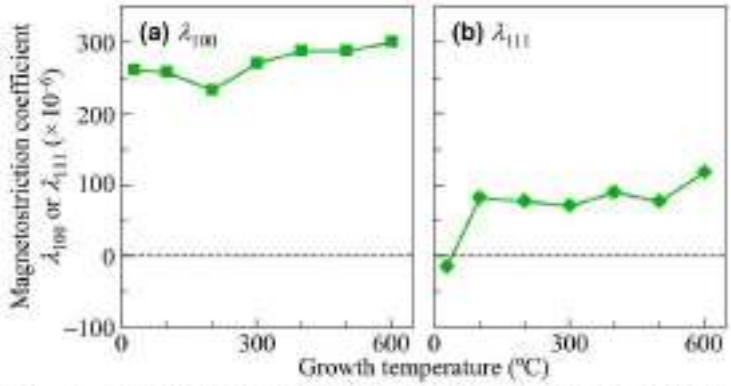

Fig. 1 Growth temperature dependences of magnetostriction coefficients, (a) λ_{100} and (b) λ_{111} of $Fe_{50}Co_{50}(001)$ single-crystal film formed on VN underlayer.

O78 - Modification of interface-controlled parameters of magnetic tunnel junctions by ion irradiation

6. Magnetic thin films, multilayers, surface and interfaces

Bruno Teixeira[1] , *Andrey Timopheev[2], Nuno Caçoilo[1], Léa Cuchet[2], Julien Mondaud[2], Jeffrey Childress[2], Sérgio Magalhães[3], Eduardo Alves[3], Nikolai Sobolev[1, 4]*

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Magnetic properties of materials are strongly dependent on the structure, from the intrinsic coupling to the lattice to the emergence of effective anisotropies caused by the microstructure-related spatial-dependent magnetization. Reduced symmetry at interfaces [1], lateral microstructure [2], and interlayer interactions [3] may be modified by ion irradiation, providing a route for the control of magnetism in magnetic multilayers. Being a well-established technology allowing also for lateral patterning [1], it helps to explain the interest on the ion irradiation of magnetic structures, particularly of magnetic tunnel junctions (MTJ) [4,5]. Before applications can be envisaged, however, it is necessary to understand the full extent of effects produced by the irradiation on the interface-controlled parameters of MTJ stacks.

To that end, we irradiated an MTJ multilayer with 400 keV Ar^{+} ions at fluences (Φ) up to 5×10^{15} cm^{-2}. The stack was comprised of Substrate/Ta/CuN/Ta/Ru/IrMn/PL/Ru/RL/MgO/FL/Ta/Ru layers, where PL, RL and FL are the pinned, reference and free layers made of CoFe(B) alloys. Ferromagnetic resonance (FMR) was used to measure the effective anisotropy field of the FL, H_{K1}, encompassing interfacial perpendicular magnetic anisotropy (k_{s1}/t), shape ($4\pi M_S^2$), and volume (K_v) anisotropy. All magnetic layers are in-plane magnetized ($H_{K1} < 0$). The tunnel magnetoresistance ratio ($TMR=(R_{AP}-R_P)/R_P$) was measured with a current-in-plane 4-point probe. Before irradiation μH_{K1}=-10.7 kG and TMR = 193%.

The anisotropy keeping the magnetization in-plane decreased with increasing fluence (fig. a, c). This tendency, opposite to the observed in [4] for MgO/FeCoB/MgO, is explained by a stronger decrease of M_S due to intermixing at the top FL/Ta interface than of k_{s1} at the MgO/FL interface.

The TMR dropped to 74% at $\Phi = 3\times10^{13}$ cm^{-2}, following the decrease in R_{AP} (fig. b). The intermixing at MgO/FeCoB cannot explain this initial loss of TMR, since H_{K1} (fig. a) and R_P (fig. b) remain practically unchanged up to $\Phi = 3\times10^{13}$ cm^{-2}. The likely mechanism is instead the creation of defects within the MgO barrier, acting as spin-independent tunneling channels shunting the spin-dependent one. Above $\Phi = 10^{14}$ cm^{-2}, the RL became decoupled from the PL as seen by the two loops in R(H) (fig. b) and the appearance of an additional FMR line (fig. c).

Other effects of the irradiation, particularly those concerning the magnetic damping, will also be discussed.

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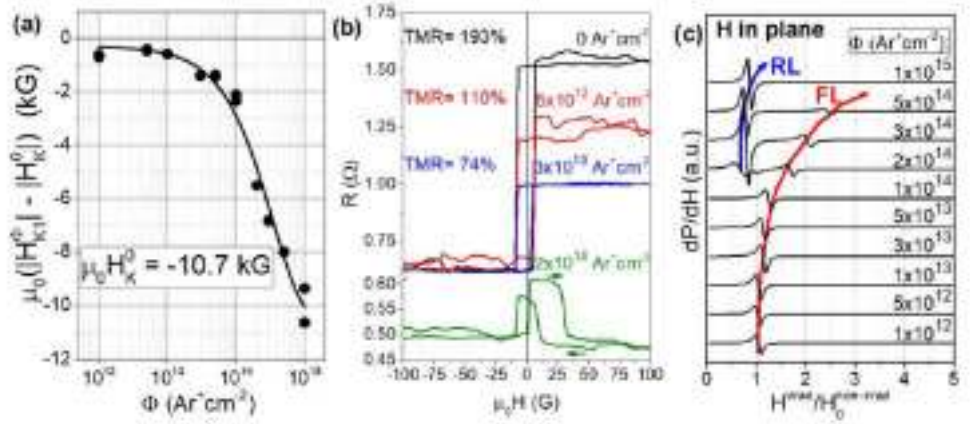

Figure. (a) changes in magnitude of the anisotropy field versus ion fluence; (b) R(H) loops for selected ion fluences; (c) FMR spectra for increasing ion fluences (H-axis normalized by resonance field before irradiation).

O79 - Nanoscale imaging of antiferromagnetic order in magnetoelectric films using single spin magnetometry

6. Magnetic thin films, multilayers, surface and interfaces

Natascha Hedrich[1] , *Patrick Appel*[1], *Brendan Shields*[1], *Tobias Kosub*[2, 3], *Juergen Fassbender*[2], *Rene Huebner*[2], *Denys Makarov*[2, 3], *Patrick Maletinsky*[1]

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The development of nanoscale magnetometry using the Nitrogen-Vacancy (NV) center in diamond has opened up a world of nanoscale sensing applications. These centers, consisting of a single electronic spin, make for an atomic-scale sensor, capable of imaging nanoscale magnetic systems with high sensitivity and minimal invasiveness. NV-based magnetometers are stable over a wide temperature range, from ambient conditions to cryogenic systems, and thereby provide access a plethora of physical phenomena. We integrate a single NV center into the tip of a parabolic all-diamond atomic force microscopy scanning probe, which allows us to achieve 50 nm spatial resolution and sub-$\mu T/Hz^{½}$ sensitivities [1].

We use this system to image stray fields emerging from thin, magnetoelectric, antiferromagnetic films, specifically, Cr_2O_3. This material is technologically interesting due to its room-temperature, antiferromagnetic ordering and magnetoelectric properties that allow, for example, fast electronic switching [2]. Using a combination of NV magnetometry and Zero Offset Hall Magnetometry (ZOHM) [3], we extract key material properties of Cr_2O_3 thin films by magnetic stray field imaging. Symmetry breaking leads to a fully polarized atomic monolayer of electronic spins on the surface of Cr_2O_3, whose magnetisation is directly linked to the underlying antiferromagnetic bulk order parameter (see Fig. 1a). We image the antiferromagnetic domain formation over the paramagnet to antiferromagnet transition with nanoscale resolution (Fig. 1b) and together with ZOHM, extract the inter-granular exchange coupling and local critical temperature distribution. Furthermore, we present recent results, where we extend our technique to the study of bulk, single-crystal Cr_2O_3 samples, where we determine surface magnetic moment densities and aim at resolving domain-wall dynamics with high spatial resolution.

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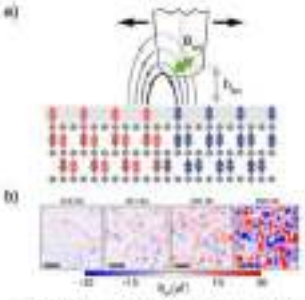

Figure 1. a) The stray field produced at the transition between two antiferromagnetic domains can be sensed by an NV embedded into the tip of an AFM during scanning. **b)** Quantitative magnetic field maps show the progression from paramagnetic (left) to antiferromagnetic (right) as the sample is cooled (scale bar is 500 nm).

O80 - Non-collinear magnetic order in SrIrO3 - La0.7Sr0.3MnO3 heterostructures

6. Magnetic thin films, multilayers, surface and interfaces

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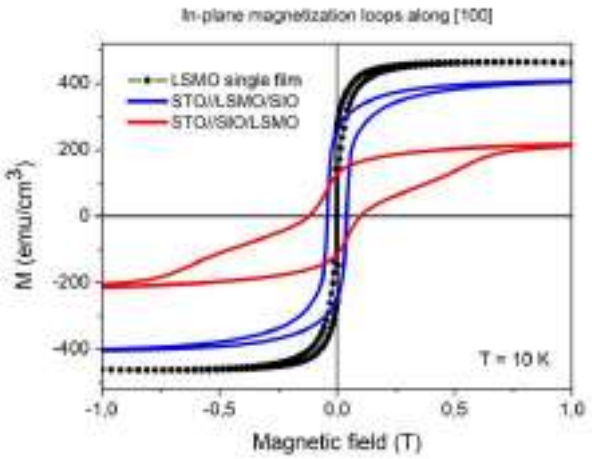
Iridate compounds are of high scientific interest, since they show emergent phenomena due to competition between the relevant energy scales of electron correlation, bandwidth and, most importantly, strong spin-orbit coupling. We investigate how the coupling between 3*d*-$La_{0.7}Sr_{0.3}MnO_3$ (LSMO) and 5*d*-$SrIrO_3$ (SIO) alters the magnetic properties such as magnetic order and anisotropy of LSMO which is a collinear soft ferromagnet with high spin polarization.

High quality bilayers of LSMO and SIO with different stacking sequence and thicknesses of few unit cells were coherently grown by pulsed laser deposition on TiO_2 terminated (100) $SrTiO_3$ substrates. The magnetic properties were investigated by magnetization and x-ray magnetic circular dichroism (XMCD) measurements. Structural characterization of the bilayer samples was done using x-ray diffraction and scanning transmission electron microscopy (STEM). The STEM images confirm the abruptness of the interfaces with one Mn-Ir intermixed unit cell at the interfaces. No chemical difference of the LSMO-SIO interfaces of reversed stacking sequence has been detected. We find the magnetic anisotropy of both bilayer types changed in comparison to single-film LSMO, with an out-of-plane canting of the easy axis direction. In case of the LSMO grown on SIO, these changes are very pronounced, making LSMO a canted hard magnet. Based on the assumption that LSMO returns to strained bulk-like behavior in sufficient distance from the interface, this leads to non-collinear magnetic order of Mn induced by the interface to SIO. The strong difference induced by growth sequence hints at an impact of lattice structure, i. e. rotation patterns of oxygen octahedrons, on magnetic anisotropy and the strength of magnetic interactions. Non-collinear magnetic order at oxide interfaces is vitally important for spintronics devices.



O81 - One scan microwave absorption study in [Ti/FeNi(X)]n/Ti/Cu/Ti/[FeNi(X)Ti]n multilayers

6. Magnetic thin films, multilayers, surface and interfaces

Sergei Shcherbinin[1, 2] , *Andrey Svalov*[1], *Stanislav Volchkov*[1], *Galina Kurlyandskaya*[1, 3]

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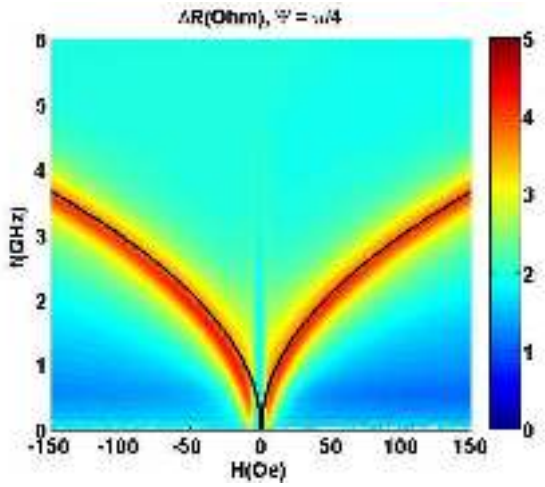
$[Ti(6\ nm)Fe_{19}Ni_{81}(X)]_n/Ti(6\ nm)/Cu(500\ nm)/Ti(6\ nm)/[F_{19}Ni_{81}(X)Ti(6\ nm)]_n$ (n = 1-5; X = 25, 50, 100 nm) multilayered structures were prepared by magnetron sputtering onto glass substrates through metallic masks to form 12 mm × 0.5 mm elongated elements. During deposition, external magnetic field of 250 Oe was applied in plane of the film along the short side of the element in order to create well defined uniaxial magnetic anisotropy. Giant magnetoimpedance (GMI) and ferromagnetic resonance (FMR) parameters were studied as a function of the number of magnetic layers n = 1-5 and the thickness of the FeNi layer X = 25, 50, 100 nm.

We designed and developed special sample holder (based on a coplanar transmission line) for precise measurements of the parameters of ferromagnetic resonance of multilayered elements in the frequency range of 1 to 40 GHz. Obtained results allowed us to construct a prototype of a detector of weak magnetic fields based on $[Ti(6\ nm)/FeNi\ (50\ nm)]_5/Ti(6\ nm)/Cu(500\ nm)/Ti(6\ nm)/[FeNi\ (50\ nm)/Ti(6\ nm)]_5$ sensitive element. The maximum achieved sensitivity with respect to applied field value was 10 μOe. In the frequency range 0.02-6 GHz, the dependences of the sensitive element impedance on the angle ψ between the main axis of the elongated element and the direction of an external constant magnetic field were found. Figure shows the increment of the real part of the impedance on the strength of an external constant magnetic field for a sample located at an angle ψ = 45° to the field direction as an example. A comparison of the experimentally obtained increments of the real and imaginary parts of the sensor impedance with the real and imaginary parts of the components of the main diagonal of the magnetic susceptibility tensor obtained by modeling in the COMSOL Multiphysics program was done. The frequency shift of the FMR maxima relative to the Kittel frequencies (ψ = 0) is calculated, the justification of the asymmetry and broadening of the FMR peaks when element was rotated with respect to the direction of an external constant magnetic field is discussed.

This work was supported by the RSF grant 18-19-00090.



O82 - Perpendicular Nanomagnetic Logic Based on Ultra-low Anisotropy Co\Ni Multilayers

6. Magnetic thin films, multilayers, surface and interfaces

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Perpendicular Nanomagnetic logic (pNML) is listed as a potential “Beyond-CMOS” candidate in the International Roadmap for Devices and Systems 2017 (IRDS). PNML thereby utilizes the anti-parallel dipole-dipole coupling of adjacent nano-magnets with perpendicular magnetic anisotropy to achieve complex logic operations [2]. In recent years we have demonstrated a comprehensive family of Boolean and non-Boolean logic elements on device-level and forecasted a potential power dissipation of low single digit Atto-Joules per NAND/NOR operation utilizing global on-chip clocking [1]. The vast majority of the total energy required is thereby dissipated by the field-coils, which need to drive the magnetization reversal. The minimally achievable clock field is, therefore, one of the defining figures of merit and should ideally fall well below 20 mT.

In this work, we present Co\Ni based multilayer stacks with ultra-low (near threshold) perpendicular magnetic anisotropy as a replacement for the established high anisotropy Pt\Co multilayers. The multilayers are sputter deposited onto silicon substrates, patterned by means of Focused-Ion-Beam lithography and analyzed via laser as well as wide-field MOKE and extraordinary-hall-effect measurements. To assess the switching fields H_s, several hundred single-domain, circular magnetic islands with radii between (0.25 and 1 µm) were characterized. Magnets with as-grown PMA were found to exhibit comparable coercivities with respect to Pt\Co (> 200 mT). Whereas coercivities one order of magnitude smaller are achievable via post-deposition annealing of IP stacks (turning the easy axis OOP) consisting of asymmetric alloy-like Co\Ni multilayers - either on a thin Pt seed e.g. $Pt_1\backslash Co_{0.25}[Ni_{0.7}\backslash Co_{0.15}]_{x5}$ (H_{s_mean} = 21.5 mT, σ_{fab} < 5 mT) or directly on Ta e.g. $Ta_{15}[Co_{0.2}\backslash Ni_{0.4}]_{x5}$ (H_{s_mean} = 4.3 mT, σ_{fab} < 2 mT)
It was assessed and furthermore confirmed, that artificial nucleation centers (ANC), created via local (50 nm × 50 nm) 50 kV Ga^+ ion-implantation in these layers, can be deployed as an effective method by which DW nucleation can be controlled, and the reciprocity in coupling be broken. The statistical data obtained from a sweep of the applied ion dosages from 10e12 to 10e15 ions/cm2, however, indicate a limited coercivity reduction factor of 1.2 - 2 instead of the 5 - 8 reported on in the past for Pt\ Co magnets [3]. Considering the remaining very low OOP anisotropy after annealing in combination with depinning fields in the single digit *mT* range (< 3 mT), this is expected behavior.
Logic blocks, as for example inverters and three-input majority gates, were realized with clock fields as low as 10 mT ($Pt_1\backslash Co_{0.25}[Ni_{0.7}\backslash Co_{0.15}]_{x5}$) thus even undercutting the 20 mT criterium. These results underline the potential of Co\Ni to enable on-chip field clocking of pNML circuits with competitive current densities. The continuous work now focuses on maximizing the dipole-dipole coupling by optimizing the comparably low magnetic moment of the Co\Ni stacks (compared to Pt\Co) - addressing both the stack composition as well as the number of repetitions.

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O83 - Range of interlayer exchange coupling in Fe/MgO[001] multilayers

6. Magnetic thin films, multilayers, surface and interfaces

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Fe/MgO/Fe tunnel junctions are well known for their large tunnel magnetoresistance, but their interlayer exchange coupling (IEC) [1] is less explored. Stacking several interlayer exchange coupled Fe/MgO/Fe tunnel junctions on top of each other can lead to new and interesting phenomena. For example, a sequential layer-by-layer magnetic switching in interlayer exchange coupled Fe/MgO[001] superlattices (the crystalline counterpart of a multilayer) has been observed [2]. The discrete magnetic switching sequence could be rationalized by an IEC exceeding nearest neighbor interactions. Here, we report the first systematic investigation on the range of IEC in Fe/MgO[001] multilayers. For that, three series of samples with various number of Fe/MgO bilayer repetitions (N) were grown on single crystalline MgO(001) substrates. Hystereses curves with discrete magnetization steps were obtained as illustrated in Figure 1, consistent with previous results [2]. The inferred IEC strength was obtained from the saturation field of the samples and is illustrated in Figure 2, for the first $[Fe(13Å)/MgO(21Å)]_N$ and second $[Fe(20Å)/MgO(17Å)]_N$ series. When the interaction is restricted to nearest neighbors, the normalized coupling strength would approach 2 with large number of repeats (N) since most Fe layers have 2 nearest neighbors, as discussed in ref. [3]. Our results are therefore consistent with a strong contribution from long-range interactions, which is seen in a normalized coupling strength well above 2 for all samples with N>2. The results are essential for the understanding of the IEC in tunnel junctions and could even serve as a base for the development of three-dimensional data structures.

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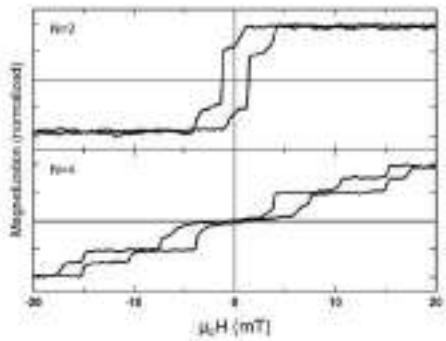

Figure 1 Representative room-temperature magnetization measurements along the easy axis of samples from the second series.

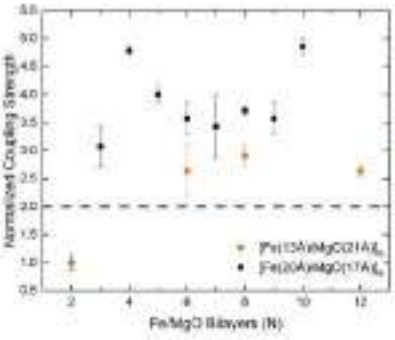

Figure 2 Normalized coupling strength as a function of the bilayer repetitions. The dashed blue line represents the coupling strength of samples with large N, with only nearest neighbor interactions.

O84 - Reversible tuning of physical properties via oxygen desorption/absorption in La0.7Sr0.3MnO3-δ films

6. Magnetic thin films, multilayers, surface and interfaces

Oleg Petracic[1] , *Lei Cao[1], Paul Zakalek[1], Alexander Weber[2], Ulrich Rücker[1], Jürgen Schubert[3], Alexandros Koutsioubas[2], Stefan Mattauch[2], Thomas Brückel[1]*

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An oxygen vacancy induced topotactic transition from perovskite to brownmillerite and vice versa in epitaxial $La_{0.7}Sr_{0.3}MnO_{3-\delta}$ thin films is identified by real-time x-ray diffraction. A novel intermediate phase with a non-centered crystal structure is observed for the first time during the topotactic phase conversion which indicates a distinctive transition route. Polarized neutron reflectometry confirms an oxygen deficient interfacial layer with drastically reduced nuclear scattering length density, further enabling a quantitative determination of the oxygen stoichiometry ($La_{0.7}Sr_{0.3}MnO_{2.65}$) for the intermediate state. Associated physical properties of distinct topotactic phases (i.e. ferromagnetic metal and anti-ferromagnetic insulator) can be switched reversibly by an oxygen desorption/absorption cycling process.

L. Cao, O. Petracic, P. Zakalek, A. Weber, U. Rücker, J. Schubert, A. Koutsioubas, S.Mattauch, and Th. Brückel, *Reversible Control of Physical Properties via an Oxygen-Vacancy-Driven Topotactic Transition in Epitaxial $La_{0.7}Sr_{0.3}MnO_{3-\delta}$ Thin Film*s, Adv. Mater. **2018**, 1806183 (2018)

O85 - Role of interface properties on magnetic exchange in MnGa/FeCo and MnBi/FeCo bilayer nanostructures

6. Magnetic thin films, multilayers, surface and interfaces

Sareh Sabet[1] , *Ashkan Moradabadi*[1, 2], *Saleh Gorji*[3, 4], *Min Yi*[1], *Qihua Gong*[1], *Mohammad H. Fawey*[3, 4], *Erwin Hildebrandt*[1], *Di Wang*[3, 5], *Hongbin Zhang*[1], *Bai-Xiang Xu*[1], *Christian Kübel*[3, 5], *Lambert Alff*[1]

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Synthesis of exchange coupled hard/soft magnetic materials is one promising way to design energy efficient rare-earth free magnetic materials for application as permanent magnets and in spintronics. In this study, we investigated the magnetic exchange coupling behaviour for two different experimental bilayer systems of MnBi/FeCo and MnGa/FeCo and modelled their physical behaviour in a combined density functional theory and micromagnetic approach. Exchange coupled bilayers with various soft magnetic layer (FeCo) thicknesses were deposited in a DC magnetron sputtering unit from alloy targets. Our TEM evaluations confirm growth of highly textured (001) MnBi layer and a polycrystalline FeCo film with coexisting amorphous and (110) regions. We note that the hard/soft interface in this case shows roughness. However, in case of MnGa/FeCo system, epitaxial growth of single crystalline (001) hard and soft layers with smooth interface is evident from TEM evaluations which is resulted from a rather low lattice misfit. Based on magnetic measurements, in MnBi/FeCo bilayer using a Co-rich FeCo layer results in better exchange properties with an optimum thickness of ~ 1 nm, however, a complete single-phase hysteresis cannot be obtained for higher FeCo thicknesses. On the other hand, more coherent hysteresis plots and higher critical thickness of ~ 2 nm is observed in the case of MnGa/FeCo system. Our combined experimental and theoretical nanostructure model, by the means of TEM analysis as well as DFT and micromagnetic simulations, shows that in addition to the thickness of soft magnetic layer the interface roughness, affected by layers growth properties, and FeCo composition close to the interface also directly control the degree of exchange coupling in such exchange spring systems. This study correlates the interface structure to the physics of exchange coupling and provides means to engineer high-performance exchange coupled 2D nanostructures for permanent magnets or spintronic devices.

O86 - Spin Hall Magnetoresistance in Antiferromagnetic Insulator/Pt Heterostructures

6. Magnetic thin films, multilayers, surface and interfaces

Matthias Opel[1] , *Johanna Fischer[1, 2], Olena Gomonay[3], Richard Schlitz[4, 5], Kathrin Ganzhorn[1, 2], Nynke Vlietstra[1, 2], Matthias Althammer[1, 2], Hans Huebl[1, 2, 6], Sebastian T.B. Goennenwein[4, 5], Rudolf Gross[1, 2, 6], Stephan Geprägs[1]*

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Antiferromagnetic materials promise improved performance for spintronic applications, as they are robust against external magnetic field perturbations and allow for faster magnetization dynamics as compared to ferromagnets. The direct observation of the antiferromagnetic state, however, is challenging due to the lack of magnetization. Here, we probe the antiferromagnetic insulator NiO by investigating the spin Hall magnetoresistance (SMR) effect in a heavy metal electrode of Pt in a NiO/Pt bilayer heterostructure. While we rotate an external magnetic field in the easy plane of NiO and record the longitudinal and the transverse resistivity of Pt, we observe an amplitude modulation consistent with the spin Hall magnetoresistance (see Figure). In comparison to Pt on collinear ferrimagnets [2], the modulation is phase shifted by 90° and its amplitude quadratically increases with the magnitude of the magnetic field [1]. We explain the observed magnetic field dependence of the SMR in a comprehensive model, taking into account magnetic field-induced modifications of the domain structure and magnetoelastic effects in the antiferromagnetic layer [1]. Our detailed study shows that the SMR is a versatile tool to gain understanding of the magnetic spin configuration and to investigate magnetoelastic effects in antiferromagnetic multi-domain materials. With our generic model, we are finally able to estimate the strength of the magnetoelastic coupling in NiO.

We gratefully acknowledge financial support by the Deutsche Forschungsgemeinschaft via SPP 1538 (Projects No. GO 944/4 and No. GR 1132/18). O.G. acknowledges support from the Alexander von Humbolt Foundation, the ERC Synergy Grant SC2 (No. 610115), the Transregional Collaborative Research Center (SFB/TRR) 173 SPIN+X, and EUFETOpen RIA Grant No. 766566.

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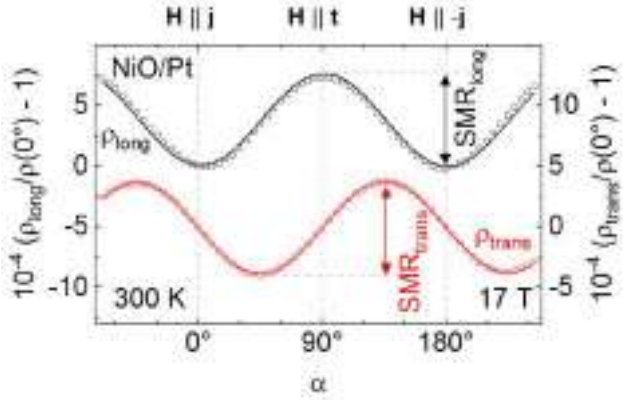

Fig.: Angle-dependent magnetoresistance of NiO/Pt at 300 K and 17 T.

O88 - Sustainable and magnetic nanoporous FePd with enhanced SERS sensibility

6. Magnetic thin films, multilayers, surface and interfaces

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Nanoporous metals are advanced materials constituted by ligaments and pores which size can range from tens of nanometers up to microns. This imply a wide variety of properties that can allow their use in different applications ranging from catalysis, biosensors and substrates for surface-enhanced Raman scattering (SERS). In this work, a continuous $Fe_{70}Pd_{30}$ layer (thickness ranging in the interval 50-200 nm) is deposited by rf-sputtering on a SiO_2 substrate. Pd-rich nanoporous thin films were produced by dealloying a polycrystalline solid solution of $Fe_{70}Pd_{30}$ (at.%) by free-corrosion at room temperature in a aqueous solution of 2 M hydrochloric acid. During this process, the Fe less noble atoms were partly dissolved in the electrolyte leaving a nanoporous film enriched in the Pd noblest atoms [1].
The evolution of the morphology, stoichiometry and crystal structure was investigated and related to the different dealloying times. The roughness of the films increases increasing the dealloying time. After 2 hours of dealloying, the sample developed a hierarchical structure of pores and ligaments and its final composition was determined to be $Fe_{52}Pd_{48}$ by EDS analysis.
The magnetic properties at room temperature were investigated for the in-plane and out-of-plane configuration. Removing the iron from the alloy results in a noticeable decrease of the magnetic moment of the sample and in the development of a paramagnetic component in the hysteresis loop. Moreover, the mechanism for the rotation of the magnetization and the value of the coercive field are affected by the nanostructuring process which takes places promoted by the dealloying process.
Meso- and nanoporous materials show a noticeable SERS effect [2], which is one of the most promising methods for the detection of small concentration of organic molecules and nanoparticles [3]. In order to investigate the presence of SERS effect in the aforementioned samples, we use as a probe molecule bipyridine in ethanol solution with different concentration. Indeed, a SERS enhancement was found, and the detection limit was estimated for a bipyridine concentration of 10^{-12} M.

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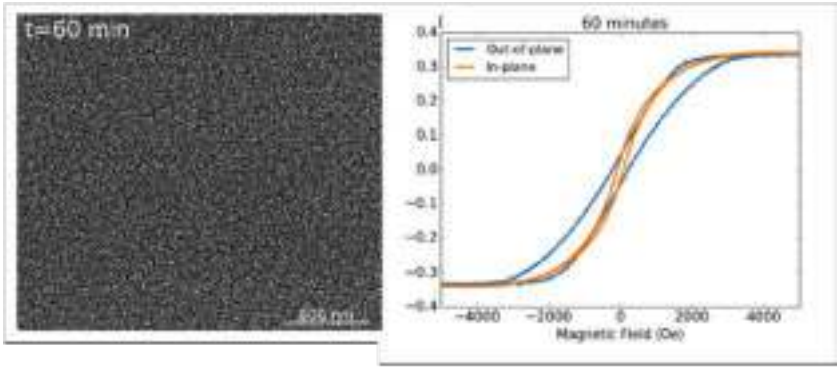

Left: SEM image of a FePd film submitted to dealloying for 60 minutes; right: room-temperature hysteresis loops in the in-plane and out-of-plane configuration for the same sample.

O89 - Temperature evolution of magnetic domain structure and anisotropy in ferro-/antiferromagnetic layers

6. Magnetic thin films, multilayers, surface and interfaces

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The asymmetric exchange interaction, like Dzyaloshinskii-Moriya interaction (DMI), is being widely investigated in thin layered structures with perpendicular magnetic anisotropy. It opens possibilities to create new low power consumption magnetic recording media with high data storage densities based on skyrmion stabilization and movement [1]. Many works were focused on transitions metals grown on a substrate with large spin-orbit coupling [2] where strong magnetic field was necessary (H≥1T) to stabilize the skyrmions. The most extensive studies were carried out for ultra-thin multilayered films with two or even more interfaces between heavy metals (HM) and transition metal ferromagnets (FM) [3] because multilayer stacks can stabilize skyrmions at room temperature (RT) without magnetic field [4]. Nowadays, one of the main challenges is stabilization of skyrmion structure at RT without magnetic field. So, a new path to control the topologically stable spin textures with DMI is needed. One of the possible solutions might be a replacement of HM capping layer with oxide (like MgO, Al_2O_3, or NiO) where enhanced DMI where observed [1, 5, 6].

The aim of the present work is to study the evolution of magnetic domain structure and magnetic anisotropy as a function of temperature/magnetic field in Au/Co/NiO layer where DMI was observed [6]. Presented results are supported by complementary techniques such as polar magneto-optical Kerr effect magnetometry and microscopy, magnetic force microscopy and X-ray magnetic circular dichroism with photoemission electron microscopy studies (XMCD-PEEM). In studied system the antiferromagnetic NiO layer increases perpendicular magnetic anisotropy of Co layer due to exchange bias coupling (the strength of this coupling might be tuned by temperature variation). It was observed that increasing temperature (approaching to Neel temperature of NiO layer) the magnetic anisotropy changed sign resulting in spin reorientation from easy axis to easy plane. This annealing effect enabled sample demagnetization with submicrometer size skyrmion/buble domain structure at RT. Evolution of domain structure was investigated as a function of temperature using XMCD-PEEM.

Supported by National Science Centre in Poland under the Sonata-Bis (DEC-2015/18/E/ST3/00557) and the Beethoven 2 (DEC-2016/23/G/ST3/04196) projects.

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O90 - Tuning magnetic chirality by dipolar and RKKY interactions

6. Magnetic thin films, multilayers, surface and interfaces

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Chiral domain walls and skyrmions are topologically protected magnetic entities which have gained enormous interest in recent years because of the variety of possible applications in nanoelectronics. The stabilization of chiral domain walls and skyrmions at room temperature is achieved in magnetic multilayers and is attributed to the interfacial Dzyaloshinskii-Moriya interaction (DMI). It is commonly assumed that the chirality of the domain walls is constant throughout the thickness of the multilayered structure. However, recent experimental and theoretical work has shown that due to the presence of dipolar interactions the chirality varies across the thickness of the multilayered structure. This influences directly the stabilization energy of chiral domain walls and skyrmions and affects how they are manipulated by electrical currents [1].

Here, we show that we can directly image the reversal of the domain wall chirality caused by a competition between the interfacial Dzyaloshinskii-Moriya interaction (DMI) and dipolar interactions [2]. We image the chirality of the domain walls using *in-situ* scanning electron microscopy with polarization analysis (SEMPA) and tune the strength of the interactions by systematically varying the thickness of the magnetic layers.

The analysis of the domain walls in a $[Pt/CoB(0.7nm)/Ir]_{x6}$ Pt/CoB(1.0nm) stack reveals the presence of counterclockwise Néel walls (see figure 1), as expected from the DMI in the investigated sample [3]. Increasing the thickness of the top CoB layer to 1.2 nm leads to a reversal of the domain wall chirality. This is due to a reduction of the DMI strength by increasing the CoB thickness, whereas the dipolar interactions are unaffected. At 1.2 nm, the dipolar interactions are therefore dominant and prefer the formation of clockwise Néel walls.

We verify our interpretation by an analytical model and micromagnetic simulations. Additionally, we suggest that the competition of the dipolar and DMI interactions can be further tailored by the hitherto neglected Ruderman-Kittel-Kasuya-Yosida interaction (RKKY). Knowledge of the strength of the RKKY interaction and the dipolar interactions is essential to extract an accurate DMI value for the investigated system. Our work therefore reveals that dipolar interactions play a key role in the stabilization of chiral spin textures.

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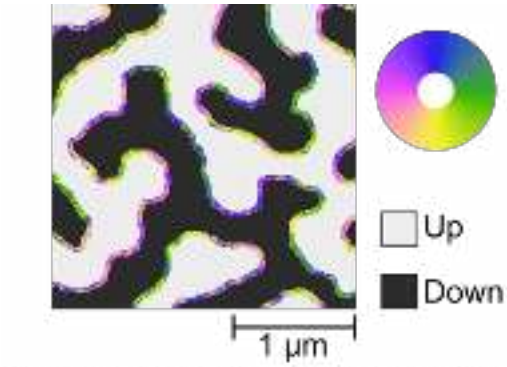

Figure 1: SEMPA image of the multidomain state of [Pt/CoB(0.7nm)/Ir]x6 Pt/CoB(1.0nm). The out-of-plane domains are indicated by the black and grey areas. The in-plane magnetization in the domain wall is indiated by the colorwheel. The magnetization in the domain wall systemetically points from down domain towards an up domain revealing the presence of counterclockwise Néel walls.

O91 - Tuning non-collinear magnetic states by hydrogenation

6. Magnetic thin films, multilayers, surface and interfaces

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The hydrogenation of the Fe atomic bilayer on Ir(111) has proven to be an efficient way to modify its magnetic properties and to allow for the stabilization of a skyrmionic phase in this system [1]. Going further in the study of the effect of the incorporation of atomic H on complex spin structures, we used spin-polarized scanning tunneling microscopy (SP-STM) to investigate the changes of the nanoskyrmion lattice of the Fe monolayer on Ir(111) upon hydrogenation.
The magnetic state of the pristine Fe monolayer on Ir(111) depends on the stacking of the Fe layer. The nanoskyrmion lattice is either hexagonal and commensurate with the atomic lattice in the hcp case [2] or square and incommensurate in the fcc case [3]. When the fcc layer is hydrogenated, two different superstructures can form. For a small amount of hydrogen, we obtain a p(2x2) superstructure in which the H atoms are localized in hollow sites of the Fe film. When we incorporate more H atoms, an irregular roughly square structure appears. Since the underlying Ir(111) substrate has a three-fold-symmetry, three structural rotational domains of this square superstructure are present in the film.
In both cases, our measurements reveal that the magnetic state is affected by the H superstructure [4]. In the low H concentration phase, the spin structure follows the hexagonal pattern imposed by the H atoms, resulting in a hexagonal nanoskyrmion lattice which can be described as the superposition of three cycloidal spin spirals. This nanoskyrmion lattice exhibits a net out-of-plane magnetic moment. Consequently, two opposite magnetic domains coexist and our experiments show that they can be switched using an out-of-plane magnetic field. Furthermore, a detailed comparison between the experimental data and simulations of the expected SP-STM signal allows the determination of the position of the H atoms with respect to the magnetic configuration.
In the roughly square phase, SP-STM measurements indicate the existence of three rotational magnetic domains corresponding to the structural domains. The magnetic unit cell seems commensurate with the rougly square H superstructure. Our results are compatible with a magnetic state obtained by the superposition of two cycloidal spin spirals.
This work thus demonstrates that the nanoskyrmion lattice in the Fe monolayer on Ir(111) can be tuned by hydrogenation. Whereas the strong non-collinearity and the nanoscale magnetic period of the magnetic state are preserved, its symmetry can be controlled by the incorporated amount of hydrogen, without the need to change the symmetry of the substrate.

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O92 - Visualizing the magnetism of the Nd (0001) surface

6. Magnetic thin films, multilayers, surface and interfaces

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Neodymium (Nd) has one of the most complicated magnetic behaviours among elemental metals, exhibiting several magnetic phase transitions below the Néel ordering temperature of 19.9 K [1]. Magnetic neutron and X-Ray diffraction experiments identify multi-***q*** structures [2], susceptible to temperature and applied magnetic fields. As these techniques lack spatial resolution, the details of the magnetic structure at the atomic scale remain a puzzle.

Spin-polarized scanning tunneling spectroscopy (SP-STM) has proven to be a powerful technique for deciphering the magnetic phenomena at the atomic scale. By using combined SP-STS with *ab initio* calculations, we *visualize* the non-collinear magnetic order present at the Nd (0001) surface. We quantify the magnetic field and temperature dependence of the spectral weight of the ***q***-states, from both measurements and atomistic spin dynamics [3]. We identify a glassy behaviour, which we can relate to the crystalline symmetry and the energy landscape of the material.

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O93 - XPS and XMCD-PEEM Studies of magnetic anisotropy induced in Ni layer deposited on LiNbO3 substrate

6. Magnetic thin films, multilayers, surface and interfaces

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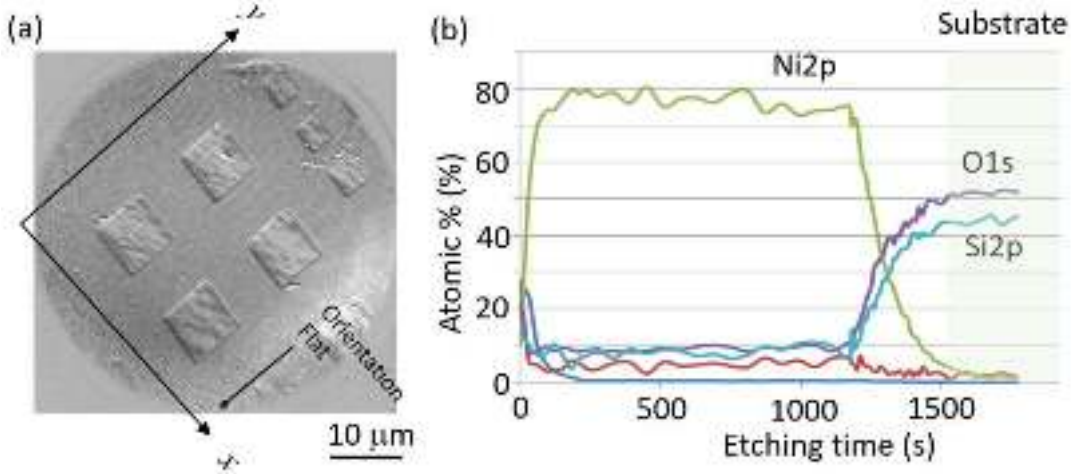
In single-phase multiferroics, the magnetoelectric coupling effect can be hardly observed at room temperature. In addition, it is very difficult to control and design the magnetoelectric coupling effect in the single-phase multiferroic materials. Recently, artificial multiferroic heterojunctions such as ferromagnetic/ferroelectric layers have attracted much attention because they have been extensively explored and exhibited a great potential in various fields. Introduction of the heterojunctions can provide the controllability and multifunctionality in the system comprising ferromagnetic/ferroelectric layers. Here, one of the artificial multiferroic heterojunctions, Ni/$LiNbO_3$, was focused because an uniaxial magnetic anisotropy is spontaneously induced and the magnetization is directed along the X-axis of $LiNbO_3$ substrate. As a result, the competition between magnetic shape anisotropy and uniaxial magnetic anisotropy enables the control of magnetic domain structure and magnetization reversal characteristics. For example, formation of a closed loop magnetic domain structure in the micron-scale soft magnetic magnets, in general, is expected because of the strong magnetic shape anisotropy. In Ni squares deposited on the $LiNbO_3$ single crystal substrate, on the other hand, X-ray circular dichroism photoelectron emission microscopy (XMCD-PEEM) observations revealed stripe magnetic domain structure was spontaneously formed (Fig. 1(a)).

In this study, to understand the physical mechanism which induces the uniaxial magnetic anisotropy through the heterojunction, X-ray photoelectron spectroscopy (XPS) and XMCD-PEEM were carried out at the laboratory and SPring-8 BL17SU, respectively. To investigate the origin of uniaxial magnetic anisotropy induced by the heterojunction between the patterned Ni layer and $LiNbO_3$ substrate fabricated by means of electron beam lithography and lift-off techniques using a magnetron sputtering, we measured the XMCD-PEEM images and XMCD spectra. In addition, we measured the depth profile of XPS spectra for some systems comprising 30-nm-thick Ni layer deposited onto $LiNbO_3$, Si, and SiO_2/Si substrates. Figure 1(b) presents a typical depth profile of XPS for the Au-cap/Ni/SiO_2/Si system. By comparing the data obtained from some systems, we found that the XPS peak of Ni shifted near the interface between Ni layer and $LiNbO_3$ substrate. By comparison of some XPS depth profiles and spectra, these XPS peak shifts are attributed to the modulation of electronic state distribution near the interface through magnetoelastic, magnetostriction, and interference effect. In addition, combining the XMCD-PEEM observation and XPS measurements, we found that the heterostructure can induce the uniaxial magnetic anisotropy in the Ni layer on the $LiNbO_3$ substrate and control the magnetic domain structure.

Thus, the material design by the introduction of heterojunction opens a door to develop and create novel artificial materials and to investigate the new magnetic properties.


(a)
Orientation Flat
10 µm
(b)
Substrate
Ni2p
O1s
Si2p
Atomic % (%)
80
60
40
20
0
0
500
1000
1500
Etching time (s)

7. Magnetism in alloys and intermetallics

O94 - Composition and thickness dependence of bulk out-of-plane anisotropy and AHE in CoFeB:Gd alloy films

7. Magnetism in alloys and intermetallics

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Considerable research has been conducted on rare earth-transition metals (RE –TM) alloys including the bulk perpendicular magnetic anisotropy (PMA) and most recently associated with spin-orbit torque investigations [1]. The PMA is hosted in the amorphous microstructure of this ferrimagnetic system and hence can be affected by details of the deposition technique [2] and is linked to bond orientation anisotropy [3]. Here, with the addition of B to the TM, we further engineered the amorphous base to develop the PMA and report the magnetisation behaviour and the anomalous Hall effect (AHE).

Here we studied thin film stacks of Ta (5nm)/RE-TM (t)/Ta (1nm) as a function of RE concentration and film thickness. Samples were prepared by co-sputtering of two targets on oxidized Si substrates. The RE element used was Gd, while the TM elements studied was $Co_{20}Fe_{60}B_{20,}$ which is commonly used in spintronic applications. Room temperature magnetisation was investigated with longitudinal and polar magneto-optical Kerr effect (MOKE) magnetometry. The AHE was measured with magnetotransport. Sample composition was confirmed with energy dispersive x-ray spectroscopy (EDX) and sample structure (thickness, density and roughness) was studied using x-ray reflectivity.

Figure 1 shows the development of the anisotropy in the CoFeBGd system with Gd concentration. Below 20.4 atomic% Gd, magnetization was in-plane and above this an out-of-plane component develops. Between 21.3% and 22.5%, the magnetization was only out-of-plane and between 22.5% to 24.1% Gd an in-plane contribution develops and above which samples have only in-plane anisotropy. Between 20.4 - 24.1 % Gd (shaded region in figure 1a) shows PMA with low switching fields (< 500 Oe) in both MOKE and Hall effect measurements. No magnetic response was observed at the compensation at about 21.9 % Gd, which is typical of ferrimagnets [4]. Thickness dependent measurements for 22.4 % Gd shows differences in switching fields between Hall and MOKE methods and a peak in the switching field between 20-30 nm, while the AHE resistivity increased rapidly with thickness up to 20 nm and continued to rise more slowly up to 100 nm.

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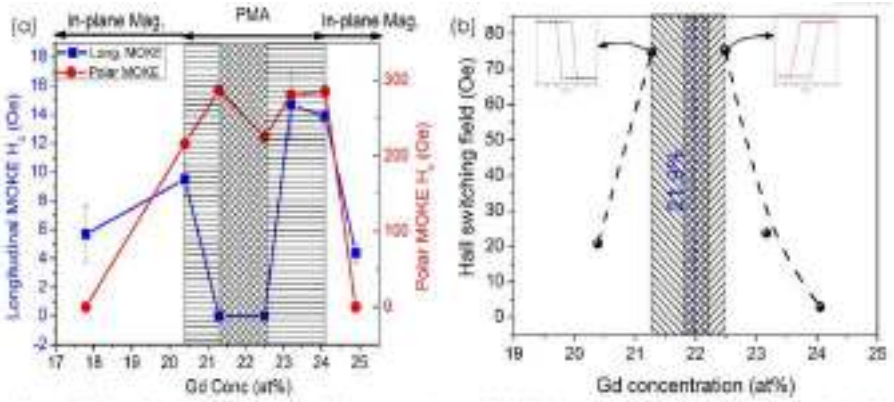

Figure 1: Plot of (a) coercivity against Gd concentration and (b) Hall measurement switching field against Gd concentration in GdCoFeB alloy showing behaviour associated with region around the compositional compensation point at 21.9% at RT

O95 - Discovery of new stable Fe-Nd-X structures with machine learning

7. Magnetism in alloys and intermetallics

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We develop a framework of applying Machine learning models targeted to fast screening new stable crystal structures for Fe-Nd-X compounds with (X=B, N, O, C). Start from 5976 existed structures from rare-earth transition binary compounds in Open Quantum database [1], we create candidates for the structure of Fe-Nd-X compounds by substituting transition metal sites with Fe, rare-earth sites with Nd. Two approaches are applied to the created structures to estimate their stability: (1) fast screening by Kernel ridge regression, logistic regression and decision tree models which are optimized on the existed stable structures data set and (2) density functional theory (DFT) calculation for final verification. The phase stabilities of these new structures are evaluated from the phase diagram obtained by existed structures. As a result, among 60 candidates that pass through the logistic regression filter, we found 32 new compounds which are validated the stability by DFT calculation. Comparing to the ground truth of 37 stable structures found by applying the DFT calculation exhaustively, the logistic regression filter obtained a recall score of 86.5%. The obtained results show a high potential of applying Machine learning methods in screening new stable structure by the substitution strategy.

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O96 - Electron transport in high-entropy alloys: AlxCrFeCoNi as a case study

7. Magnetism in alloys and intermetallics

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The high-entropy alloys $Al_xCrFeCoNi$ exist for concentrations of Al varying in a broad interval ($0 < x < 2$). Their structure is changed with increasing Al content from the fcc to bcc phase [1], [2]. Using the first-principles calculations (TB-LMTO-CPA) [3] we investigated the effect of varying Al concentration on their magnetic properties (mainly the magnetic moments on individul alloy components) and on transport properties including the residual resistivity, the spin-disorder resistivity, the anisotropic magnetoresistance, and the anomalous Hall resistivity [4]. We made a detailed comparison of theoretical results with available experimental data and have found a generally good agreement. In particular, the calculated residual resistivity of the bcc phase agrees perfectly with experiment for all studied alloy compositions. On the other hand, additional non-intrinsic electron scattering mechanisms are present in the fcc phase which deserve further examination.

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O97 - Electronic and magnetic properties of Y(Fe1-xCox)2 Laves phases: experimental and DFT study

7. Magnetism in alloys and intermetallics

Mirosław Werwiński[1] , *Bartosz Wasilewski[1], Natalia Pierunek[1], Zbigniew Śniadecki[1], Ján Rusz[2], Olle Eriksson[2]*

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Laves phase AB_2 compounds form the largest group of intermetallic phases. In this work we focus on the pseudo-binary Laves phase system $Y(Fe_{1-x}Co_x)_2$. These alloys have recently attracted much attention due to their extraordinary magnetic properties [1-4] and capability to absorb hydrogen. Furthermore, YCo_2 alloys with rare-earth elements $R_{1-x}Y_xCo_2$ (R = Er, Gd) are considered as magnetocaloric materials for application in magnetic refrigerators. Whereas $DyFe_2/YFe_2$ magnetic thin films have been investigated as reversible magnetic exchange springs.

We investigated theoretically and experimentally the concentration dependent magnetic phase transition in $Y(Fe_{1-x}Co_x)_2$ pseudobinary Laves phase system. The experimentally observed maximum in a dependence of electronic specific heat coefficient γ versus Co concentration x was explained within the local density approximation (LDA). A critical Co concentration at which a ferromagnetic-non-magnetic phase transition occurs does not coincide the maximum in γ. Previous experimental studies have shown that a similar situation takes place also for $Zr(Fe_{1-x}Co_x)_2$.

The main result are the calculated and measured dependencies of γ(x) showing a maximum on the Co-rich side of $Y(Fe_{1-x}Co_x)_2$ phase. The calculated with LDA-VCA maximum in γ occurs at $x_{max} \sim 0.91$, while the ferromagnetic–non-magnetic phase transition takes place at critical Co concentration $x_{crit} \sim 0.925$. The rather unexpected observation that $x_{max} \neq x_{crit}$ was explained based on the evolution of the electronic band structure with x. We investigated also how the Fermi surface, density of states, and magnetic-non-magnetic energy difference vary with x around the x_{crit}. For the first time we also showed the DOS at the Fermi level as function of the fixed spin moment. Furthermore, using the CPA and ordered compound methods we calculated the basic magnetic properties of $Y(Fe_{1-x}Co_x)_2$ in the whole range of concentrations.

We conclude that the picture of the ground state electronic structure within the LDA is sufficient to model the magnetic transition and to explain the origins of the maximum in γ(x). The experimental examination of γ versus x on the Co-rich side of the $Y(Fe_{1-x}Co_x)_2$ phase revealed a shift of $x_{max-exp}$ in comparison to the theoretical x_{max}. We suggest it is due to presence of structural disorder in our samples, inducing the long range magnetic ordering for $x > x_{crit}$ but also theoretical result suffers from limitations of LDA and VCA.

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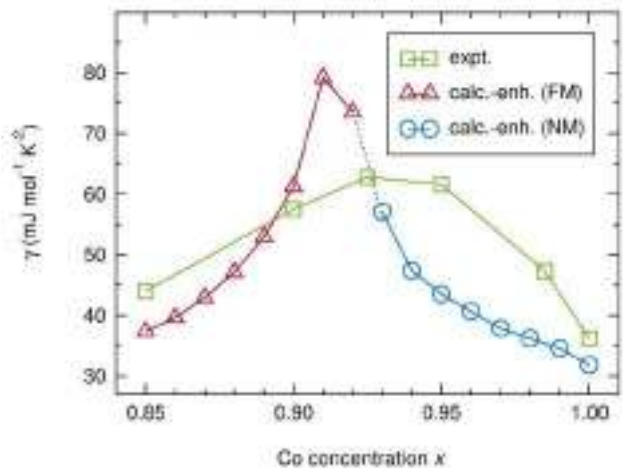

O98 - Experimental investigation of intermetallics with coexisting 3d magnetism and intermediate valent Yb

7. Magnetism in alloys and intermetallics

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Rare-earth based Kondo systems generally involve Yb or Ce alloyed with non-magnetic elements. These alloys may present interesting physical properties such as intermediate valency, heavy fermion behavior, non-conventional superconductivity, quantum criticality [1]. In recent years, we have evidenced the very unusual physical properties of Yb in $YbMnGe_{6-x}Sn_x$, including high temperature magnetic ordering of intermediate valence Yb (upon to 125 K), unusual thermal dependence of the Yb valence for intermediate Sn contents, and Yb magnetic instability occurring at quite low Yb valence ($u_{Yb} \approx 2.75$) [2,3]. Most of these scare behaviors have been ascribed to the strong exchange field produced by the *T* = Mn sublattice at the Yb site. For a better understanding of the role of the *T* exchange field, we are investigating the new $YbMn_{6-y}Fe_yGe_{6-x}Sn_x$ alloys. The Fe doping favors antiferromagnetic ordering of the 3*d* (= Mn/Fe) sublattice and is thus expected to progressively reduce the exchange field at the Yb site. As a first step of this study, we will present results obtained on the $YbMn_{6-y}Fe_ySn_6$ series, using AC / DC magnetization experiments, neutron diffraction as well as pressure dependent X-ray absorption and XMCD experiments at the Yb L_{III} edge. In particular, we will show that for some compositions, pressure may induce two Yb magnetic instabilities likely associated with quantum critical effects.

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O99 - Giant energy product in FePt L10 nano material

7. Magnetism in alloys and intermetallics

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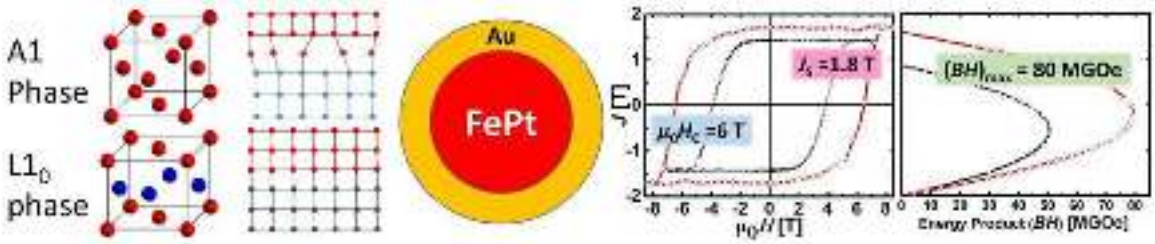
The nano-island hard magnetic $L1_0$-Phase FePt thin films were prepared on MgO(100) and LSAT (100) substrate by magneto co-sputtering at 800°C. The chemical ordering is improved by heat-treatment and reduction of tensile strain between film and substrate as proved by x-ray diffraction, and high-resolution electron microscopy. The influence of high chemical ordering on the magnetic properties were studied by superconducting quantum interference device (SQUID). With higher crystalline structure, the coercivity of $L1_0$-FePt increases up to 6 T. The magnetic saturation polarization exceeds 1.8 T supported by a 3 nm Au layer resulting in an extremely high maximum energy product of 80 MGOe at room temperature, which exceeds the record for NdFeB by 30 %. In addition, we verified this exceptional magnetic performance by x-ray absorption spectroscopy/x-ray magnetic circular dichroism (XAS/ XMCD) studies showing a strong increase of the Fe magnetic spin and orbital moments in the FePt $L1_0$-phase by spin polarized electron transfer. Our result on the high performance nano-sized hard magnetic components will also open up a new paradigm of room temperature spintronic devices, information technology, micro-robotics and medicine based.



O100 - High-field soft x-ray spectroscopies of the highly anisotropic ferrimagnet TmFe5Al7

7. Magnetism in alloys and intermetallics

Sh. Yamamoto[1] , *D.I. Gorbunov[1], H. Akai[2], H. Yasumura[3], Y. Kotani[4], T. Nakamura[4], A.V. Andreev[5], H. Nojiri[3], J Wosnitza[1, 6]*

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Ferrimagnetic intermetallic compounds based on rare-earth and transition metals are not only attractive for potential application as permanent magnets but also from the fundamental viewpoint due to the complex interplay between itinerant 3*d* and localized 4*f* electrons. In particular, RFe_5Al_7 with heavy rare-earth elements shows interesting magnetic properties characterized by competitive exchange and anisotropy interactions. Field-induced first-order phase transitions have been observed in macroscopic measurements of $TmFe_5Al_7$ in high magnetic fields [1]. This is expected to reflect simultaneous stepwise rotations of two nonequivalent sublattice magnetizations as is indirectly observed in $HoFe_5Al_7$ [2]. However, it has been challenging to directly access the magnetic orbitals in such high fields. Here, we present the direct observation of the evolution of each sublattice magnetization along with the external fields for $TmFe_5Al_7$, which gives a microscopic picture of the field-induced phase transition. We performed soft x-ray magnetic circular dichroism (MCD) measurements in pulsed magnetic fields at the Fe $L_{2,3}$ and Tm $M_{4,5}$ edges. We observed the pronounced variations of the MCD spectra near the critical field. Furthermore, magneto-optical sum rules were applied for extracting the spin and orbital contributions. We succeeded in fully revealing the magnetic structure along the field direction from a collinear ferrimagneic state into the forced-ferromagnetic state through a canted structure. Additionally, our microscopic data made it possible to simulate the magnetization process and extract the anisotropy constants of $TmFe_5Al_7$.

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O101 - Investigation of rare-earth lean hard magnetic Sm-Fe-V films

7. Magnetism in alloys and intermetallics

Andreas Kaidatzis[1] , *Christos Serletis*[2], *Margaritis Gjoka*[1], *Vassilios Psycharis*[1], *Konstantinos Efthimiadis*[2], *Dimitrios Niarchos*[1]

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Rare earths (R), a crucial component of high-performance permanent magnets, have been marked as “critical raw materials” by the European Commission and the U.S. Department of Energy. Currently, there is an intense research effort to develop R-free/lean magnets as alternatives to Nd-Fe-B (2:14:1 phase) and Sm-Fe(Co) (1:5 phase) magnets. Promising candidates are the R-Fe 1:12 compounds, having the tetragonal $ThMn_{12}$-type structure, as this is the most R-lean structure known to form in the (R, Fe)-based compound family. Although R-Fe_{12} alloys are not thermodynamically stable, R-based compounds have been synthesized in bulk and thin film form, utilizing a third element (usually a light transition metal, e.g. Ti, V, or Al) to stabilize the $ThFe_{12}$-type structure [1, 2, 3, 4]. In most of the studies, Nd or Sm is usually used as R. However, Nd requires nitrogenation for obtaining uniaxial anisotropy and this additional process step increases the possibility of the $ThMn_{12}$ phase to decompose. Thus, in this work we will present the study of magnetron sputtered $SmFe_{11}V$ films, deposited on pre-heated amorphous SiO_2/Si, monocrystalline MgO(001), or polycrystalline Ta-foil substrates. X-ray diffraction, scanning electron microscopy, and vibrating sample magnetometry are employed for obtaining the film crystal structure, surface morphology and magnetostatic properties. The process parameters (deposition temperature, process gas pressure, thickness) are optimized for obtaining the tetragonal $ThMn_{12}$-type crystal structure and minimizing the parasitic α-Fe phase. For optimum deposition conditions onto amorphous SiO_2/Si substrates, a magnetic coercivity in excess of 7 kOe (see figure) is obtained and the films are shown to have primarily the $ThMn_{12}$ crystal structure with crystallites textured along the (001) direction. Finally, the effect of V addition is studied and the minimum percentage for obtaining uniaxial anisotropy is determined. A detailed structural, microstructural, and magnetic characterization study of the system will be presented.

ACKNOWLEDGEMENTS

Funding from the E.C. is acknowledged (Grant No. 318144 and 280670)

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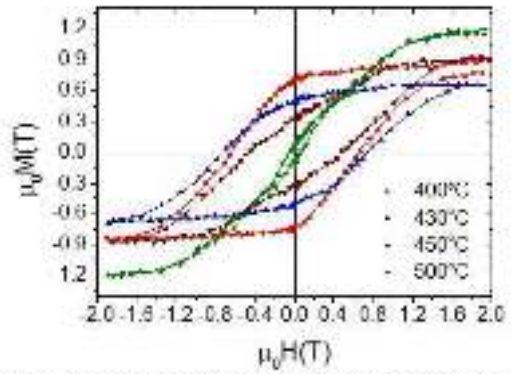

Figure Perpendicular-to-the-plane hysteresis loops of 2 um thick Sm-Fe-V films deposited at various temperatures onto amorphous SiO_2/Si substrates

O102 - Magnetism and structure of amorphous grain boundaries of permanent magnets: First principles study

7. Magnetism in alloys and intermetallics

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The details of structural and magnetic properties of grain boundary (GB) phases has become one of the important issues in the field of application of permanent magnets. In particular, we targeted the amorphous structure appearing at the grain boundary phases appearing in the experiment [1].
In order to clarify the structural and magnetic properties of the amorphous grain boundary phases, we performed first principles calculation of Nd-Fe amorphous alloys having different Nd composition ratios using OpenMX [2].
From the structural analysis of amorphous Nd-Fe alloy, it was shown that the Gabriel graphs represent the first nearest neighbor networks well in the examined amorphous systems [3]. We also calculated the exchange coupling constants between two atoms in the Nd-Fe amorphous using Liechtenstein method [4]. We obtained strong distance dependences and fluctuations of exchange coupling constants and Curie temperature which reaches maximum at around the Nd composition ratio of 50 %. These features indicate the complexity of the nature of amorphous magnetism. In the presentation, we will also discuss the relationship between the exchange coupling constants and coordination structures.

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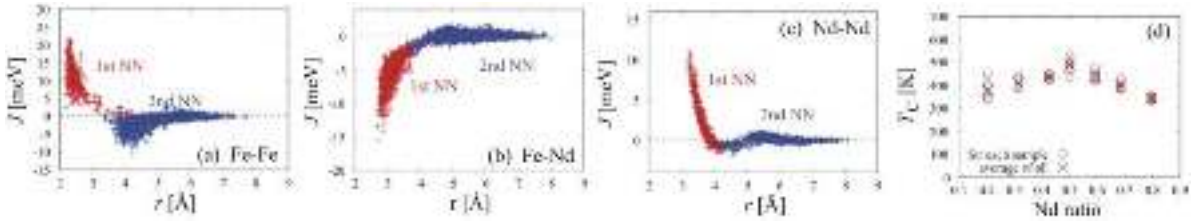

O103 - Magnetism in high-purity bulk (Cr1-xMnx)2AlC MAX-phase upon manganese incorporation.

7. Magnetism in alloys and intermetallics

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MAX-phases are the relatively new class of compounds with the common $M_{n+1}AX_n$ chemistry where M is an early transition metal, A is an A-group element and X is either C or N. Due to the natural nano-lamellar crystal structure MAX-phases combine metallic and ceramic properties such as high values of electronic and thermal conductivity, easy machinability, good tolerance to oxidation, mechanical damages and thermal shock. The major part of MAX-phases are paramagnets although some representatives such as $(Cr_{1-x}Mn_x)_2AlC$ were anticipated to possess the long-range magnetic ordering. Magnetism of MAX-phases is strongly correlated to the phase purity of the samples which is especially crucial for the bulk ones as the bulk synthesis techniques are frequently deficient to obtain the necessary quality. Besides, it’s problematic to successfully include dopant element, for example manganese, to the MAX-phase structure as the solubility limit is low for the major part of synthesis techniques.

Herein we observe how the initial method of the bulk MAX-phase synthesis, the arc melting technique, can be optimized for the sake of producing almost phase-pure samples of $(Cr_{1-x}Mn_x)_2AlC$ MAX-phase. The optimization procedure was conducted in three steps. On the first step, Cr_2AlC MAX-phase samples with different initial components stoichiometry (2Cr:xAl:C, where x = 1 - 1.5) were produced in order to get the pure MAX phase. On the second step, other parameters of the synthesis process such as the pressure in the melting chamber and annealing time were taken into account and precisely investigated. On the third step, manganese was added to the initial powders mixture as the dopant element in order to explore its solubility limit and to prove the sufficiency of its incorporation to the MAX-phase structure. All the samples were investigated by means on the XRD and SEM-EDX analysis to both quantitatively and qualitatively observe their phase composition.

The final series of $(Cr_{1-x}Mn_x)_2AlC$ MAX-phase samples with x = 0, 0.025, 0.05 and 0.1 was produced by means of the fully optimized arc melting technique. Their structural properties and phase purity was also confirmed using XRD and SEM-EDX techniques. Their magnetism was explored by SQUID magnetometry. Magnetization (M) vs the applied field (H) curves taken at the room temperature and at 2 K both with the M vs temperature (T) dependency in the range from 2 K to 350 K revealed the canted antiferromagnetic (AFM) state in the whole range of the studied temperatures. Manganese was successfully included to the MAX-phase structure and enhanced the net magnetic moment although not changing the resulting type of magnetic ordering. This result opens the way to further tune the magnetic properties of $(Cr_{1-x}Mn_x)_2AlC$ MAX-phase and to possibly trigger the theoretically predicted AFM-FM transition which makes this compound promising for the variety of practical applications.

O105 - Towards realization of the iron-rich SmFe3Co-(Ni,Cu) phase employing the high entropy alloy concept

7. Magnetism in alloys and intermetallics

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Although RCo_5 (R=Rare-Earth) alloys with the $CaCu_5$-type structure are stable and can be processed to make magnets with energy products in the range of 20-25 MGOe, their Fe counterparts with the same structure in bulk form are thermodynamically unstable [1]. Indications of stabilization in thin films were reported by [2,3]. In such structures the R occupy the 1a site while the transition metal ions occupy two crystallographically different sites, 2c and 3g, in the space group P6/mmm. Ab-initio calculations have been performed by a number of groups [4] on the hypothetical 1:5 structure and have derived the crystallographic and magnetic properties of these alloys, which if they can fabricated will have interesting properties for permanent magnet applications. Previous efforts to substitute Co with Fe slightly improved the magnetization but the substitution is limited to less than 10 % [5]. In this work we will present data based on the high entropy alloy concept of the transition metals Fe_3Co-(Ni,Cu) [6]. In Fig.1 we are describing our approach for obtaining the $SmFe_3Co$-(Ni,Cu) by considering the heat of formation and the valence concentration of stable compound like $SmNi_5$, $SmCo_5$ and $SmCu_5$, which together with the structural factor lead to the series $SmFe_3\{Co_{1-x}(Ni,Cu)_x\}$. Long time annealing is needed to allow the diffusion of Co,Ni and Cu elements to occupy the remaning 2c sites. Crystallographic and magnetization data will be presented.

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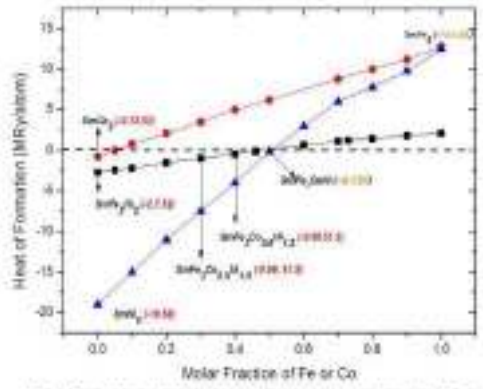

Fig. 1. Revised graph of the heat of formation vs molar fraction of Fe or Co. Next to the Alloy formulas in parentheses the energy of formation and the valence electrons are given. Characteristic of the stable compounds are the negative energy of formation and the large valence concentration.

O106 - Tuning of austenite-martensite fraction on transport and magnetic properties in NiMnSn Heusler alloy

7. Magnetism in alloys and intermetallics

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The structural, magnetic and electronic transport properties in the disordered $Ni_{45.5}Mn_{43.5}Sn_{11}$ magnetic shape memory Heusler alloy system have been studied in details by X-ray diffraction, magnetization and resistivity measurements. The high temperature austenite phase has cubic $L2_1$ structure with lattice constant 6.050 Å. First order martensite phase transition has been clearly observed at around 270 K from magnetization and resistivity measurements [Fig 2]. Magnetization and electronic transport measurements under high magnetic field have been performed in order to investigate field-induced effect on martensite transformation [Fig. 5]. From the thermo-magnetization curves it is seen that martensite transition temperature shifts by 2.4 K towards lower temperature with the application of only 1 T magnetic field. Temperature dependence of austenite phase fraction in the vicinity of the martensite transition is estimated from the isothermal magnetization versus magnetic field curves. Field-induced transformation of martensite state into austenite phase and arrest of austenite phase in the martensite phase observed from both magnetization and electronic transport behaviors in the vicinity of martensite transition are possibly related to the dynamics of the coexisting phase fractions. The tuning of the coexisting austenite and martensite phase with external parameters like magnetic field and temperature is found to be very important for comprehensive understanding of physical properties of a multicomponent system.

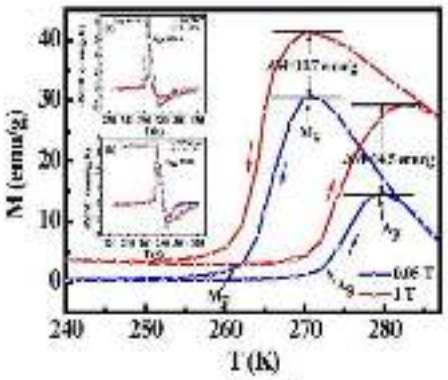

Figure 2

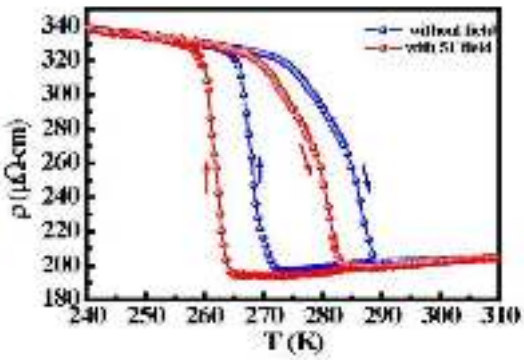

Figure 5

O107 - Tuning the magnetic anisotropy of high-coercive MnBi thin films

7. Magnetism in alloys and intermetallics

Melek Villanueva[1] , *Elena Hernández[2], Peter Stephen Normile[2], Jose Ángel De Toro[2], Julio Camarero[1, 3], Cristina Navío[1], Alberto Bollero[1]*

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Mn-based alloys have been proposed as viable candidates [1, 2] for several applications comprising energy, transport and electronic systems. In particular, the low temperature phase MnBi (LTP-MnBi) is a ferromagnetic intermetallic compound that is attracting increased attention due to its outstanding properties, such as a large magnetic anisotropy (1.6 MJ/m^3), a theoretical $(BH)_{max}$ of 20 MGOe and a high Curie temperature of 711 K. On top of those properties, MnBi stands out for its unusual positive temperature coefficient, resulting in an increased coercivity of the LTP-MnBi when increasing the operational temperature (interesting for high temperature applications). Despite these exceptional perspectives, experimental results are still distant from theoretical estimations in many aspects, e.g., an optimized combination of magnetization and coercivity [3-5]. The study of MnBi thin film systems may provide insight on the mechanisms behind magnetization and coercivity development. Moreover, the possible control of the magnetic anisotropy in thin film systems is of interest for applications in diverse spintronic devices.

In this study, we investigate the correlation between morphological, microstructural and magnetic properties. We demonstrate the control of the orientation of the magnetic anisotropy (perpendicular or parallel to the film plane) in MnBi thin films. The study has been done systematically by changing the deposition temperature (T_D) from room temperature to 473 K (every 50 K) in the preparation of MnBi thin films (60 nm thick) grown by magnetron sputtering onto glass substrates followed by in-situ annealing.

X-ray diffraction (XRD) indicates well-oriented LTP-MnBi with its hexagonal c-axis perpendicular to the film plane (thus with out-of-plane magnetocrystalline anisotropy) for T_D below 473 K. For T_D=473 K the LTP-MnBi films grow with the c-axis parallel to the film plane (thus providing in-plane anisotropy). Accordingly, the choice of T_D affects the magnetic response, as exemplified by the room temperature hysteresis loops shown in Fig. 1a for two films grown at 323 and 473 K, displaying coercivity values of 4.3 kOe (out-of-plane) and 16.0 kOe (in-plane), respectively. Among the films exhibiting a well-defined out-of-plane magnetic anisotropy, the maximum RT coercivity (9 kOe) was obtained for the film grown at T_D=373 K. As a consequence of the positive temperature coefficient of the LTP-MnBi the coercivity increases up to 19.3 kOe measured at 400 K for the film grown at 473 K (see Fig. 1c).

It is worth mentioning that the deposition temperature dramatically influences the microstructure of the films. EDX-SEM analysis showed hexagonal-like isolated LTP-MnBi plates going from islands 2-5 mm in size (T_D=298 K) to features consisting of coalesced plates with a size of about 40-80 mm (T_D=423 K) as those shown in Fig. 1b.

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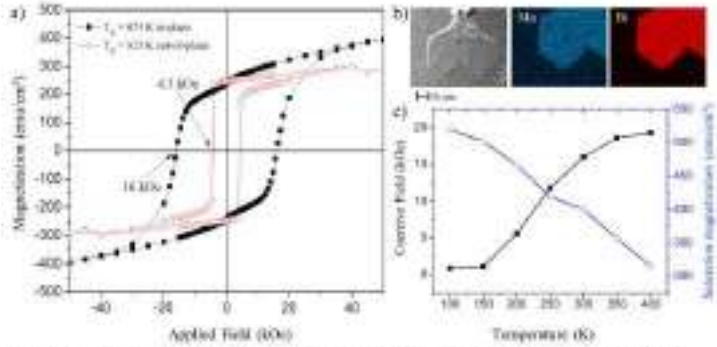

Fig. 1. a) M-H curves of LTP-MnBi grown at 323 K (open red circles) and 473 K (black squares). b) EDX-SEM mapping of a MnBi plate from sample grown at 423 K. Scale bar: 10 μm. c) Evolution of coercivity and magnetization with temperature for the film grown at 473 K.

O108 - Weak itinerant magnetic properties of (La,Y)2Ni7 compounds driven by their stacked structures

7. Magnetism in alloys and intermetallics

Valérie Paul-Boncour[1] , *Jean-Claude Crivello[1], Nicolas Madern[1], Junxian Zhang[1], Léopold Diop[2], Véronique Charbonnier[1], Judith Monnier[1], Michel Latroche[1]*

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A_2Ni_7 compounds (A = Rare Earth) have raised interests for their fundamental magnetic properties [1-8]. They crystallize into two polymorphic crystal structures which are either hexagonal (Ce_2Ni_7-type, $P6_3/mmc$) or rhombohedral (Gd_2Co_7-type, $R\text{-}3m$) depending on the number of stacking sequences made of one AB_2 and two AB_5 subunits (B = Ni) [1]. Along the c axis, there are two stacking sequences for the hexagonal and three for the rhombohedral structure (Fig. 1). Particular interest has been raised on the itinerant magnetic behavior of La_2Ni_7 [3-5] and Y_2Ni_7 [6-8] which both contain non-magnetic A elements. Hexagonal $2H$-La_2Ni_7 is a weak itinerant antiferromagnet (wAFM) with T_N=50 K and rhombohedral $3R$-Y_2Ni_7 is a weak itinerant ferromagnet (wFM) with T_C=55 K. To understand the origin of these different magnetic structures, we have performed DFT calculations for these binary alloys. Their magnetic instability is related to the presence of a sharp peak of state density near the Fermi level. A stable AFM structure has been found for hexagonal La_2Ni_7, whereas Y_2Ni_7 is more stable in FM configuration whatever the polymorph structure is. These calculations show how the magnetic order is driven by the geometric stacking of AB_2 and AB_5 subunits.

Then, in order to follow the progressive change from wAFM 2 H-La_2Ni_7 towards wFM $3R$-Y_2Ni_7, the crystal structure and magnetic properties of the pseudo-binary system $La_{2-x}Y_xNi_7$ have been investigated. The compounds with $0 \leq x \leq 1$, adopt the hexagonal structure with a progressive Y for La substitution in the AB_2 sites, whereas for $1.2 \leq x < 2$ they crystallize in both hexagonal and rhombohedral structures with Y filling the AB_2 sites and replacing progressively La in the AB_5 sites. The average cell volume decreases linearly versus Y content, whereas the c/a ratio presents a minimum at $x = 1$ due to geometric constrains. The magnetic properties display two different behaviors for $0 \leq x \leq 1$ and $x > 1$. For $x \leq 1$, the magnetic ground state varies from wAFM to very wFM as the Y content increases and several metamagnetic transitions are observed. All the compounds with $x > 1$ are wFM with $T_C = 55$ K. This relation between the structure type and the magnetic order can be explained thanks to the DFT calculations, showing the specific behavior of the Ni atoms located in the AB_2 unit. It confirms that the difference between the magnetic properties of 2 H and $3R$ structures originates in the number of stacking sequences of AB_2 and AB_5 subunits.

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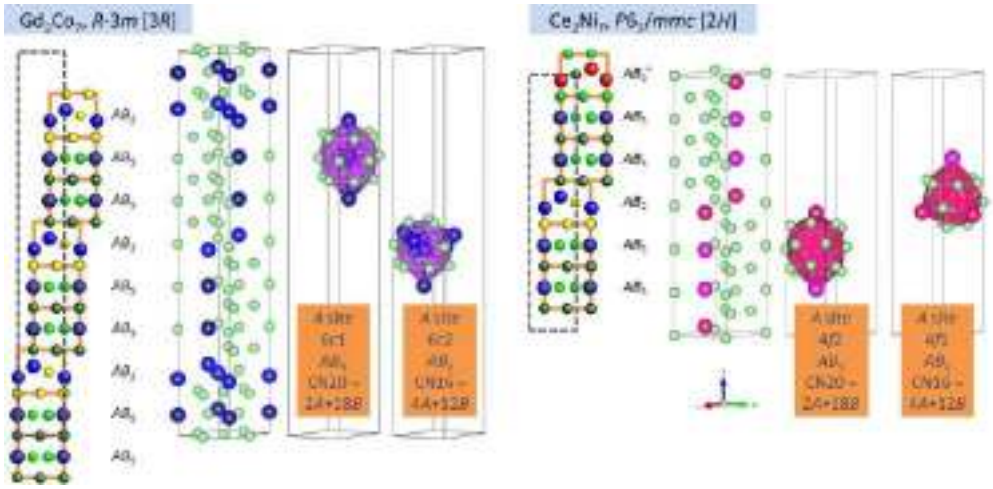
Gd2Co7, R-3m [3R]
Ce2Ni7, P63/mmc [2H]

8. Novel magnetic techniques

O109 - A liquid jet setup for hard x-ray RIXS-XMCD: application to iron oxide nanoparticles in dispersion

8. Novel magnetic techniques

S. Lafuerza[1] , *J. Muro*[2, 3], *A. G. Roca*[2], *J. Piella*[2], *M. Busquets-Fité*[2], *E. Casals*[2], *H. Elnaggar*[4], *M. Rovezzi*[1, 5], *P. van der Linden*[1], *Y. Watier*[1], *J. Nogués*[2, 6], *V. Puntes*[2, 6, 7], *P. Glatzel*[1]

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The combination of resonant inelastic x-ray scattering (RIXS) with x-ray magnetic circular dichroism (XMCD) in the hard x-ray energy regime results in a powerful tool to extract element- and site-selective magnetic information. A key advantage of this technique compared to the most widely applied soft x-ray XMCD is bulk sensitivity (the probing depth here is on the order of a few μm versus a few nm for soft x-rays). After the pioneering experiment in bulk magnetite Fe_3O_4 [1], RIXS-XMCD has been further exploited by probing the whole volume in various magnetically interesting nanosized systems, from buried Fe_3O_4 thin films of a few tens of nm [2] to bi-magnetic core-shell nanoparticles [3,4].
Motivated by the recently demonstrated potential of this advanced magneto-spectroscopy to characterize nanosystems, we have developed a liquid jet setup for RIXS-XMCD experiments on magnetic nanoparticles (NPs) in dispersion. In particular, we show the applicability of our setup on Fe_3O_4 NPs which are intensively investigated as they lead to many biomedical and environmental applications. So far, most of the x-ray spectroscopic studies on Fe_3O_4 NPs were performed on dried powder samples which is not ideal as the properties may differ from those of NPs dispersed in liquid emulating the media for applications.
Fe 1*s*2*p* RIXS-XMCD experiments were performed at beamline ID26 of the ESRF synchrotron (Grenoble, France) on a large number of nominal Fe_3O_4 NPs in liquid phase, covering different synthesis methods, sizes and shapes. A first screening of the samples was performed by Fe K edge high-energy resolution x-ray absorption near edge structure (XANES), measuring the samples as frozen solutions in a continuous He flow cryostat. These measurements revealed the need to limit the total illumination time per point in the small NPs (< 15 nm) due to radiation damage. In contrast, in our liquid jet setup the sample is continuously circulated (Fig. 1) and the x-rays always shine on a fresh spot enabling the more time consuming RIXS-XMCD measurements. The sample magnetic saturation is provided by a compact electromagnet developed at the ESRF sample environment, which allows a field up to ±0.5 Tesla. The collected data in nominal Fe_3O_4 NPs in dispersion suggest an average electronic and magnetic structure corresponding to an iron oxide phase that is more oxidized than stoichiometric bulk magnetite but different from γ-Fe_2O_3, the Fe^{2+}-deficient Fe_3O_4 (Fig. 1). This is in agreement with a XANES study on powder NPs [5].

Our results on RIXS-XMCD experiments in a liquid jet setup, the first to our knowledge, show the feasibility of the method and open up the door for bulk-sensitive magneto-spectroscopic characterization of ferrofluids without the need to freeze the sample and avoiding possible radiation damage.

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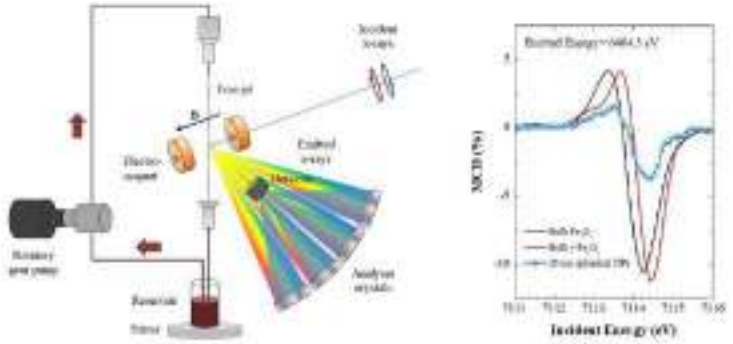

Figure 1. Left: Scheme of the continuous flow liquid jet setup for RIXS-MCD measurements at beamline ID26 of the ESRF. Right: Diagonal RIXS-MCD cuts taken at constant emitted energy corresponding to the maximum of the Fe $K\alpha_1$ line for bulk Fe_3O_4 and γ-Fe_2O_3 and one sample of nominal Fe_3O_4 20 nm spherical nanoparticles dispersed in dibenzyl ether measured in the liquid jet setup.

O110 - All-optical magnetic imaging with a single nitrogen vacancy defect in idamond

8. Novel magnetic techniques

Florentin Fabre[1] , *Angela Haykal[1], Aurore Finco[1], Saddem Chouaieb[1], Waseem Akhtar[1], Kumari Gaurav Rana[2], Olivier Boulle[2], Liliana Prejbeanu[2], Anike Purbawati[3], Nicolas Rougemaille[3], Johann Coraux[3], Vincent Bouchiat[3], Jan Vogel[3], André Sulpice[3], Manuel Nuñez-Regueiro[3], Vincent Jacques[1]*

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Experimental methods allowing for the detection of single spins in the solid-state, which were initially developed for quantum information science, open new avenues for the design of highly sensitive quantum sensors. In that context, the electronic spin of a single nitrogen-vacancy (NV) defect in diamond can be used as an atomic-sized magnetometer, providing an unprecedented combination of spatial resolution and magnetic sensitivity under ambient conditions [1]. This technique has recently emerged and offers valuable information on technologically relevant magnetic materials [2].
Static magnetic fields are commonly measured by recording the Zeeman-shift of the NV defect electronic spin sublevels through optical detection of the magnetic resonance (ODMR) [1]. Such a measurement protocol becomes however challenging when magnetic fields larger than 5mT are applied perpendicular to the NV spin quantization axis. In this moderate-field regime, off-axis magnetic field components induce mixing of the electron spin sub-levels, leading to a drastic reduction in ODMR contrast so that quantitative magnetic field imaging can no longer be performed [3]. This situation is inevitably reached as soon as the NV sensor is brought in close proximity to a ferromagnet, *i.e.* when high spatial resolution is required. However, spin state mixing is also accompanied by an overall reduction of the NV defect photoluminescence (PL) intensity. Such a magnetic-field-induced PL quenching can be exploited to map regions of magnetic samples producing large stray fields with high spatial resolution [4,5].
In this work, we perform magnetic imaging with a scanning-NV magnetometer operating in the PL quenching mode under ambient conditions. As sketched in Fig. 1(a), we employ a single NV defect located at the apex of a nanopillar in a diamond scanning-probe unit. Once integrated into an atomic force microscope, this device enables scanning of the NV sensor in close proximity to the sample [6]. All-optical magnetic field imaging is performed by monitoring the NV defect PL intensity while scanning the magnetic sample. Using this technique, we first report on magnetic imaging of skyrmions in exchange-biased multilayerstacks such as Pt/Co/IrMn with diameters about 50 nm at room temperature and zero magnetic field [Fig. 1(b)]. Compared to magnetic force microscopy, the main advantage of scanning-NV magnetometry is here the absence of magnetic back-action on the sample which provides unambiguous field measurements. This is particularly important for the study of spin textures in ultrathin films, which are often sensitive to magnetic perturbations. We then present preliminary results on two-dimensional (2D) ferromagnets. We show that flakes of $CrTe_2$ exhibit a ferromagnetic order at room temperature. This observation is a first step towards the integration of 2D ferromagnets in van der Waals heterostructures operating under ambient conditions.

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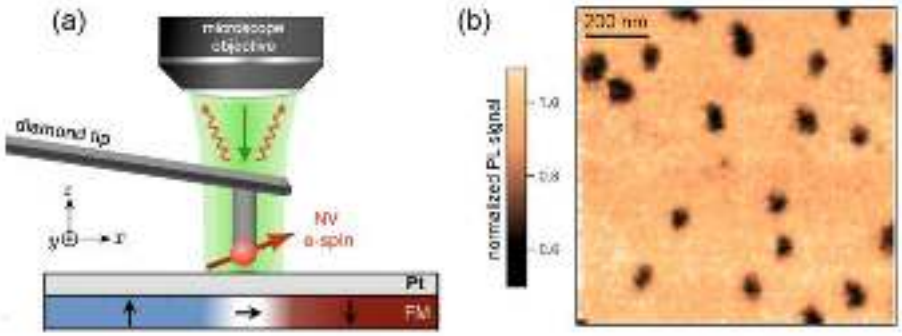

Figure 1: *(a) Principle of a scanning-NV magnetometer operating in PL quenching mode. (b) PL quenching image of magnetic skyrmions in a Pt/Co/IrMn multilayer stack.*

O111 - Complex magnetic configurations in CoNi nanowires studied by 2D and 3D electron holography

8. Novel magnetic techniques

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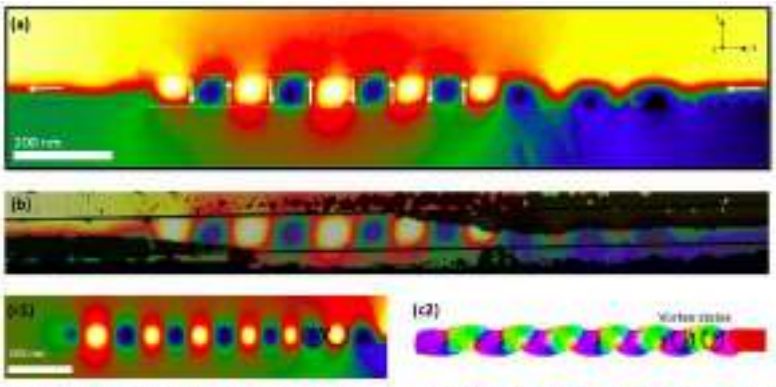
Understanding the magnetic configurations in cylindrical nanowires (NWs) is a current topic for the development of future spintronic devices. In such ferromagnetic systems, the equilibrium state is defined by minimizing the magnetic energy, where shape, crystal structure, and composition are contributing factors. This study aims to analyze the complex magnetic structure, such as type and position of domain walls, in CoNi cylindrical NWs. These NWs exhibit grains of both fcc and hcp crystal phase, where the hcp phase has the c-axis oriented perpendicular to the nanowire axis. Lorentz TEM, 2D electron holography (EH) and 3D electron holographic tomography (EHT) have been used to determine the magnetic configuration of these NWs. These results have been correlated with the local crystallographic structure obtained by diffraction and HR-TEM, and chemical composition obtained by STEM EELS. Micromagnetic simulations have been carried out to support the experimental results.

EH reveals two distinctly different types of configurations within a single NW: periodical vortices in regions with perpendicular easy axis orientation, and a curling state parallel to the nanowire axis. These vastly different domains are found to be due to local variations in the crystalline orientation and/or structure, which give rise to changes in the crystallographic and uniaxial anisotropies. Micromagnetic simulations have confirmed this complex magnetic configuration.



(a) Experimental magnetic phase image reconstructed from EH of a CoNi NW. (b) Superposition of (a) with crystallographic results of the same region. Black areas represent fcc phase and displayed phase regions hcp phase. (c2) and (c1) show respectively the simulated spin orientation and its simulated phase image with easy axis orientation perpendicular to the nanowire axis.

O113 - Depth-selective Conversion Electron Mossbauer Spectroscopy using a multi-parameter analyser

8. Novel magnetic techniques

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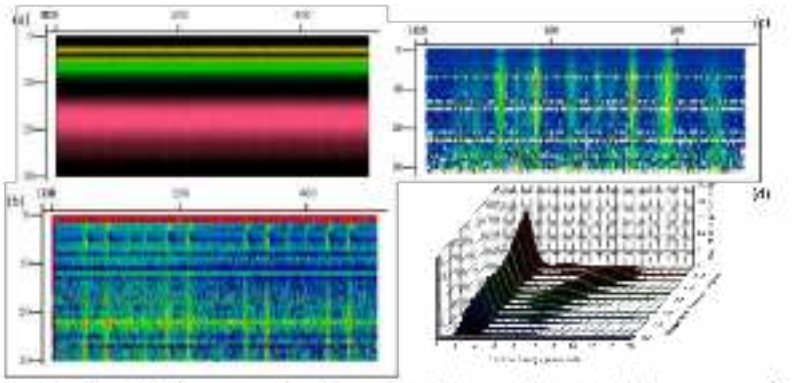
Few techniques surpass Mossbauer spectroscopy, when it comes to the chararacterisation of the magnetic order and chemical local eironment of iron-containing magnetic materials. The vast majority of data aquired, however is obtained on bulk or powder samples, in transmission mode, and on setups where the energy discrimination is done in hardware and before the binning action of a multi-channel scaler, whose channels scan through Dopler velocities in a constant acceleration drive system. Depth-profiling conversion electron Mossbauer spectrometry (which is much better suited to thin film and multi-layer characterisaiton), on the other hand has been the realm of high-resolution electron detectors within high-vacuum environment, using slow and expensive hardware and acquiring one energy slice at a time.
Here we focus our attention on the development of aquisition hardware and data processing software, allowing for the optimal use of gas-flow proportional low-energy resolution electron detectors to obtain depth-selective (^{57}Fe) Mossbauer spectra quickly and efficiently. The hardware consists of He-NH_3 (5 % buffer) premixed gas proportional counter, suitable for hosting thin film on substrate samples of lateral size under 15 mm, and capable of operating at pressures in excess of 2 bar. Standard Canberra charge-sensitive pre-amplifiers are used for signal conditioning, in conjunction with a high-voltage power supply and adjustable gain pulse-shaping post-amplifier. The resulting voltage pulpulses are processed by a in-house developed multi-parameter analizer, which utilizes a number of 10 MHz analog to digital converters, a channel counter and scaler and set of hardware electronic latches, to prepare a digital word of adjustable length (3 to 5 byte segments, as required), which characterises, for example the Mossbauer velocity and pulse integral energy, for each and every pulse detected. The digital data is then passed onto a number (3 to 5) Enhanced Parallel Port PCI-bus digital I/O cards, capable of buffering the data and generating the necesary interrupt requests, to command an IBM PC-compatible computer to aquire, record and bin into multi-dimensional matrices the incomming events. This cheap and effective solution, allows for the processing of up to 30,000 to 100,000 pulses per second, at peak speed (depending on the number of parameters sampled). As the process is hardware-driven to a large extend, the essential part of computing resources are still available for real-time data display and further processing.
We would like to illustrate the capabilities of this system with just a couple of examples of clean and on-purpose oxidized α-Fe surfaces. We focus first on the raw data, which now is at least two-dimensional. The electron escape energies or the energies of the captured X-ray of γ-quanta, represent one of the dimensions, while the other is occupied by the fine-energy scale or the Doppler modulation velosity as shown in the figure. After digital post-procesing (effective optimal discrimination), the Mossbauer spectra are visible quite clearly at both low-energy (conversion electrons), at intermediate energies (characteristic X-rays) and at the primary γ-energy. As electron events of high energy correspond to interaction with the surface layers (< 100 - 200 nm) oxidized layers are clearly discriminated against the bulk.



O114 - Influence of epitaxial strain on the magnetic order in antiferromagnetic thin films

8. Novel magnetic techniques

Angela Haykal[1] , *Johanna Fischer[2], Théophile Chirac[3], Waseem Akhtar[1],* ***Aurore Finco***[1], *Stéphane Fusil[2], Manuel Bibes[2], Vincent Garcia[2], Jean-Yves Chauleau[3], Michel Viret[3], Vincent Jacques[1]*

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Antiferromagnetic materials attract a growing interest in spintronics owing to their promising properties: they are not sensitive to external magnetic perturbations, do not produce parasitic stray fields, and show a fast magnetization dynamics. However, because they do not have a net magnetization, direct real-space imaging of magnetic structures in these systems remains challenging. Therefore, we use scanning NV-center magnetometry to probe the magnetic state of antiferromagnets. This non-perturbative technique is based on the spin properties of a single nitrogen-vacancy defect in diamond and combines a nanoscale spatial resolution with a high magnetic sensitivity under ambient conditions. We focus here on the study of the antiferromagnetic order in the multiferroic compound bismuth ferrite (BFO). At room temperature, BFO exhibits a large electrical polarization and an antiferromagnetic order with a cycloidal modulation with a period of 64 nm in the bulk. The propagation direction of the cycloid is strongly coupled to the direction of the electrical polarization. This magnetoelectric coupling allows the electric field control of the magnetic order, which is a desired feature in the view of developing new devices with a low power consumption. Such devices would necessarily use thin films of BFO, in which epitaxial strain is induced by the growth substrate. Previous investigations have demonstrated that NV-center magnetometry is able to measure the cycloid in thin films [1], and here we go further and study the effect of epitaxial strain on the magnetic order [2]. By using different substrates to grow BFO thin films, we tune the epitaxial strain and then perform direct imaging of the resulting magnetic state. Our measurements reveal that a moderate strain modifies the propagation direction of the cycloid with respect to the electrical polarization. In highly strained films, the cycloidal modulation disappears and only antiferromagnetic domains can be observed.

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O115 - Resonant X-ray Imaging of Skyrmionic Spin Textures

8. Novel magnetic techniques

Murray Wilson[1] , *Max Birch[1], Luke Turnbull[1], Aleš Štefančič[2], Felix Groß[3], Angus Laurenson[4], Erick Burgos-Parra[5], Geetha Balakrishnan[2], Joachim Gräfe[3], Feodor Ogrin[4], Horia Popescu[5], Peter Hatton[1]*

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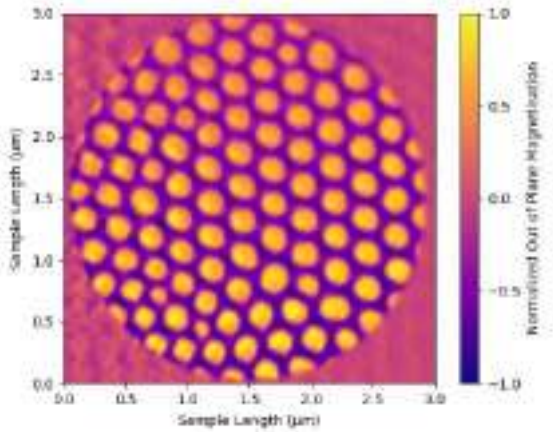
Skyrmions are topologically protected nanoscale magnetic objects that appear in certain chiral magnets. They have been proposed for application in novel spintronics devices as stable, mobile, memory elements. For such applications, it is important to understand the detailed skyrmion structure in various conditions. While much can be learned from scattering techniques, such methods can fail to yield useful information on very disordered or isolated skyrmion arrangements, where no regular lattice is present. In many of these cases, direct magnetic imaging of the skyrmion state gives substantially more information to help understand the physics of the systems.

Lorentz transmission electron microscopy is a powerful imaging technique that has a high spatial resolution and is commonly used to study skyrmions and related spin textures in very thin films. However, it measures only the in-plane component of the B-field projected through the sample, and can generally only measure with the magnetic field applied parallel to the electron beam. In contrast, X-ray imaging techniques measure the out of plane magnetisation, can measure somewhat thicker samples, and can measure with fields applied in any direction. This makes them very complementary to electron microscopy. Using the very short pulse length available at synchrotrons, these techniques can also be used to stroboscopically image dynamic behaviour with very high time resolution.

In this talk, I will discuss our recent work applying resonant extended-reference X-ray holography and scanning transmission X-ray microscopy to skyrmion systems. Using these techniques we have imaged many systems such as the proposed 'biskyrmion' state in MnNiGa, as well as helices, skyrmions, and cones in FeGe and Cu_2OSeO_3. These measurements have demonstrated the ability to produce high contrast images of these magnetic textures with resolutions down to 18 nm. The attached figure shows an example image of the magnetism in our MnNiGa lamella measured by X-ray holography, which appears consistent with a type-II bubble state, rather than the proposed biskyrmion state. Furthermore, by imaging FeGe we have revealed interesting features of the skyrmion state such as the details of the transition between helical and skyrmion domains when currents are driven through the sample. These techniques will continue to provide important insight about these long-wavelength incommensurate structures in the coming years as synchrotron technology further improves.


Sample Length (μm)
Sample Length (μm)
Normalized Out of Plane Magnetization
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1.0
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−1.0
−0.5
0.0
0.5
1.0

O116 - Stroboscopic and single shot dynamic magneto-optical imaging – from microseconds to nanoseconds

8. Novel magnetic techniques

Matic Jovičević Klug[1] , *Patrick Hayes[1], Oliver Váhovský[1, 2], Mona Mintken[1], Kornel Richter[1, 2], Viktor Schell[1], Eckhard Quandt[1],* ***Jeffrey McCord***[1]

[1] Kiel University, Institute for Materials Science

[2] University of Pavol Jozef Šafárik, Institute of Physics

The imaging of dynamic magnetic phenomena is essential for the understanding and the optimization of magnetic materials and device structures. Magnetic domain imaging provides the most direct access to the effective magnetic properties of materials from the macroscale down to the nanoscale. Therefore, the analysis of the magnetic domain development by quasi-static magnetic domain imaging [1] has become an essential part for the characterization of magnetic materials. Using pulsed LED illumination sources, magnetic imaging with millisecond time resolution is possible. On the other hand, the stroboscopic wide-field imaging of magnetization dynamics with picosecond and faster time resolutions is achievable [2,3], but is limited to a high frequencies defined by the laser's repetition rate. Single shot imaging is not used for fast magnetic field excitations. The imaging of magnetization response in the range from microseconds to nanoseconds, or in the MHz regime is nearly unexplored. Furthermore, complex irreversible magnetic processes have been scarcely analyzed by unfolding single magnetization events occurring during various high frequency excitations of magnetic materials.

Here, we introduce an imaging setup allowing for the imaging of magnetization responses with a flexible adjustable time resolution. Using a high-power solid-state laser with variable exposure, stroboscopic and single shot imaging with laser pulses down to 10 nanoseconds is shown. Examples, displaying the feasibility of the various magnetic imaging modes, are the imaging of current induced domain wall propagation in magnetic nanowires (Fig. 1a) and domain repeatability in the magnetic reversal in electrical steel samples (Fig. 1b). Results of single shot and stroboscopic imaging with down to one microsecond time-resolution are directly compared. Imaging of electrically induced magnetization reversal in magnetoelectric composite samples at 0.5 MHz with 20 nanoseconds exposure reveals modulated magnetization reversal modes due to magneto-elastic self-energy effects (Fig. 1c and 1d). Single shot imaging of nucleation modes of magnetic bubbles with 10 nanoseconds time resolution display different stages of bubble generation (Fig. 1e). Other examples of the relevance of dynamic magnetic domain imaging in the MHz regime will be shown.

Magnetic domain observations of magnetization dynamics dominated by domain wall nucleation and movement dominated processes, also on a single shot level, are now accessible directly from DC to the nanosecond regime with continuously variable illumination exposure.

We thank the DFG for support through the Collaborative Research Centre CRC 1261 Magnetoelectric Sensors: From Composite Materials to Biomagnetic Diagnostics.

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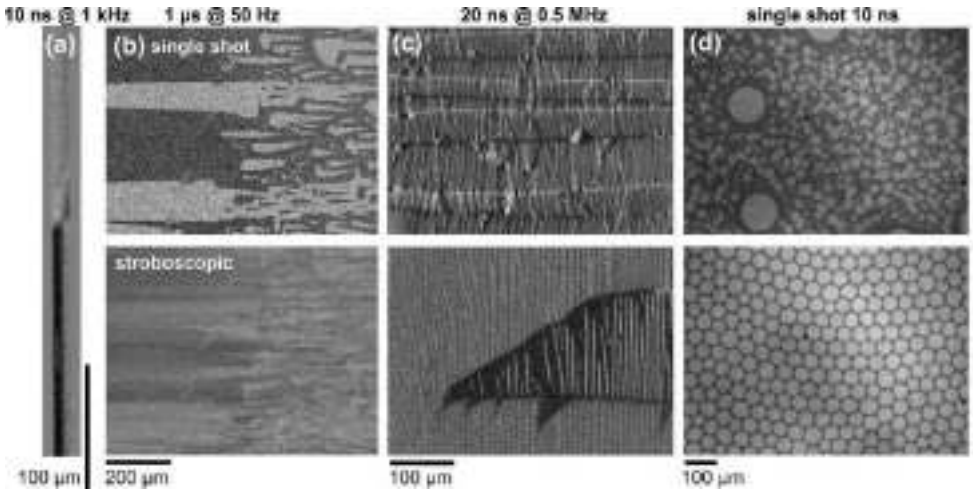
10 ns @ 1 kHz
1 µs @ 50 Hz
20 ns @ 0.5 MHz
single shot 10 ns
(a)
(b) single shot
(c)
(d)
stroboscopic
100 µm
200 µm
100 µm
100 µm

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

O117 - A Growing Improvement: Controlling the Nano-structuring of Ferrite Magnets

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

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Permanent magnets are fundamental in most modern devices, ranging from tiny electronics in smart devices to massive generators in giant wind turbines. Rare-earth (RE) elements like neodymium or dysprosium are often used in the production of some of the strongest magnets available on the marked, however, political, economic, and environmental circumstances surrounding RE containing magnets have led to an increased interest in RE-free alternatives[1]. One such alternative is the inexpensive yet widespread ferrites. Although it has been used as a permanent magnet for decades, strontium hexaferrite ($SrFe_{12}O_{19}$) has gained new interest, as recent studies on the nano-structuring of the material have shown significant improvements on its magnetic performance.[2,3]
Nano-structuring is used to control both, size and morphology of the particles. The size is tuned in order to ensure single-domain particles, which is crucial for optimizing the coercivity of the magnet. The morphology of the nano-particles is used to obtain a powder, which will develop aligned magnetic domains during compaction into dense pellets. This is accomplished by synthesizing platelet-shaped particles with uniaxial magnetic anisotropy parallel to the platelet normal and subsequently compacting these powders using Spark Plasma Sintering. The compaction is performed at elevated temperature, which leads to particle growth, adding a further complication as the particles might grow past the single-domain limit. In order to study the particle growth within the compacted pellets, it is proposed to use *in situ* neutron diffraction to probe the entire pellet volume during heating. Cold-pressed pellets of $SrFe_{12}O_{19}$ will be produced using powders with various morphologies. The pellets will subsequently be sintered and the microstructural changes will be followed *in situ* by means of neutron powder diffraction. The results will provide information on the compaction mechanisms, which will allow rational design of compacted ferrite magnets with enhanced magnetic properties.
The neutron experiments will be an expansion of a study following the microstructural changes in annealed $SrFe_{12}O_{19}$ nano-powder using an in-house *in situ* X-ray diffraction setup, which has been developed at Aarhus University. The setup combines a commercial area detector with an in-house build Large Area Soller Slit, which allow fast data acquisition, versatile sample environments, and a unique spatial resolution[4,5].

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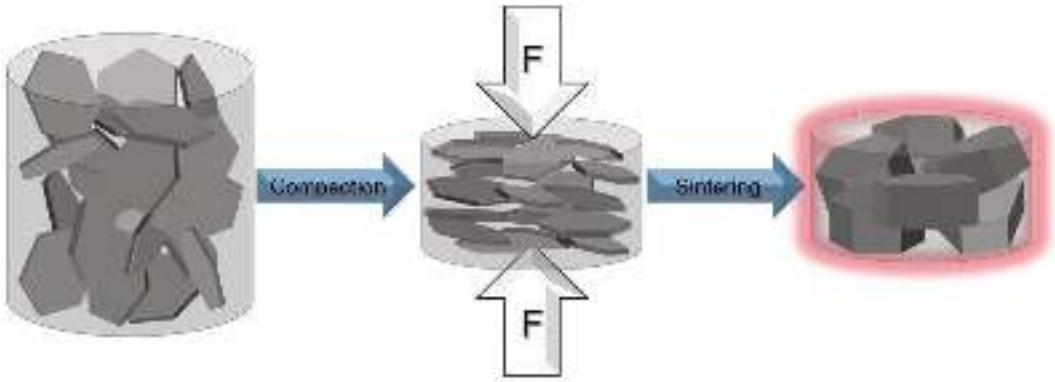

Fig. 1 – Illustration of the compaction concept. Platelet shaped nano-particles are cold-pressed into a dense pellet and subsequently sintered. The sintering process will be followed in situ using powder neutron diffraction in order to investigate the morphology and size change of the particles.

O118 - Ab-initio phase stabilities of Ce-based hard magnetic materials and comparison with experiments

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

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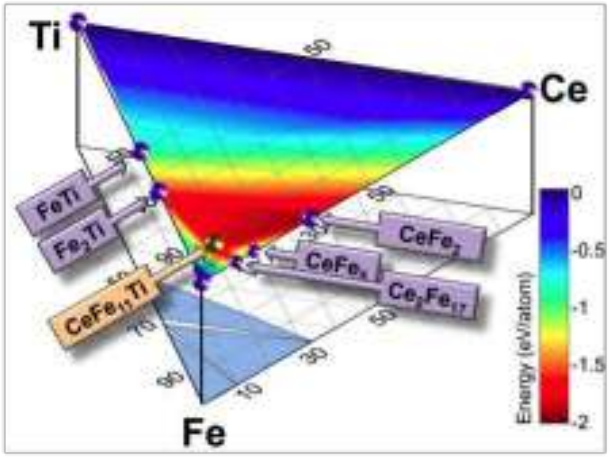
Recent developments in electric transportation and renewable energies have significantly increased the demand for hard magnetic materials with a reduced critical rare-earth content, but with properties comparable to (Nd, Dy)-Fe-B permanent magnets. Though promising alternative compositions have been identified in high-throughput screenings, however, the thermodynamic stability of these phases against decomposition into structures with much less favorable magnetic properties is often unclear. In order to have a better understanding, we performed *ab initio* calculations of finite temperature phase stabilities of Ce-based alloys. The Helmholtz free energy $F(T, V)$ is calculated for all relevant competing phases using a sophisticated set of methods capturing vibrational, electronic, magnetic and configurational entropy contributions. The study includes unary Ce, binaries of Ce-Fe and Fe-Ti phases, and ternary Ce-Fe-Ti phases. In a first step, we test the performance of our approach and find good agreement with experimental data. In a second step, we calculate the finite temperature phase formation diagram. This diagram shows that the presence of the $CeFe_2$ phase prevents any formation of the targeted hard magnetic Ce-Fe-Ti alloys. This observation is supported by recent EDS experiments. In a third step, we, therefore, extend our study to quaternary alloys. Specifically, we study the effects of Cu and Ga substitution by introducing a screening scheme that allows testing all 3*d* and 4*d*-elements. Theoretical results have been confirmed experimentally by employing reactive crucible melting (RCM) and suction casting method. Our *ab initio* based free energy calculations reveal that the presence of the $CeFe_2$ Laves phase suppresses the formation of $CeFe_{11}Ti$ up to 700 K. The result is in agreement with RCM, in which CeFe11Ti is only observed above 1000 K, while the $CeFe_2$ and Ce_2Fe_{17} phases are stable at lower temperatures.



O119 - Advanced thermal stability investigation of the L10-Phase in the ternary Mn-Al-Ga-System

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

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The intrinsic magnet properties of the ferromagnetic $L1_0$ (P4/mmm, cP4) phase in Mn-Al and Mn-Ga alloys makes them promising candidates for rare earth free permanent magnets. However both binary systems have a drawback. In the Mn-Al system, the $L1_0$ phase is metastable and therefore high temperatures lead to the decomposition of the $L1_0$ phase into the β-Mn and γ_2 (R3m, Al8Cr5 type) equilibrium phases. The $L1_0$ phase in the Mn-Ga system is thermodynamically stable; however, the global supply of Ga is critical and the high raw materials costs are high. A possible solution to these problems may be offered by ternary Mn-Al-Ga alloys.

Researches on the ternary alloys showed the possibility to form the $L1_0$ phase in a wide contribution range from $Mn_{55}Al_{45-x}Ga_x$ with $0 < x < 45$. The intrinsic magnetic properties of these ternary alloys showed comparable or even superior values compared to the binary systems. One particularly interesting result of these investigations is the formation of two $L1_0$ phases with different composition and different phase formation processes, in one alloy.

The thermal stability of the $L1_0$ phases was investigated at 700°C. As series of heat treatments from 2 h up to 14 days was carried out showing an increased thermal stability compared to the binary Mn-Al alloys with only small Ga additions. Heating durations of more than 4 h resulted in slow decomposition. Using x-ray diffraction method (XRD) it was shown that the decomposition starts with the formation of β-Mn followed by the production of γ_2. Microstructural investigations combined with EDX measurements revealed strong diffusion processes during the decomposition. After 7 days half of the sample still contained a $L1_0$ phase with slightly changed composition compared to the initial two phases. These results show that the thermal stability of the $L1_0$ phase in the Mn-Al system can be improved with small additions of Ga. Higher processing temperatures and longer durations may be envisaged for these alloys, which may result in better performance in applications.

O120 - An innovative processing route to prepare single crystalline Nd2Fe17 alloy fine powder

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

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The process to prepare anisotropic (single crystalline) *R*-Fe (*R* : rare earth element) fine powder as a permanent magnet material is limited. One of the reported processes is reduction-diffusion (R-D) process [1]. However, due to the limitation of the process conditions, the average particle size becomes larger than ~500 nm. Recently, we developed a new process that combines an induction thermal plasma apparatus with a glove box (ITP-GB) system [2]. This system enables us to prepare and handle nano-sized oxide-free metal single crystalline powder produced under a low oxygen environment [3]. In this work, as a first step, we applied this process to prepare Nd-Fe alloy powder and evaluate the particle size, the existing phases and the magnetic properties of them.

The mixed powder of Fe powder (particle size of 3~5 μm, purity 99.99 %, oxygen level 0.095 wt%, Kojundo Chemical Lab. Co., Ltd., Japan) and Nd powder (particle size <50 μm, oxygen level 0.25 wt%) were used as starting powder. The atomic ratio of Fe and Nd is Fe : Nd = 3 : 2. The Nd powder was prepared by a gas atomize facility (MAKABE R&D CO., LTD.). Ar was used as the plasma and carrier gas, and their flow rates were 35 and 3 L/min., respectively. The mixed powder was then introduced from the top of the plasma torch at a feed rate of up to 0.3 g/min. The detail of the set-up of our thermal plasma apparatus was described in ref.1. Synchrotron radiation X-ray diffraction was performed at the BL5S2 beamline of the Aichi Synchrotron Radiation Center. The incident X-ray energy of 14 keV was chosen. The powders for these measurements were filled in individual quartz capillaries with a diameter of 300 mm. Both of the ends of each capillary were sealed with epoxy in a glovebox to prevent oxidation. The microstructure was studied by transmission electron microscopy (TEM), JEOL, JEM-2100F/HK.

The XRD pattern indicated the existence of the Nd_2Fe_{17} phase although unprocessed Nd and Fe phases were also found as sub phases. No oxide phase was detected by the XRD measurement. From TEM observations, the particle size was around 100 nm. Also, each particle was found to be in a single crystalline state from the selected area diffraction patterns. Therefore, the thermal plasma process can be used as a novel route to prepare the single crystalline Nd_2Fe_{17} alloy fine powder.

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O121 - Anisotropic nanocomposite Nd-Fe-B magnets produced by die-upsetting with the aid of Nd-Cu alloys

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

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Exchange coupled nanocomposite magnets (NCMs) possess nano-sized two-phase microstructure composed of dispersed soft magnetic phase embedded in hard magnetic phase matrix [1-3]. This class of materials are expected to replace Nd-Fe-B magnets because of their predicted giant energy products. Recent works in the literature however have demonstrated that controlling the orientations of HP grains is not enough to achieve excellent properties; the surface area of the interfaces having a suitable (i.e. strongly coupled) orientation relationship must be maximized, too. [4, 5] The current authors have been working on various severe plastic deformation techniques at a wide range of temperatures [6,7], but the texture control was not successful. Texture control by hot deformation can be done when the Nd content is richer than the stoichiometric value [8,9], but it is extremely challenging when the alloy composition becomes Fe-rich unless non-magnetic elements such as Cu and Ga are doped [10,11]. Tang et al reported an interesting approach [12,13]. They added Nd-Cu alloys which made it possible to form Nd-rich phases at grain boundary regions so that the texture is aligned after die upsetting.

In the current work, die-upsetting at elevated temperatures was applied to various Nd-lean Nd-Fe-B nanocomposite magnets. Particularly, influences of addition of eutectic Nd-Cu alloys having low melting points on texturing were investigated. X-ray diffraction and magnetic property measurements were carried out for the deformed samples to check whether texture is induced. A series of the experiments clearly demonstrated that no texturing occurs in the case of the alloys without a Nd-Cu alloy while textured magnets were successfully obtained when Nd-Cu was added as shown in Fig. However, the texture obtained by the current attempt was not very strong. Detailed multi-scale electron microscopy revealed that the textured region was limited to where Nd was enriched and α-Fe phases disappeared. The strategy to obtain an ideal microstructure of NCMs is discussed during the talk.

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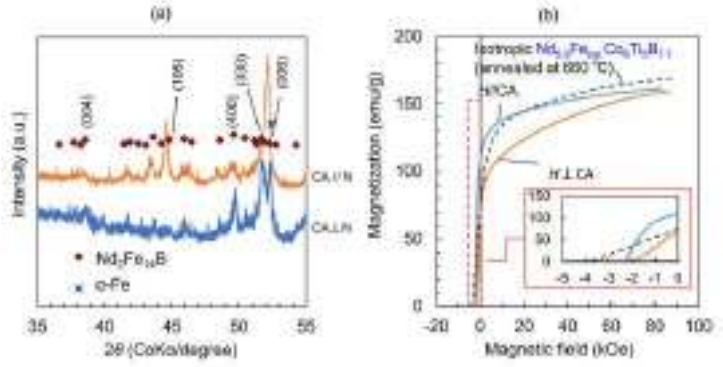

Fig. (a) XRD patterns measured from the two perpendicular diffracted surfaces of a die-upset sample ($Nd_2Fe_{14}Co_2TiB$-14Nd-$Cu_{0.1}$). CA//N and CA⊥N respectively represents a normal of the measurement plane is parallel and normal to the compression axis. (b) The demagnetization curves measured two perpendicular directions of the same alloy. A clear evidence of texturing is demonstrated.

O122 - Ce based permanent magnets of the CaCu5 structure type

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

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Abstract

Permanent magnets typically need large magnetocrystalline anisotropy to retain magnetization upon demagnetization. This anisotropy can be achieved through a coupling of 3*d* and 4*f* elements as in $Nd_2Fe_{14}B$. Out of the 4*f* elements Cerium is by far the most abundant, and thus it has the least inherent supply risk. Thereby, Ce based permanent magnets could potentially be viable “gap magnets”, meaning that if their performance exceeds that of ferrites, they could fill an important gap to that of Nd based magnets.

Recently,[1], [2] Pauli paramagnets, such as $CeCo_3$ have been shown to be able to be “rehabilitated” into ferromagnets with large anisotropy and transition temperatures well above room temperature. These materials are found to be near a ferromagnetic instability through band structure calculations and thus can be tipped over to the ferromagnetic state. Using the international crystallographic database, we have identified more than 800 possible candidates based on Cerium and magnetic 3*d* elements. When removing highly toxic and rare elements such as thallium and gold, there are 50 candidates left that crystallize in the $CaCu_5$ structure type.

So far, two of these candidates, previously not characterized magnetically have been synthesized through induction melting and characterized using SQUID magnetometry. However, these show antiferromagnetic ordering or a low transition temperature. A combinatorial work based on solid state reactions, experimental magnetism and quantum mechanical based calculations will elucidate these materials to hopefully find new materials with ferromagnetic instabilities to tip them over, previously not characterized materials or completely new materials.

Acknowledgment

Financial support from the Swedish foundation for strategic research (SSF), the Swedish centre for Smart Grids and Energy Storage (SweGRIDS) and the Swedish energy agency is gratefully acknowledged.

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O123 - Changes of magnetic properties of melt-spun (Hf,Cr)-Co-B in response to thermomechanical treatment

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

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Rare earth elements are crucial components of widely used hard magnetic materials characterized by the highest magnetic anisotropy and high energy product $|BH|_{max}$, which makes them attractive for industry. There is continuous search for non-rare-earth magnetic materials with the magnetic anisotropy sufficient to fulfill the gap between Nd–Fe–B and hard ferrites. The Hf-Co-based alloys are considered as candidates for hard magnetic materials of this type. So far, they have been found to show high Curie temperature, but their magnetic anisotropy is not sufficiently maximized. Additionally, there is still open discussion on the crystal structure of the hard magnetic crystalline phase. Moreover, grain refinement is believed to play a crucial role in improvement of magnetic properties, especially anisotropy. Sufficient grain refinement can be achieved by partial substitution with transition metal elements or by thermomechanical treatment.
X-ray diffraction patterns of as-quenched $Hf_2Co_{11}B$ ribbons confirmed their fully amorphous structure. The evolution of crystalline structure of $Hf_2Co_{11}B$ ribbons upon isothermal annealing and/or plastic deformation and its influence on their magnetic properties were investigated. Isothermal annealing induced crystallization of this alloy and as a result led to a coexistence of two Hf_2Co_{11} phases with slightly different crystal structures and different values of magnetic anisotropy [1]. The presence of the hard magnetic phase was confirmed by electron diffraction. The high pressure torsion process caused the amorphization of annealed crystalline sample, slightly increasing thermal stability of the alloy. Amorphous material after annealing is characterized by coercive field equal to 0.7 kOe, which decreased to 0.2 kOe after plastic deformation. The subsequent reannealing of the deformed sample caused a significant improvement of the coercive field up to 1.3 kOe. This shows that a combined severe plastic deformation and heat treatment allow tuning of the structure and consequently also the magnetic properties.
In $Hf_2Co_{11}B$, Hf was partly replaced by atoms of Cr to improve magnetic anisotropy and glass forming ability. Increasing Cr content decreased the stability of the amorphous alloy and for higher Cr content the melt-spun ribbons were crystalline. Activation energy of crystallization decreased from 336 ± 15 kJ/mol for $Hf_2Co_{11}B$ to 270 ± 13 kJ/mol for $Hf_1Cr_1Co_{11}B$ alloy, along with glass forming ability of Cr containing alloys which questioned their usefulness.

Acknowledgement
This work was supported by the National Science Centre, Poland, within the project No. 2016/23/N/ST3/03820.

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O124 - Charge transfer as a mechanism for entropy changes

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

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Despite the efforts done and the achievements obtained so far in the field of magnetocaloric materials, there are still many challenges to apply the magnetocaloric effect in solid state refrigeration and improve the performance of the magnetic refrigerators prototypes. In this context, the search for new materials and new physical mechanisms able to produce large caloric effects continues to attract the attention of researchers all over the world.

In this work, we theoretically discuss the entropy change driven by a charge transfer mechanism. For this purpose, we use the two subband model in which a strongly correlated narrow band is coupled with a wide conduction electrons band. In the model, the energy bandwidth and the hybridization parameter control the charge transfer between the subbands. The entropy and the caloric functions are calculated using the standard relations [2]. We apply the model to discuss the barocaloric effect $YbInCu_4$, which exhibits around 42 K a transition from a local magnetic moment regime to an itinerant electron behavior. Our theoretical results, show the existence of a large entropy change around 42 K due to the charge transfer from the 4f subband to the conduction electron sea. Besides, the isothermal entropy change upon pressure variation exhibits sizeable values in a wide temperature range. This outstanding theoretical prediction, which needs experimental data to be confirmed, can be very important for solid state refrigerators technology.

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O125 - Controlling of particle size to improve the coercivity of SmCo5 hard magnet

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

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Rare-earth magnets have been widely used for magnetic, electronic, energy applications in the world. Among these strong magnetic matierials, $SmCo_5$ rare-earth hard magnet has the largest anisotropy field, while the coercivity of a magnet is usually less than 30% of its anisotropy field.[1] The coercivity is enhanced, when the grain size (spherical shape) is in the stable single-domain (SSD) range. Theoretical calculation predicts the SSD range of $SmCo_5$ to be 740-870 nm,[2] however, at present, there has been no experimental data supporting the claim. Herein, we used an improved chemical method to synthesize $SmCo_5$ particles with an average particle size (APS) range from 202 nm to 810 nm by tuning the reaction condition of the precursor, named T1, T3, T5, T8, T12, T16 based on reaction time (see Figure 1a). We found that the morphology and composition of the precursor play a significant role in determining the phase composition and APS of the final product. The maximum coercivity of 2632 kA m^{-1} (33.1 kOe) was obtained when the APS reached 805 nm (Figure 1b). SEM images and recoil loops demonstrate that samples with high coercivity are uniform and the coherent rotation happens during the demagnetization process. Henkel plots and δM plots verify the existing of strong exchange coupling interaction between particles, resulting in the high M_r/M_S ratios. This is the first time to optimize the coercivity of $SmCo_5$ based on single domain theory and the optimized APS fits very well the predicted SSD range (Figure 1c).

Key words: $SmCo_5$ particles; high coercivity; single-domain size; chemical method

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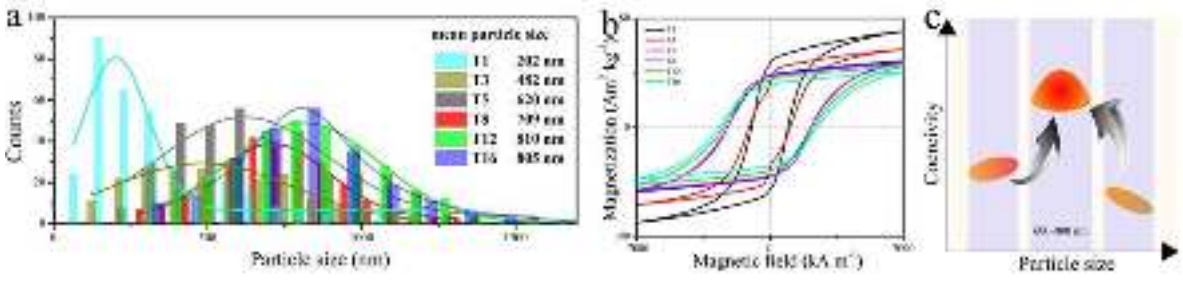

Figure 1 (a) the size distribution and (b) hysteresis loops of different samples, (c) schematic presentation of single domain theory

O126 - Development of wash treatment in R-D technique for synthesis of high coercivity Sm2Fe17N3 powder

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

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We have reported a submicron-sized $Sm_2Fe_{17}N_3$ powder with high coercivity, up to 24.7 kOe (J. Alloys Compd. 695 (2017) 1617-1623). In this study, we attempted to produce $Sm_2Fe_{17}N_3$ having even higher coercivity by an investigation and a development of a wash treatment in a reduction-diffusion technique.

Synthesis of $Sm_2Fe_{17}N_3$ powder by a reduction-diffusion technique requires a wash treatment to remove Ca residues, but it is typically associated with a decrease of coercivity. Microscopic observations and synchrotron X-ray diffraction measurements revealed the causes of the coercivity decrease in the wash treatment, and a new wash treatment to prevent this decrease was developed. As a result, we successfully demonstrated $Sm_2Fe_{17}N_3$ powders having about 20 % higher coercivity than that in the previous reports, achieving up to 28.1 kOe (Fig.1).

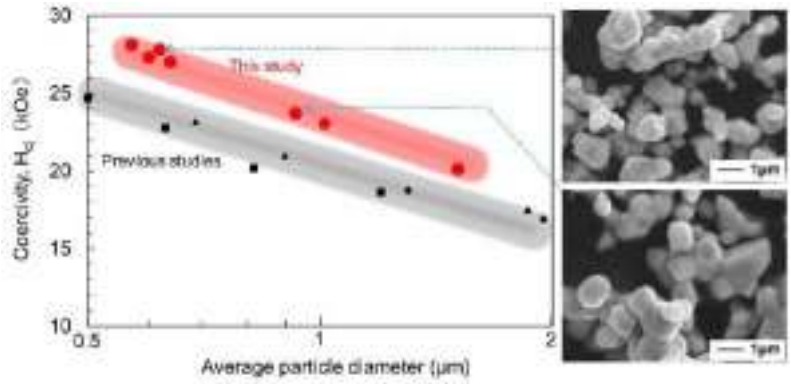

Fig. 1 Comparison of dependence of coercivity on mean diameter in this study and in previous studies and SEM images of representative samples.

O127 - Effect of High Pressure Torsion on Crystallization and Magnetic Properties of Fe73.9Cu1Nb3Si15.5B6.6

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

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$Fe_{73.4}Cu_1Nb_3Si_{15.5}B_{6.6}$ is a widely used industrial soft magnetic material with high saturation polarization and is manufactured as an amorphous tape by melt spinning. Magnetic properties relate to grain size and their orientation. Grain size is controlled by annealing whereas their orientation is controlled by introducing anisotropy to the material during the annealing process with either an external magnetic field or plastic deformation. The aim of this work is to assess the possibility to create $Fe_{73.4}Cu_1Nb_3Si_{15.5}B_{6.6}$ bulk samples, and to investigate the changes of magnetic properties arising from Severe Plastic Deformation (SPD) which has not been possible so far. High Pressure Torsion (HPT), the most efficient SPD method, was applied in this work.

Bulk samples were produced by stacking melt-spun $Fe_{73.4}Cu_1Nb_3Si_{15.5}B_{6.6}$ and subjecting it to HPT at different loading conditions and temperatures. Ring samples for magnetic measurements were cut by means of spark erosion machining.

Before and after HPT processing, the samples were investigated to assess their microstructural and crystallographic features on different scales. XRD and DSC measurements were performed to study the changes in crystallization behaviour and grain orientation. For detailed analysis of the local changes in the crystal structure, microscopic investigations (SEM, TEM, etc.) were carried out. Moreover, dynamic mechanical analysis (DMA) was performed to precisely determine the glass transition temperature. The magnetic properties of selected bulk ring samples at room temperature were investigated by frequency-dependent hysteresis measurements of the ring samples.

XRD measurements indicate significant changes in crystallographic orientation. SEM and TEM analysis confirm these findings and give further information on the size, phase and orientation of the different grains. Magnetic hysteresis measurements will be shown to further indicate the changes in magneto-crystalline anisotropy.

Following these results, temperature and degree of HPT-processing of $Fe_{73.4}Cu_1Nb_3Si_{15.5}B_{6.6}$ will be optimized to facilitate the formation of nanocrystals. Finally, it is expected that the results obtained in this work will enable to optimize the magnetic properties of similar iron-based bulk metallic glasses.

O128 - Effect of particle size on permanent magnet-polymer composites and resulting flexible filaments

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

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Advanced additive manufacturing (AM) is attracting much interest in many high-tech sectors due to the possibility of designing and fabricating high-performance elements with complex shapes and tuned properties [1]. For permanent magnet (PM) applications, developing magnets by AM with no geometrical constrictions, high filling factor (FF) and no deterioration of their magnetic properties is a challenge [2]. Nowadays, AM studies in the field of PMs focus mainly on NdFeB-based magnetic composites. However, it is of large scientific and technological interest the inclusion of rare earth-free PM alternatives such as improved ferrites and the promising MnAl-based alloys, which might partially fill the gap between conventional ferrites and NdFeB provided successful development of their PM properties [3].

In this study, homogeneous composites (PM particles/polymer) consisting on gas-atomized τ-phase MnAlC, NdFeB, Sr-ferrite and hybrid (NdFeB/Sr-ferrite) powders with different mean particle size (5-50 μm) and polymers have been analyzed. MnAlC composites were synthesized by solution casting (Fig. 1(a)) allowing for a tuned FF above 85% [4]. Composites were extruded into magnetic and flexible filaments, continuously and with a length exceeding 10 m (Fig. 1(a) and inset in Fig. 1(b)). Magnetic measurements have been used to accurately determine the FF of composites and filaments and the no deterioration of PM properties of the starting particles.

Particle size was observed to be a crucial parameter to obtain flexible filaments [4,5]. When extruding composites based on fine particles (< 20 μm) it is possible to maintain their FF and coercivity (e.g., filament based on Sr-ferrite particles (5 μm) that preserves coercive field (H_c~3 kOe, Fig. 1(b)) and FF (92%)). However, high coercive NdFeB (50 μm) composites (H_c=10.2 kOe, Fig. 1(b)) were extruded obtaining filaments with slightly diminished H_c (around 5%) and a reduction in FF of around 15% [5]. This fact has been ascribed to the larger particle size which affects to the composite rheology under the exerted pressures during extrusion. Extruding composites containing particles with different sizes (e.g., hybrids with H_c~8 kOe resulting from combining coarse NdFeB and fine Sr-ferrite particles, Fig. 1(b)) allows for maintaining a FF=90%. Similar effect occurs for MnAlC, where an optimized fine-to-coarse particles ratio leads to flexible filaments with increased FF, enhancing extrusion effectiveness [4].

This study shows that composites with PMs properties can be efficiently synthesized and processed for developing PM filament with a high FF. This filament has been used for fabricating basic 3D elements as a proof-of-concept under a controlled printing temperature.

Authors acknowledge B. Skårman, H. Vidarsson, P.-O. Larsson (Höganäs AB, Sweden), A. Nieto and R. Altimira (IMA S.L., Spain) for fruitful collaboration and discussions.

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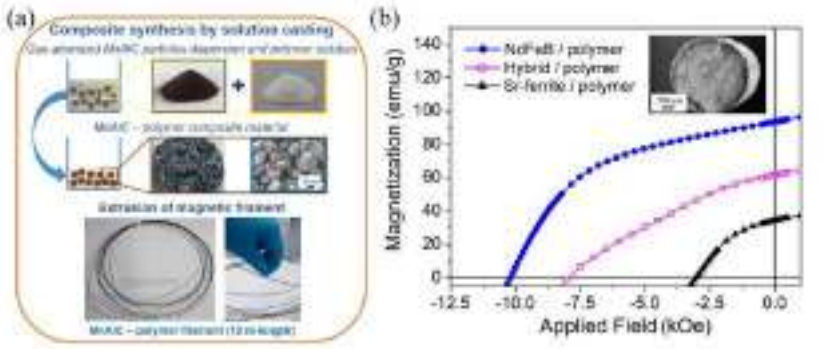

Figure 1. (a) Scheme of the composite synthesis process including images of the gas-atomized MnAlC particles, polymer, MnAlC - polymer composite (SEM image showing its internal morphology is also presented) and extruded magnetic filament. (b) Second quadrant of representative room temperature hysteresis loops measured for materials based on NdFeB, hybrid (NdFeB/Sr-ferrite) and Sr-ferrite particles. Inset shows a SEM image of the circular cross section of a magnetic filament.

O129 - Fabrication of bulk MnAlC magnets by hot-pressing from ε-phase gas-atomized and milled powder

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

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Permanent magnets (PMs) are widely used in energy, transport and electronic applications. Alternative PM materials to those containing rare-earth (RE) elements are investigated in order to plug the gap between ferrites and NdFeB magnets, which should be done under the premise of looking at feasible candidates [1]. MnAl alloy has shown up as a promising RE-free PM candidate provided development of the ferromagnetic $L1_0$ or τ-phase [2]. MnAl has an estimated maximum energy product $(BH)_{max}$=12 MGOe and lower density compared to $Nd_2Fe_{14}B$ (5.2 vs. 7.6 g/cm^3) [3], which might allow for competing with bonded NdFeB magnets. Studies on MnAl usually focus on obtaining a maximum content of τ-phase for an enhanced magnetization, but with an excessively reduced coercivity. We have recently shown the possibility of increasing coercivity by microstructural modification and controlled phase transformation through rapid-milling and variation of the impact energy [4].

In this study, hot-pressing experiments have been done at 600 ºC using as starting material both gas-atomized and milled (60 s) MnAlC powder and, importantly, starting from pure ε-phase. Hot-pressing applied to τ-phase MnAlC alloy has been reported in literature [5]. By comparison, we have used the combination of temperature and pressure attained in the hot-pressing process to manage simultaneously the ε-to-τ transformation and end with a bulk MnAlC magnet. Density of the obtained magnets was in all cases between 94 and 98%.

X-ray diffraction (XRD) patterns show the full transformation of ε- into τ- phase during hot-pressing (Fig. 1(a)), proving that the temperature used for the experiment was adequate not only for compacting (see inset in Fig. 1(b)) but also for achieving the phase transformation. The hysteresis loops measured by VSM showed an enhancement of the coercive field of up to 25% for the magnet, while maintaining the magnetization at remanence in comparison to that of the gas-atomized powder after annealing under identical conditions (Fig. 1(b)). This result is consequence of a sustained reduced mean crystallite size (25 nm) due to the relatively low temperature used during compaction, the induced strain (0.40%) and the formation of a small amount of beta-Mn phase accompanying the τ-phase ((Fig. 1(a)) [4]. Hot-pressing experiments done on the milled powder resulted in a slightly larger coercivity and a decreased magnetization, in good agreement with an enlarged content of the beta-Mn phase measured by XRD. No preferential orientation was induced on the hot-pressed powder, with additional work in progress. We have obtained similar results when compacting the starting material with a crystallographic structure based on τ-phase, which points to the possibility of the simultaneous formation of the $L1_0$-phase in MnAlC alloy together with the increase in coercivity in a single step compaction process as a promising route for developing MnAl-based magnets.

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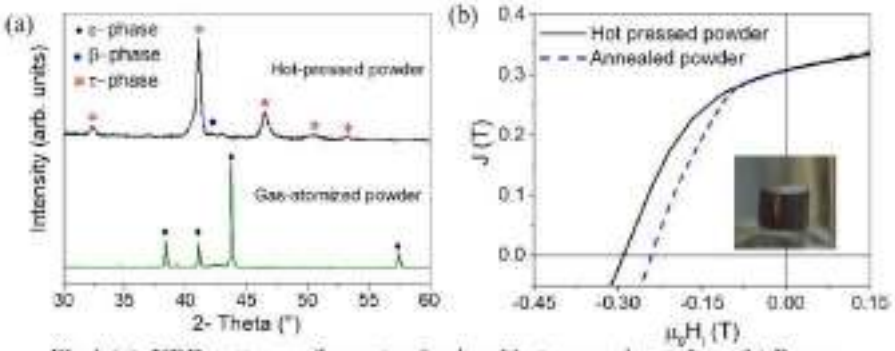

Fig.1 (a) XRD patterns of gas-atomized and hot-pressed powders. (b) Room temperature hysteresis loops (second quadrant) of the annealed and the hot-pressed powders. Inset shows the resulting compacted magnet.

O130 - Fe-Si and Fe-Si/Permalloy powders/compacts obtained by mechanosynthesis and spark plasma sintering

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

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The paper presents a review of our research on the obtaining and characterisation of some soft magnetic powders produced by mechanical alloying from Fe-Si systems and sintered composite compacts Fe-Si/Supermalloy obtained by spark plasma sintering. The Fe-Si powders were produced at classical composition (4.5 wt%, 6.5 wt%) and at high Si content (10 wt% and 15 wt%) [1, 2] by dry milling under argon atmosphere. To study the influence of milling time on the structure, microstructure and magnetic properties of the alloyed powders, different milling time was used ranging from 1 to 20 h. A heat treatment at 400 °C for 4 h in vacuum was performed in order to remove the internal stresses (induced by milling) and to improve the solid-state reaction of the new synthesized phase. The nanocrystalline/composite compacts were obtained by spark plasma sintering technique from nanocrystalline composite Fe-Si/Ni_3Fe powders, figure 1 [1]. The powders and sintered compacts were investigated by X-ray diffraction, SEM+EDX, DSC, TG, IR, magnetic measurements (M(T), M(H), B(H)). The crystallite mean size was estimated at 12-14 ± 2 nm, depending of alloy and of milling time. The magnetization measurements at 300 K in magnetic fields up to 8 T showed a continuous decrease of the spontaneous magnetization with increasing milling time. In Fe-10wt% Si powders the heat treatment leads to the formation of the Fe_3Si compound with DO3-type superstructure for low milling times [2]. The spark plasma sintering parameters (time and temperature) influence the preserving of the composite and nanocrystalline phases, and magnetic (permeability, coercive field) and electrical properties.

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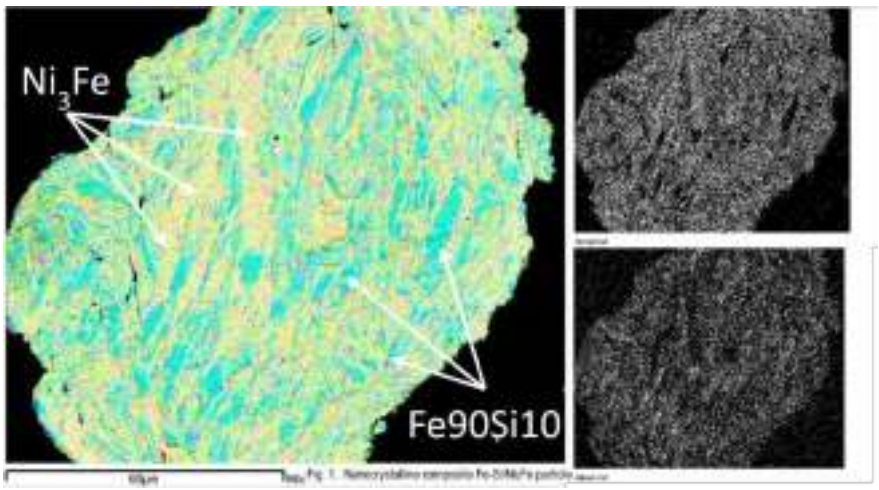

O131 - Ferrite magnets improved through size, shape and texture control

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

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Hexagonal ferrite $SrFe_{12}O_{19}$ have been thoroughly investigated as a hard magnetic material. The structure crystallizes in the space group $P6_3/mmc$, with unit cell parameters *ab*=5.88 Å and *c*=23.09 Å and the magnetic anisotropy axis is aligned along the *c*-axis, *i.e.* the magnetic easy axis. A schematic illustration is shown in Figure 1, here it is illustrated how optimized performance relies on control over eight orders of magnitude including control of phase, size, shape, and relative orientation of the hexaferrite nanocrystals.[1,2] Many of these parameters are controlled through the synthesis conditions, which we have optimized by following *in situ* the synthesis process of $SrFe_{12}O_{19}$ nanocrystallites using synchrotron radiation.[3] In addition, we have developed different synthesis approaches, which allow control over the size and shape of the produced nanocrystallites. The employed methods include: supercritical flow, hydrothermal autoclave, sol-gel, and modified sol-gel. [4, 5, 6] As a result, we are able to tailor the $SrFe_{12}O_{19}$ crystallite size (*AB*, *C*) and morphology, resulting in platelet-like crystallites with *A*/*C* aspect ratios ranging from *A*/*C* >10 to ~1.

We have used Spark Plasma Sintering to prepare the final magnets. The as-prepared magnetic nanopowder has been investigated by neutron powder diffraction, likewise has the final pellet been investigated by neutron pole figure measurements to extract the texture information. The neutron data clearly demonstrated a correlation between the aspect ratio of the starting nanoplatelets and the alignment of the crystallites in the produced magnets. The insight gained through these neutron studies is vital for the design of materials, the improvement of sample processing and the enhancement of magnetic performance.

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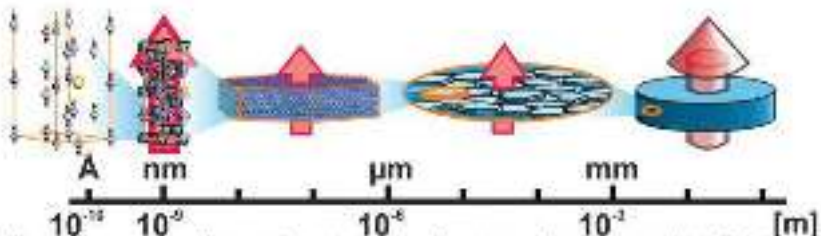

Figure 1: Correlation between magnetism and structure throughout ten orders of magnitude. Funding from the European Commission is thankfully acknowledge, project: AMPHIBIAN (H2020-MNBP-2016-720853)

O132 - Guiding principle for high-performance Co-doped ferrite magnet

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

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The hard ferrite magnet is one of commercially important permanent magnets used in various fields as a key material. The base material of the ferrite magnet is the magnetoplumbite-type (M-type) hexagonal ferrite such as $SrFe_{12}O_{19}$, in which there are five crystallographically inequivalent Fe sites. It is now well known that the substitution of small amount of Co for Fe enhances the uniaxial anisotropy and magnetization, and hence the magnetic performance as a hard magnet. The anisotropy field is increased almost linearly with the Co content at least up to the Co:Fe fraction of 1:11 [1]. It has also been established that, in general, Co atoms occupy more than one Fe sites in the M-type structure. In this presentation, we will show that, based on the result of ^{59}Co-NMR measured fo La-Co co-substitited strontium ferrite [2], only Co atoms substituted at the tetrahedrally coordinated $4f_1$ site contribute to the enhancement in the uniaxial anisotropy and that the Co site selectivity can be improved, possibly, by uniaxial chemical pressure along the c axis although the Co orbital moment, which is responsible for the anisotropy enhancement, is reduced slightly with applying the uniaxial pressure. In other words, the improvement of the Co site selectivity covers the slight deterioration of the local anisotropy of $4f_1$-Co. These observations indicate further potential of the Co-doped ferrite magnet with controled Co content and tell us the guiding principle to develop the higher-performance ferrite magnet for future generation.

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O133 - Heat Capacity and Magnetocaloric Effect in (Eu,Sr)VO2H

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

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In compounds of transition elements (T) and rare earths (R), usually the magnetic exchange constants vary in the order J(T-T) >> J(R-T) > J(R-R). In such cases the R-T exchange acts as an external field on the R atoms. This effective field produces an interesting effect of enhancement of the magnetocaloric effect, which is high over a wide temperature range in $GdCrO_4$ [1]. On the other hand, the oxi-hydride $EuVO_2H$ is a novel compound made of Eu^{2+}, V^{3+}, O^{2-} and H^-, with a crystal structure of distorted perovskite, *P4/mmm*, Z =1, a = 3.934(1) Å, c = 3.667(1) Å, with H^- replacing one O^{2-} in the ideal perovskite. Eu^{2+} has the same electronic configuration than Gd^{3+}, ground manifold L = 0, S = 7/2, J = S, with a negligible anisotropy. We present here measurements of heat capacity at constant magnetic fields of 0, 0.5, 1, 3, 5, 7, and 9 T for $EuVO_2H$ and $Eu_{0.95}Sr_{0.05}VO_2H$ (See Figure). V^{3+} orders antiferromagnetically above room temperature. Eu^{2+} orders ferromagnetically at T_C = 9.5 K and 8.9 K, respectively. The entropy content of the anomalies is $\Delta S_{an}/R$ = 1.59 and 1.20, respectively, in both cases below the theoretical values, ln8 = 2.08 and 0.95*ln8 = 1.98, for the spin-only Eu^{2+} ion. This smaller entropy can be qualitatively explained by a mean-field model. Acording to it, Eu^{2+} would be partially polarized above 10 K by the staggered effective exchange field produced by the V^{3+} ions. Below T_C the R-R exchange would order ferromagnetically the perpendicular components, reaching finally a non-collinear configuration. The magnetocaloric effect is high, reaching the values - ΔS_T = 37.5 $Jkg^{-1}K^{-1}$ and 31.4 $Jkg^{-1}K^{-1}$, respectively, at 10 K for a magnetic field of 9 T, and - ΔS_T > 20 $Jkg^{-1}K^{-1}$ in the temperature range 5 K < T < 30 K. This makes them very interesting materials for cryogenics, using adiabatic demagnetization.

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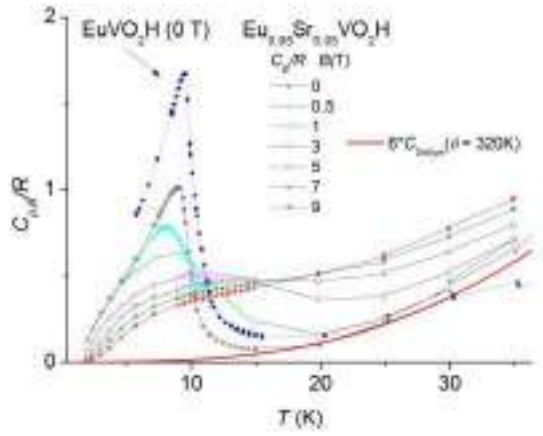

O134 - Identifying new hard magnetic ThMn12 phase from ab initio investigations

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

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Turning towards environmental friendly technologies such as collecting energy from renewable resources e.g. with wind power plants, or using electric transportation and magnetic cooling is accompanied by an increasing demand for materials suitable for permanent magnets. Today nearly all high performance magnets are based on $Nd_2Fe_{14}B$ which for practical applications also contains some Dy. To meet the need not only more permanent magnets are needed but new materials should have a smaller environmental footprint. Fe rich phases with the tetragonal $ThMn_{12}$structure have moved back in the focus since they contain about 35% less RE than the commercially used Nd-Fe-B compounds. However, the binary phase does not form for any RE in case of Fe and some nonmagnetic additions Z are needed, i.e. $REFe_{12-x}Z_x$, which might reduce the magnetic performance.

Here, we present a systematic first principles study of $REFe_{12-x}Z_x$with RE = Nd, Y, Ce, Sm and different phase stabilizing elements like Z = Ti, V, Mo aiming to tune the magnetic performance towards large magnetocrystalline anisotropy and high Curie temperatures. The systems were characterized using a combination of different state of the art first principles methods (VASP [1], RSPt [2]).

The phase stability and the magnetic properties were calculated depending on the Ti, Mo, and V concentration. Aiming to minimize the phase stabilizing element and such improve the magnetization. In addition, reduction of RE was envisaged and the effect of the non-rare earth element Y was extensively studied for $(Nd_{1-z}Y_z)Fe_{12-x}Z_x$systems.

We find that the Nd-Y (Sm) system is stable in a large composition range. In case of $(NdY)Fe_{12-x}Ti_x$the systems were found stable for x larger or equal to 0.5, see Fig. 1 (for Nd). $SmFe_{12-x}V_x$the V concentration could be reduced from x = 2 to 1 which led to an increase of the magnetization by 17% compared to the commonly used concentrations of V. In view of the MAE a replacement of Nd by Y turned out to be preferable over a reduction of Ti. A uniaxial MAE of 1.3 MJ/m^3 ($(NdY)Fe_{11}Ti$) and 1.7 MJ/m^3 ($SmFe_{11}V$) [3] are predicted. The latter could be verified in recent experiments.

This work is supported by the European Research Project NOVAMAG (EU686056) and the Swedish Foundation for Strategic Research (SSF).

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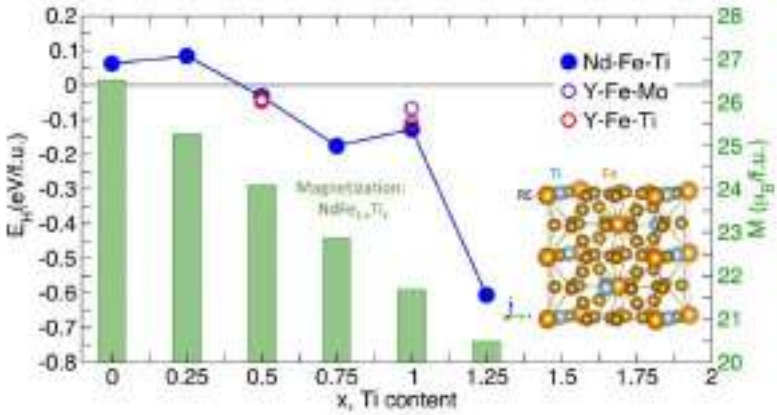

Figure 1: Calculated heat of formation of $RFe_{12-x}Ti_x$ (circles). Bars denote the magnetic moment of $RFe_{12-x}Ti_x$ per formula unit.

O135 - Magnetocaloric effect in magnetic shape memory alloys: experiment and theory

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

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The Heusler-type magnetic shape memory alloys (SMAs) can be tentatively divided into two groups: metamagnetic and ferromagnetic. The metamagnetic SMAs (MetaMSMAs), typically Ni-Mn-X (X=Sn, In, Sb), exhibit the conventional magnetocaloric effect (MCE) near the Curie temperature and inverse giant MCE in the temperature range of magnetostructural phase transformation. The ferromagnetic SMAs (FSMAs), typically based on Ni-Mn-Ga, exhibit a conventional MCE near the Curie temperature of austenite and giant MCE in the temperature range of martensitic transformation (MT) merged with the phase transition from paramagnetic austenite to ferromagnetic martensite.
The brief overview of experimental research on MCE in both Heusler-type MetaMSMAs and FSMAs will be presented with the emphasis on the results obtained by the direct measurements of MCE using a magneto-thermal techniques, such as the adiabatic one and/or method of heat capacity measurements under magnetic field. In addition, we will restrict ourselves to the MCE measurements made under the field achievable in the permanent magnet systems.
The Landau theory of martensitic-type magnetostructural transformations exhibited by magnetic SMAs is used for the quantitative description of giant MCE and heat capacity of shape memory alloys. The difference between this approach to theoretical description of giant MCE and orthodox thermodynamic theory of MCE is discussed.

O136 - Micromagnetic simulation of surface anisotropy effects in SmFe_12 type permanent magnets

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

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Ab-initio simulations of $SmFe_{12}$ show that Sm ions on (100) surfaces can be seriously anomalous. From the calculated free energy of the surface unit cell we estimated the surface anisotropy constant to be K_s = 2.67 mJ/m^2 favoring out-of-plane magnetization on the four side surfaces of the considered cubical model. For the computations we added a surface anisotropy term to the total energy in our micromagnetic solver [1]. The associated energy density is $e_s = K_s(1-(\mathbf{n}\cdot\mathbf{m})^2)$, where K_s is the surface anisotropy constant, **n** is the normal vector to the grain surface, and **m** is the unit vector of the magnetization [2].
In order to study the influence of surface anisotropy on magnetization reversal, we compared four different simulation runs for a cubic grain: The coercive field as a function of grain size
(i) without demagnetizing field and without surface anisotropy;
(ii) with demagnetizing field but without surface anisotropy;
(iii) without demagnetizing field but with surface anisotropy;
(iv) with demagnetizing field and with surface anisotropy.
Case (i) gives the Stoner-Wohlfarth switching field with one-degree misalignment. In case (ii) the coercive field decreases monotonically with particle size owing to demagnetizing effects. Without demagnetizing fields but with surface anisotropy, case (iii), the coercive field decreases with decreasing grain size as the surface to volume ratio increases. Consequently, for case (iv), in which both demagnetizing effects and surface anisotropy are considered, we expect a maximum of the coercive field as function of grain size where reduction due to surface anisotropy gets negligible but reduction due to grain size is still small.
For $SmFe_{12}$ (bulk anisotropy constant K_u = 2.81 MJ/m^3) the maximum coercive field is found for a grain size of around 20 nm when both demagnetizing effects and surface anisotropy are considered. At a grain size of 120 nm the coercive field for $SmFe_{12}$ is $\mu_0 H_c$ = 4.9 T for case (ii). In case (iv) the surface anisotropy reduces the coercive field by 20 percent to $\mu_0 H_c$ = 3.9 T. Demagnetizing effects cause the nucleation of reversed domains near corners or edges. In $SmFe_{12}$ surface anisotropy favors out-of-plane rotation of the magnetization at the same spots. Consequently, the surface anisotropy term reduces coercivity significantly even for larger grains.
Work supported by the NOVAMAG project (EU H2020, Grant Agreement No. 686056) 2020.

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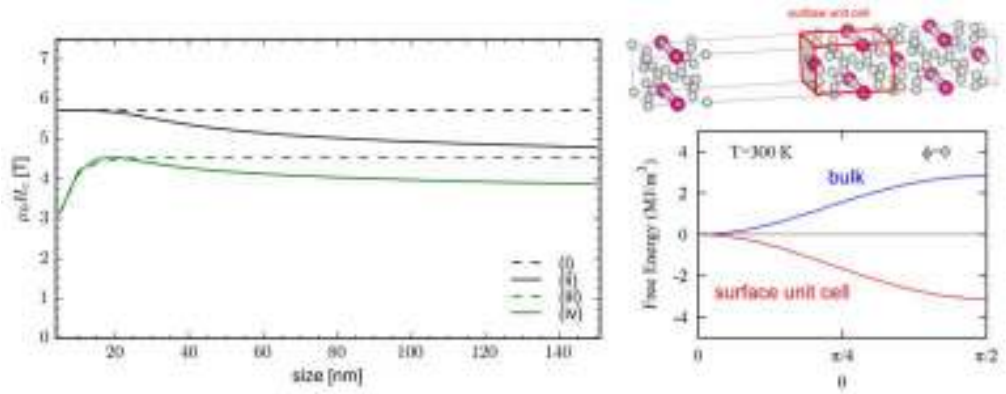

LHS: Coercive field of a $SmFe_{12}$ cube as a function of size. Dashed lines: no demagnetizing effect, solid lines: with demagnetizing field. Black: no surface anisotropy, green: K_s = 2.67 mJ/m^2. *RHS top:* Supercell used for ab-initio calculations. *RHS bottom:* Free energy as function of the magnetization angle.

O137 - Ni45Co5Mn(37-x)In(13+x) Alloy Magnetic Properties

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

Mohammadreza Ghahremani[1, 2] , *Amir Aslani*[2], *Marjan Hosseinnia*[3]

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[2] George Washington University

[3] Notre Dame of Maryland University

The use of Maxwell equations to calculate the entropy change (ΔS) in materials that have a first-order phase transition (FOPT) has been questioned as they are only valid at thermal equilibrium. Though, it has been recently shown that this artifact can be minimized after using the appropriate protocol for the measurements.

The hysteresis losses and magnetocaloric effect of $Ni_{45}Co_5Mn_{(37-x)}In_{(13+x)}$ alloy have been studied in this work. The ingots were prepared by vacuum arc melting technique under an argon atmosphere and were annealed at 900 C for 24 h followed by water quenching.

To study the magnetocaloric effect of $Ni_{45}Co_5Mn_{(37-x)}In_{(13+x)}$ alloy family (x=0, 0.4) the isofield temperature-dependent magnetization curves, M(T), were derived from isothermal magnetization loops for both ascending and descending magnetic fields, and the entropy changes (ΔS) were derived and are shown in Fig. 1.

This figure reveals three distinct results as follow. Firstly, for $Ni_{45}Co_5Mn_{37}In_{13}$ sample, the peak of the entropy change curve under 5 T applied field occurs at 308 K in the descending curve and at 314 K in the ascending curve, whereas for the 1.5 T filed these peaks happen at 318 K and 320 K, respectively. This emphasizes the fact that the variation of the maximum applied magnetic field within same stoichiometry composition can very well change the critical temperature at which the peak of the entropy change curves occur. So when synthesizing the magnetocaloric materials, one should consider the maximum applied a magnetic field in which the magnetic refrigeration system will be operational.

Secondly, even a small change in the stoichiometry composition of a material can significantly change the material's critical temperatures. As shown in Fig. 1 the critical temperature of the $Ni_{45}Co_5Mn_{36.6}In_{13.4}$ has been shifted by about 36 K to lower temperatures compared to the $Ni_{45}Co_5Mn_{37}In_{13}$. This suggests that material with high MCE at temperatures out of room temperature can be customized by changing their stoichiometry in order to shift their high MCE toward desirable temperatures. This is promising especially in finding suitable refrigerants for room temperature magnetic refrigeration systems.

Thirdly, it is observed that the entropy change curves of $Ni_{45}Co_5Mn_{36.6}In_{13.4}$ are broader than the ones for $Ni_{45}Co_5Mn_{37}In_{13}$. Relative cooling power (RCP) is given by, where ΔS_M is the refrigerant's isothermal magnetic entropy change and δT_{FWHM} is the full-width-at-half-maximum of the peak of magnetic entropy. Therefore, the RCP of the $Ni_{45}Co_5Mn_{36.6}In_{13.4}$ sample is higher than the one for $Ni_{45}Co_5Mn_{37}In_{13}$ sample. This leads to obtaining a higher refrigeration capacity in a magnetic refrigeration system.

In summary, the results of this research are very promising in synthesizing high-performance magnetocaloric materials that can be used to develop practical room temperature magnetic refrigeration systems.

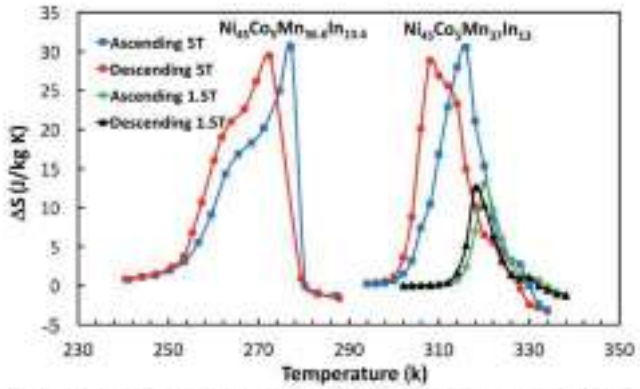

Figure 1: The entropy change of $Ni_{45}Co_5Mn_{37}In_{13}$ under 1.5 T and 5 T. The measurements for $Ni_{45}Co_5Mn_{37}In_{13}$ were performed during heating process under 1.5 T and cooling process under 5 T. For the $Ni_{45}Co_5Mn_{36.4}In_{13.6}$ sample measurement was performed during cooling process under 5 T.

O138 - Novel in situ powder neutron diffraction setups – The creation of a modern magnetic compound

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

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In order to take full advantage of the significantly increased data collection rates expected at the European Spallation Source (ESS), it is paramount that new sample environments are developed to match the performance of the coming instruments. Here, we present two newly developed sample environments for neutron powder diffraction:

1. A single crystal **S**apphire **A**ir gun **H**eater **S**etup (SAHS), specially designed for solid-gas *in situ* angular dispersive neutron powder diffraction, has been developed [1](Fig 1.1 and 1.2). Heating is provided by an air gun heater, allowing the sample to reach temperatures of up to 700°C within less than 5 minutes. The setup is based on a single crystal sapphire tube, which offers a very low and smooth background. The setup has been used to follow the creation of the spring-exchanged magnetic composite $CoFe_2O_4/CoFe_2$ made by reducing $CoFe_2O_4$ under a flow of hydrogen gas

2. An induction furnace has been developed in a collaboration with: Chalmers University in Sweden, ISIS at the Rutherford Appleton Laboratory in England, the ESS in Sweden and Aarhus University in Denmark (Fig 1.3, 1.4 and 1.5). A fully functioning prototype has been built for the Time of Flight (ToF) diffractometer POLARIS at ISIS and will lead to a second version for the diffractometer/Small Angle Neutron Scattering (SANS) instrument HEIMDAHL at the ESS. The heating is based on an induction element, which allows an extremely fast and efficient way of heating and can reach temperatures of up to 1600 °C in less than 5 minutes. Furthermore, the setup works both in vacuum and under ambient conditions and requires no heat shielding, thus reducing the beam attenuation and lowering the level of background scattering. Both setups offer: high temperatures, fast temperature stability, large sample volumes, and offer a very low attenuation of the beam. The setups have proven to be ideal for carrying out investigations of advanced magnetic materials under realistic conditions. The ability to investigate real materials, in real time under realistic conditions, is a huge advantage for scientific investigations as well as for industrial applications.

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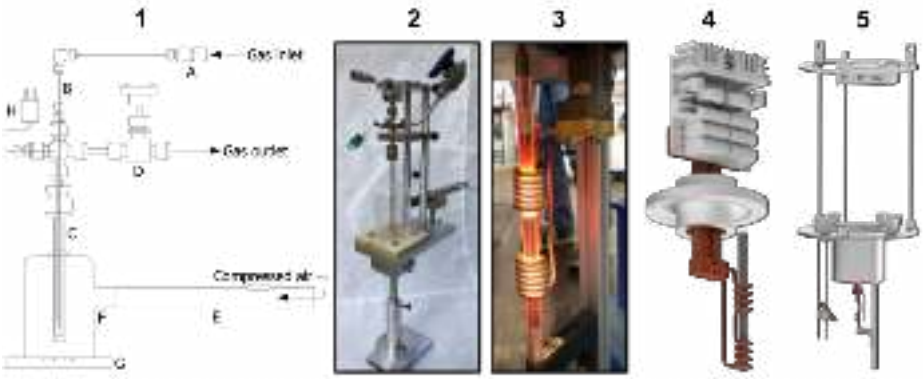

Fig. 1.1-2: Schematic and picture of the SAHS. Gas flows through the system in the following order: A Quick fit connector, B Fused silica tube, C SCS sample container, D Outlet valve. The heater airflow goes through. E Hi Heater airgun, F Heat confinement quartz dome, G Ceramic insulator with air outlet grooves. H Thermocouple. **Fig 1.3-4:** The induction furnace heat element. **Fig 1.5** The full induction furnace setup.

O139 - Particle-based simulation and experimental validation of magnetic-aligned compaction process

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

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Magnetic-aligned compaction process is one of the important process in maximizing the magnetization of the sintered magnet. In this process, the raw permanent magnetic powder is filled in a die and compacted while applying a magnetic field to produce a crystal oriented green compact having a high degree of orientation. However, when using a newly developed high-performance magnetic powder, even if the orientation process using an electromagnet that is widely used at present, it is difficult to produce a green compact having a high degree of orientation. This is attributed to the fact that the frictional force works strongly due to the miniaturization of the particles, the magnetic field that can be applied by the electromagnet is limited to 2 T or less, and the observation of the orientation behavior is difficult. In this study, we focused on the pulsed magnetic field generated by the air core coil, which can apply a stronger magnetic field than the electromagnet. In order to observe the magnetic aligned compaction process using a pulsed high magnetic field, a new simulation model based on the particle method was developed. Using the developed simulation model, we analyzed the magnetic aligned compaction process and the reliability of the simulation was verified by comparing with the experimental results.

The discrete element method (DEM) [1)] was used to analyze the motion of the magnetic powder in the compaction process. DEM can track individual particle motion in consideration of contact force and friction force acting between particles. In order to analyze the motion of permanent magnetic particles in a magnetic field, DEM is extended to take into account the magnetocrystalline anisotropy and the magnetic hysteresis [2)].

Fig.1 shows an example of simulation results of powder compaction in a magnetic field. From the simulation results, it was confirmed that the particles were aligned in the same direction of the magnetic field. Simulation was performed by changing the application timing of pulsed-magnetic field and compaction pressure, the degree of orientation significantly changed. The tendency of the degree of orientation obtained from the simulation results is consistent with the experimental results.

In conclusion, we have developed a new simulation method that can analyze magnetic-aligned compaction in a pulsed-magnetic field. As a result of comparing the degree of orientation under various conditions, simulation results were good agreement with experimental results.

Acknowledgment

This paper is based on results obtained from the future pioneering program "Development of magnetic material technology for high-efficiency motors" commissioned by the New Energy and Industrial Technology Development Organization.

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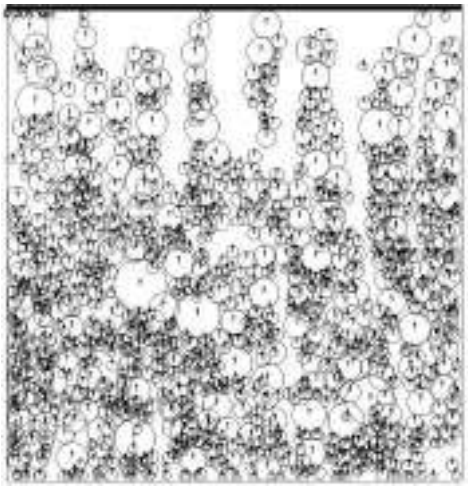

O140 - Relationship between crystal grain size of Sm2Fe17 and magnetic properties of Sm2Fe17N3 powders

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

Nobuyoshi Imaoka[1, 2] , *Kimihiro Ozaki*[1]

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[2] Asahi Kasei Corporation

$Sm_2Fe_{17}N_3$ compounds are good candidates for high-performance magnets because of their high saturation magnetization and strong uniaxial anisotropy field. Furthermore, in comparison with conventional powders, $Sm_2Fe_{17}N_3$ powders have recently been reported to exhibit a high coercivity value of 24.7 kOe [1]. This result allows the potential application of these materials to bonded as well as bulk magnets. We wish to emphasize that uniform nitrogenation is of key importance in achieving high-performance $Sm_2Fe_{17}N_3$ magnets. In the present work, we investigate the relationship between the crystal grain size of Sm_2Fe_{17} host alloy and the magnetic properties of its nitrogenated compound, $Sm_2Fe_{17}N_3$, to obtain a more uniform nitrogenation. The host alloy, Sm_2Fe_{17}, with 3 mm thickness, was produced by induction melting and annealing at temperatures of 940, 1095, and 1255 °C for 0.5 to 32 h under an argon atmosphere. The microstructure of a polished cross section of Sm_2Fe_{17} was observed by electron probe micro analysis. The crystal grain size was estimated by observation of the polished cross section etched with nital solution using an optical microscope. The melting Sm_2Fe_{17} binary alloy slowly cooled through the peritectic temperature and separated into three phases: α-Fe, Sm_2Fe_{17}, and Sm-rich phases. Fig. 1 shows the annealing time (t) dependence of the average crystal grain size (d) of the Sm_2Fe_{17} host alloys. In the area above the dashed line, the α-Fe phase completely disappeared due to the reaction of the α-Fe and Sm-rich phase. The disappearance time of α-Fe at 940 °C was 24 h, which was longer than the disappearance time of 1 and 2 h at 1095 and 1255 °C, respectively. This observation was attributed to the annealing temperature being lower than the melting temperature (1010 °C) of the Sm-rich (i.e. almost $SmFe_3$) boundary phase. The grain growth is described by the equation: $(d/dt)d = k/d$, where k is a constant. Integration of this formula considering $d = d_0$ when $t = 0$ gives the equation: $d^2 - d_0^2 = 2kt$. From this formula, the slope a of the linear line in the double logarithmic plot in Fig. 1 is determined as 0.5. By excluding the effect of d_0 from a, the values of a become 0.35, 0.42 and 0.43 at 940, 1095, and 1255 °C, respectively. We determine that solid-state Sm-rich phases during annealing inhibit the grain growth of Sm_2Fe_{17}. The hard magnetic material demonstrates increasing coercivity with decreasing crystal grain size down to a critical limit. Therefore, annealing at a lower temperature (<1010 °C) is desirable for the fabrication of Sm_2Fe_{17} host alloy, particularly by a reduction-diffusion method [1] for nanoparticles. We also report the relationship between the d of the Sm_2Fe_{17} host alloys and magnetic properties of $Sm_2Fe_{17}N_3$ powder (3 μm particle size) compacts. The coercivity, remanence, and maximum energy product values for the $Sm_2Fe_{17}N_3$ powder compacts monotonically increased with decreasing crystal grain size of the host alloys.

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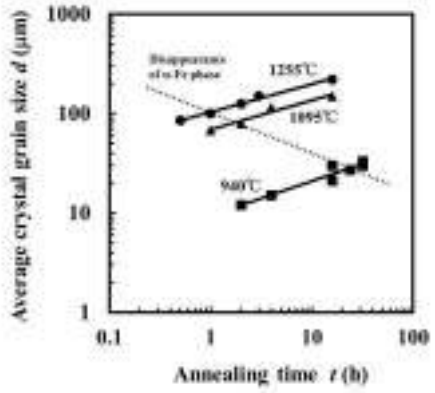

Fig. 1 Annealing time dependence of average crystal grain size of Sm_2Fe_{17} host alloys.

O141 - Role of hydrogen on the vibrational and magnetic properties of magnetocaloric LaFe_13−x Si_x H_y

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

Heiko Wende[1] , *Alexandra Terwey[1], Werner Keune[1], Joachim Landers[1], Soma Salamon[1], Benedikt Eggert[1], Katharina Ollefs[1], Valentin Brabänder[2], Iliya Radulov[2], Konstantin Skokov[2], Jiyong Zhao[3], Michael Y. Hu[3], Thomas S. Toellner[3], Ercan E. Alp[3], Carlotta Giacobbe[4], Oliver Gutfleisch[2], Markus E. Gruner[1]*

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$LaFe_{13-x}Si_x$ is one of the most promising candidates for magnetic refrigeration applications [1,2]. Its favorable first-order magnetic transition is connected to the itinerant electron metamagnetism of Fe, while loading with hydrogen allows to shift T_C to ambient conditions. Here we report on the impact of hydrogenation on the magnetoelastic coupling and on the magnetocaloric properties of $LaFe_{11.4}Si_{1.6}H_{1.6}$. This is carried out by analyzing the vibrational (phonon) density of states, VDOS, which we determined by ^{57}Fe nuclear resonant inelastic X-ray scattering (NRIXS) measurements [3-5] accompanied by density-functional theory (DFT)-based first-principles calculations (model see figure) in the ferromagnetic low-temperature and paramagnetic high-temperature phase. In experiments and calculations, we observe clear differences in the shape of the Fe-partial VDOS comparing the non-hydrogenated [3,4,5] and the hydrogenated samples. This shows that hydrogen does not only shift the temperature of the first-order phase transition, but also affects the elastic response of the Fe-subsystem signicantly. Our DFT calculations reveal that hydrogen strongly disfavors the presence of Si close to the interstitial sites. The combination of NRIXS and DFT we identify adiabatic electron-phonon coupling as the microscopic mechanism causing the cooperative interplay between electronic, magnetic and vibrational degrees of freedom in $LaFe_{13-x}Si_xH_y$. In addition, we discuss the impact of interstitial hydrogen on the magnetic interactions between the different Fe sites and give an oulook on the impact of a partial substitution of Fe with other transition metals on the vibrational properties. Funding by the DFG within SPP 1599 is gratefully acknowledged.

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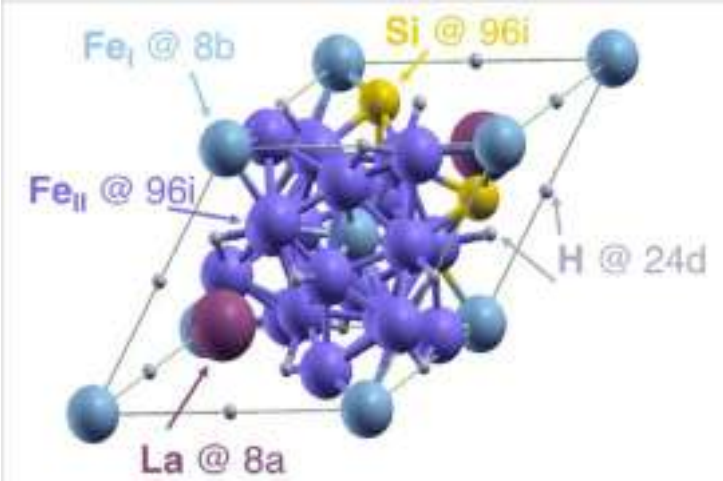

O142 - Spin Dynamics in the Mn5-xFexSi3 Series and its Significance for the Magnetocaloric Effect

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

Nikolaos Biniskos[1, 2] , *Karin Schmalzl[1], Stephane Raymond[2], Jörg Voigt[3], Karen Friese[3], Jörg Perßon[3],* ***Thomas Brückel***[3]

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Due to potential energy savings for room temperature applications, the magnetocaloric effect (MCE) has attracted increasing interest in the past years. We have performed extensive studies of structure, magnetism, magnetocaloric effect and spin dynamics in the $Mn_{5-x}Fe_xSi_3$ series of compounds [1-5]. While the magnetocaloric effect is moderate for these compounds, they are composed of abundant and non-toxic elements and can be grown as large single crystals. This allows us to perform inelastic neutron scattering studies of the spin and lattice dynamics thus giving insight into the microscopic mechanism of the MCE.

$MnFe_4Si_3$ has a phase transition from a paramagnetic to a ferromagnetically ordered phase at approximately T_C = 305 K and displays a strong anisotropy of the magnetization and the magnetocaloric effect. The anisotropy of the macroscopic properties is reflected in the anisotropy of the magnetic exchange interactions as determined by spin-wave measurements. The spin-wave stiffness amounts to $D_{(h00)}$=30(4) meVÅ^2 and $D_{(00l)}$=310(30) meVÅ^2 for the in-plane and out-of-plane magnon branches, respectively. As far as the MCE is concerned, the magnetic entropy change at 300 K amounts to about 3 J/kg·K for a field change of 2T along the a-axis. In such a field the critical fluctuations in the paramagnetic state close to T_C can be nearly completely suppressed. This strong response is an important feature connected to the MCE effect [4].

The compound Mn_5Si_3 exhibits an inverse magnetocaloric effect at the phase transition between a non-collinear low temperature antiferromagnetic phase AFM1 and the collinear antiferromagnetic phase AFM2 at T_{N1}=66K. Inelastic neutron scattering reveals that the higher temperature AFM2 phase has a very unusual magnetic excitation spectrum where propagating spin waves coexist with diffuse spin fluctuations. Thus, contrary to the intuitively expected behavior, the application of a magnetic field can induce additional spin fluctuations giving rise to an increase of the magnetic entropy. This mechanism provides a microscopic explanation of the inverse magnetocaloric effect [5].

In summary, our neutron spectroscopy studies demonstrate how the need to design functional materials for magnetic refrigeration connects with a fundamental understanding of magnetism.

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O143 - SPS-processed anisotropic permanent magnets prepared from rare-earth-lean jet-milled NdFeB powders

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

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Over the past few decades, NdFeB permanent magnets have become essential components of a variety of energy-conversion devices, such as electric motors and generators. For a number of applications, sintered NdFeB magnets produced from highly anisotropic jet-milled powders are commonly used. Such magnets offer the highest maximum energy product ($(BH)_{max}$), a convenient figure of merit for assessing the material's magnetic performance. Most often, simple brick-shaped sintered magnets are employed, although a more complex magnet design can substantially boost the performance and at the same time improve the device's compactness. Due to the material waste and limited design options, post-sintering machining of the initial sintered blocks to produce more complex-shaped magnets is an economically unattractive option. Consequently, tailoring and optimizing the shape of the sintered magnets has so far not been fully explored as a viable approach to improve the efficiency of high-performance electric devices.

In contrast to the conventional production techniques, Spark Plasma Sintering (SPS) was shown to have a high potential for the manufacture of complex and net-shaped dense sintered bodies without significant material waste. The SPS approach has already been successfully adapted for the manufacture of dense bulk NdFeB magnets from several types of NdFeB powders, including melt-spun, HDDR-processed and gas-atomized. In addition, anisotropic magnets with high $(BH)_{max}$ values have been produced by SPS processing of melt-spun powders followed by hot deformation, but the process is not applicable for the manufacture of complex geometries since the final magnetic properties depend on the degree of deformation. Until now, SPS processing of jet-milled powders has only been reported for compositions containing approximately 35 wt. % of total rare earths (RE). To reach high $(BH)_{max}$ values and at the same time render the technique more cost-competitive and resource-efficient, alloy compositions with lower RE content (around 30 wt. %) are desired.

For these reasons, we studied the effect of the SPS-specific sintering mechanisms on the microstructure and magnetic properties of bulk magnets, prepared from a jet-milled NdFeB powder with a RE-lean composition (29.7 wt. %). The SPS specimens' densities were mostly governed by the peak temperature reached during the relatively short powder-consolidation process. On the other hand, the microstructure development was related to several factors, most notably the sintering kinetics. Further post-SPS thermal treatment was found to be prerequisite for achieving favourable phase distribution, necessary for the development of hard magnetic properties. By carefully optimizing the SPS powder consolidation parameters and post-SPS heat-treatment regime, the $(BH)_{max}$ achieved ($\approx$ 250 kJ/m^3) was comparable to the values of conventionally sintered magnets prepared from the same jet-milled NdFeB powder.

O144 - Study of the high-coercivity of the Al and Cr doped Strontium hexaferrites

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

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We present a study on the origin of the magnetic properties of Al and Cr doped Sr hexaferrites. M- type hexaferrites are the most employed rare-earth free ceramics in the permanent magnet industry. Due to the recent interest in the development of rare-earth free magnets, an intense research activity has been performed to improve the magnetic properties of M- type hexaferrites. A promising route is the incorporation of non-magnetic and magnetic ions in the ferrimagnetic M-type structure in such a way to increase the total magnetization and/or the coercive field (H_c). Particularly, several groups [1-3] have investigated the Al doping of Ba or Sr M-type hexaferrites ((Ba)$SrFe_{12}O_{19}$) that exhibit higher Hc than the un-doped oxides. Moreover, the substitution of Ca with Sr leads to very high coercive field up to 2 T, albeit with reduced magnetization saturation (M_s) of 12.9 emu/g [3]. Hence, the further aim is the increase of the magnetization of these doped oxides.

In this research, we present a structural and magnetic study of Al doped SFO powders prepared by sol-gel route where part of the diamagnetic Al^{3+} ion are replaced by Cr^{3+}, ($Sr_{0.67}Ca_{0.33}Fe_9Al_{3-x}Cr_xO_{19}$ (x = 0 - 3)). High resolution powder X-ray diffraction measurements and Rietveld refinement show mostly single phase magneto-plumbite structure with small amounts of hematite and a continuous change of the lattice parameters and site occupancy with the doping with Cr. The structural analysis demonstrates the strong affinity of Al cations for the 2a and 12k sites, the Fe occupancy in the 2b and 4f1 and 4f2 sites, remaining almost unaltered. On the other hand, magnetic measurements show that the doping with Al and Cr gives rise to opposite effects: the doping with Al (Cr) increases (decreases) the coercive field while the M_s and the Curie temperature decreases (increases). The highest value of H_c = 1.4 T is obtained for $Sr_{0.67}Ca_{0.33}Fe_9Al_{2.5}Cr_{0.5}O_{19}$ with a M_s of 24 emu/g. Even if the doping induces changes of these properties, the reversal processes of all the oxides appear very similar: the shape of the loops and the remanence to saturation value (0.5) remain almost constant through the series. The temperature dependence of the magnetic properties and Singular Point Detection measurements [4] have been performed to deeply analyze the reversal process and to quantify the magnetic anisotropy. The correlation of the overall magnetic and structural properties allows concluding that the single-ion anisotropy of the M-type hexaferrites is weakly affected by the Al and Cr doping.

This research was supported by EU- H2020 AMPHIBIAN Project (H2020-NMBP-2016-720853).

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O146 - The Effect of Disproportionation Conditions on the Hydrogen Ductilisation Process for NdFeB Alloys

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

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Hydrogen has been shown to be a very effective tool in the processing of both sintered and HDDR bonded NdFeB-type magnets. Recently, the authors have proposed a new processing technique utilising the high temperature solid-Hydrogenation-Disproportionation (s-HD) reaction to produce a ductile mixture of α-Fe, NdH_2 and Fe_2B. It has been shown that, this mixture can be deformed at room temperature and recombined, under vacuum at elevated temperatures, to form a submicron $Nd_2Fe_{14}B$ grain structure, with a degree of anisotropy relative to the applied load. This process has been termed the “Hydrogen Ductilisation Process HyDP” [1].
However, it was shown that HyDP had several limitations which may be improved upon such as the degree of ductility, which in previous works was reduced by the presence of the minority $NdFe_4B_4$ phase [2, 3]. Cavitation was also shown to occur in the recombined microstructure, caused by redistribution of the Nd-rich phase during recombination [4], which will affect the density, remanence and coercivity of the final magnet.
It has been shown in this work that variations in composition and disproportionation conditions can significantly affect the ductility of s-HD NdFeB alloys and subsequently the recombined magnetic properties of HyDP material. It has been observed that, it is possible to remove the undesirable $NdFe_4B_4$ phase through compositional changes, improving the ductile behaviour. Furthermore, the disproportionation conditions used in the previous studies [1, 2] may be modified to significantly reduce the time required for complete disproportionation whilst also increasing the fine lamella structure required for high coercivity.

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O147 - The influence of anti-phase boundary on the extrinsic magnetic properties of MnAl

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

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MnAl has attracted a considerable interest since the discovery of the ferromagnetic MnAl τ-phase [1,2]. With an estimated upper limit energy product $(BH)_{max}$ of 120kJ/m^3 and a low cost of needed raw materials, it could fill the niche between high-performance rare-earth permanent magnets (PMs) and general purpose ferrites [3]. In practice, the maximum energy product of a magnetic material is affected by its microstructure and various structural defects may drastically reduce the coercivity and energy product of a PM. The MnAl τ-phase exhibits, mainly, two types of defects: anti-phase boundaries (APBs) [4] and twins [5]. We performed a multi-scale study of the extrinsic magnetic properties of the MnAl τ-phase with APB defects [6]. The intrinsic magnetic properties are predicted by performing ab-inito electronic structure calculations. Within the supercell approach we quantify for the first time the exchange interaction strength across the antiphase boundary. The effect of temperature on intrinsic magnetic properties is studied by performing atomistic spin dynamics (ASD) simulations. Within the ASD approach we also study the influence of the APB on the nucleation and depining processes of a domain wall (DW). Finally, the extrinsic magnetic properties of a realistic PM model are estimated via micromagnetic simulations. The calculated exchange interaction at the APB of the MnAl τ-phase is strong enough to form an APB decorated with a domain wall, as it is always observed in experiments. The micromagnetic simulations show that ABPs deteriorate the magnetization loop shape through nucleation of reversed domains at very low applied field values. The energy density product decreases with increasing the number of antiphase boundaries and calculated values are in good agreement with experimental observations.

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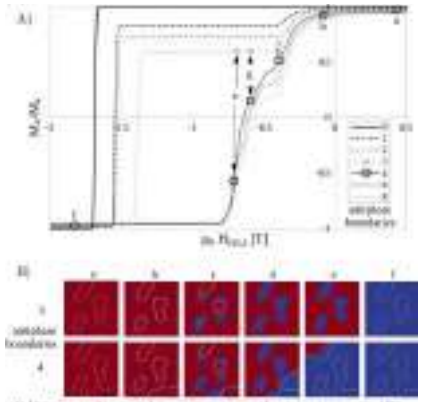

O148 - The Practical Energy Product of Cylindrical Core/shell Composed of Soft- and Hard-magnetic Materials

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

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The author has chosen not to publicise the abstract.

Field 5

Field 6

O150 - Tuning the magnetocaloric effect on Mn3Cu1-yMyN1-xCx (M=Ag, Ni) compounds

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

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Refrigeration based on the magnetocaloric effect (MCE) is a promising, environmentally friendly and efficient alternative to the conventional gas-compression technology. Although the search and development of materials focuses on the largest niche, consisting of room temperature applications, wide temperature span applications such as gas liquefaction may greatly benefit from the easy tunability of the MCE in magnetocaloric materials.
Mn_3CuN is a transition metal based antiperovskite material which undergoes a first order magneto-structural phase transition from a low temperature tetragonal ferrimagnetic phase to a high temperature cubic paramagnetic phase at around 143 K. Although first order, the volume of the cell is nearly conserved through the transition, resulting in low thermal hysteresis. This transition yields a moderate giant MCE of 13.52 J/kgK for a 5 T magnetic field change[1] with very low hysteresis losses upon cycling, a very attractive property for applications.
However, for applications, it is also desirable to tune the phase transition temperature and the resulting MCE over a wider temperature range through substitutions and interstitials. In this work we report on the magnetic and structural properties of antiperovskite materials based on Mn_3CuN with N substituted by C[2] as well as Cu partially replaced by Ag and Ni and simultaneous substitution of N by C[3].
Moderate tuning is achieved between 130 and 165 K both for pure C substitution and simultaneous C and Ag or Ni substitutions. Pure C substitution preserves both the character of the magnetostructural phase transition and the low thermal hysteresis. Entropy changes as high as 12 J/kgK were observed for a 2 T magnetic field change in $Mn_3CuN_{0.75}C_{0.25}$. Ag or Ni substitution on the Cu site yield lower entropy changes and also change the structural phase transition type. The effect of the different substitutions will be discussed in terms of structural effects (unit cell size) and number of valence electrons.

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O151 - Ultra-high performance Co-Fe-B-Si-Nb amorphous alloys for high-frequency applications

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

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The high-flux density (B_s >1.5 T), high-permeability ($\mu>10^5$), ultra-low coercivity (H_c<1 A/m), and high resistivity (>100 μΩ cm) of amorphous metals makes them a potential soft magnetic material for device miniaturization in high-frequency applications. The single largest example of commercially available amorphous alloys is melt-spun ribbons that have a thickness in the range of 20-30 μm and are used for low-frequency (50-60 Hz) power distribution transformers. However, as the operating frequency (f) of device approaches kHz range, the eddy-current loss ($W_e \alpha f^2$) sharply increases as compared to the hysteresis loss ($W_h \alpha f$) and the total core loss is dominated by W_e at f >100 kHz. The eddy current loss not only deteriorates the performance of magnetic materials but also generates a substantial amount of Joule heating that consequently complicates the design and engineering of the device. Several approaches have been proposed to overcome the challenge of eddy current losses. In this perspective, insulated powder cores fabricated by consolidating amorphous metal powders have gained substantial attention due to tremendous improvement in the material loss performance. However, the drawback of insulated-powder cores is ultra-low permeability (μ=30-50) due to the shape demagnetisation contribution of the spherical particles, which limits the flux concentration advantage of these novel materials. Magnetic cores with ultra-low loss and high permeability are highly-desirable for the miniaturisation of high-frequency drive applications.

Recently, we have demonstrated a rapid quenching approach to synthesise ultra-thin amorphous ribbons of Co-Fe-B-Si-Nb alloy to show the cost-effective advantages of in-situ thinning of ribbons over existing commercial soft magnetic amorphous alloys [1]. In the present work, we present the high-frequency material loss performance compared to existing state-of-the-art soft magnetic materials. The material loss performance and permeability of amorphous ribbons of 5.5-20 μm thickness were investigated over 50 kHz-1 MHz frequency range at various excitation fields using a custom designed solenoid setup. The power loss density (P_V=30 kW/m^3 @ B=10 mT, f=1 MHz) of the ultra-thin as-quenched ribbons was significantly lower (50 %) than the best-known commercial amorphous alloys. The ultra-low loss density of amorphous ribbons could be attributed to the ultra-low coercivity ($H_c \leq$ 5 A/m) and significantly reduced eddy current losses at high frequencies. Besides, the ultra-high permeability (>10^4) of the thin ribbons, as compared to best-in-class amorphous metal cores, makes them a superior material for device miniaturisation in high-frequency drive applications.

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P200 - Extraction and remelting NdFeB magnets from end of life electric vehicle scrap

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

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Neodymium-iron-boron (NdFeB) based magnets are being used in domestic electrical appliances, electric and hybrid automobiles, wind turbines, consumer electronics, and many other small electronic devices. In recent years, the increasing popularity of hybrid and electric cars and wind turbines is causing an increase in the demand for rare earth magnets. Recycling of rare earth elements (REE) from end-of-life products or components can not only provide a sustainable supply for the future but can also minimise environmental impacts associated with REE mining and processing. Previous work has shown that hydrogen can be used to separate NdFeB magnets from hard disk drive scrap [1]. This hydrogenated NdFeB can be directly reprocessed into new sintered magnets with magnetic properties approaching the performance of the original magnets with the addition of NdH_2 [2-3]. This addition of NdH_2 helps the flowability of the grain boundary and hence increases the density which ultimately increases the magnetic properties of the sintered magnets.

In this work, however, an indirect method of recycling the NdFeB alloy has been proposed by melting the hydrogenated NdFeB powder. Melting the alloy gives you more control over the composition. Another advantage of the direct melting is that oxygen and possibly carbon contamination can be separated to the slag phase. In this work, hydrogen was used to extract N42SH grade NdFeB magnets from automotive motor scrap in the form of a hydrogenated powder. This hydrogenated NdFeB powder was then pressed into green compacts and partially degassed to make them stable in the air. Degassing was performed by heating the green compacts in a furnace tube at the rate of 7 ^{o}C/min to 500 ^{o}C and holding it for 1 hour. A batch of 4.5 kg of degassed green compacts was then melted in a vacuum induction furnace and cast into a water-cooled steel mould. The total rare earth composition of the starting magnets, the book mould cast alloy and the dross (residue in the crucible) were determined using ICP. Afterwards, the book mould NdFeB alloy was strip cast. A Jeol JSM-7600F scanning electron microscope (SEM) was used to characterize the book mould and strip cast alloys. The strip cast alloy was then hydrogenated and milled inside an argon-filled glove box using a knife mill. The milled NdFeB was then sealed in isostatic bags, aligned in a 9 T field, iso-statically pressed into green compacts and sintered at 1080 ^{o}C for 1 hour under vacuum (~10^{-5} mbar). These recycled sintered magnets were then compared in terms of magnetic properties, density and microstructure to the starting magnet and directly recycled magnets.

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10. Micromagnetics and magnetization processes

O152 - Coercivity analysis by free energy landscape in the atomistic spin model of Nd-Fe-B magnet

10. Micromagnetics and magnetization processes

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The mechanism of coercivity in polycrystalline permanent magnets is a persistent and challenging problem. Magnetization reversal occurs through the nucleation and growth of magnetic domain. In the strongest magnet $Nd_2Fe_{14}B$, it has been pointed out that the nucleation properties near surfaces/interfaces are essential for the coercivity [1].
The nucleation process is interpreted as the transition from metastable to stable magnetic state. Under thermal fluctuations, this process occurs stochastically and results in the observation time dependence of the coercivity [2]. Additionally, the local magnetic structures near the surfaces/interfaces may affect the nucleation.
To precisely handle the above nucleation properties and evaluate the coercivity, we propose a new approach which is performed by the free energy landscape calculation with atomistic classical Heisenberg model [3,4] based on a Wang-Landau Monte Carlo method. In the presentation, we show how the nucleation and coercivity of $Nd_2Fe_{14}B$ isolated particles are affected by thermal fluctuations at the surface.

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O153 - Effect of inter-layer spin diffusion on skyrmion motion in magnetic multilayers

10. Micromagnetics and magnetization processes

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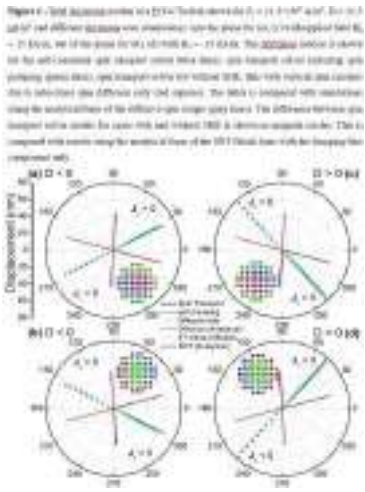
It is well known that skyrmions can be driven using spin-orbit torques due to the spin-Hall effect. Here we show, using micromagnetics modelling coupled with a self-consistent spin transport solver in multilayers, that the spin accumulation generated at the magnetisation gradients of a skyrmion results in additional vertical spin currents due to spin diffusion in adjacent non-magnetic layers. These diffusive spin currents result in additional interfacial spin torques which can be comparable to the spin-orbit torque, significantly reducing the calculated skyrmion Hall angle. This additional interfacial spin torque is similar in form to the in-plane spin transfer torque, but is significantly enhanced in ultra-thin films and acts in the opposite direction to the electron flow. The combination of this diffusive spin torque and the spin-orbit torque results in skyrmion motion which helps to explain the observation of small skyrmion Hall angles even with moderate magnetisation damping values. Further, using the self-consistent spin transport solver we also study the effect of spin-orbit torques and inter-layer spin diffusion in the presence of magnetic defects, as well as topographical surface roughness. In particular surface roughness, as small as a single monolayer variation, is shown to be an important contributing factor in ultra-thin films, resulting in strong confining potentials, and a dependence of the skyrmion Hall angle with driving current, as well as threshold current densities comparable to those found in experiments. These results may indicate an alternative method of designing devices with zero skyrmion Hall angle, by purposely creating surface confining potentials.



O154 - Exchange-bias mechanism in orthoferrite and ferrite-chromite ferrimagnets and disordered cobaltite

10. Micromagnetics and magnetization processes

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The exchange-bias (EB) effect was studied in single crystals of compensated ferrimagnets $R\mathrm{FeO_3}$ (R = Nd, Sm, Er). In these compounds, the weak ferromagnetic (FM) moment results from the canted antiferromagnetic (AFM) ordering of Fe spins below $T_\mathrm{N} \approx$ 700 K due to the Dzyaloshinskii-Moriya (DM) interactions, while the opposite compensating paramagnetic moment of R spins appears owing to a strong AFM coupling between 4f and 3d ions within the unit cell. Due to this mechanism, the Er, Nd, and Sm orthoferrites exhibit a specific T_comp at which the two opposite moments cancel each other so that the net magnetization vanishes, and below T_comp the FM moment is aligned oppositely to the moderate applied magnetic field, demonstrating a negative magnetization. It was found that all of them are analogously exchange biased around their compensation temperatures T_comp. Interestingly, in spite of very different R-Fe interactions, T_comp values, and spin-reorientation temperatures, the EB field similarly emerges and diverges upon approaching T_comp and changes sign with crossing T_comp. In addition, $\mathrm{SmFeO_3}$, with a complicated AFM order caused by the nonequivalent Fe spin configuration, shows EB also at temperatures far above T_comp and its sign alters from negative to positive with increasing cooling field.
The EB effect was also found in ceramic sample of $\mathrm{LuFe_{0.5}Cr_{0.5}O_3}$ ferrite-chromite, which is a weak ferrimagnet, composed of two canted Fe and Cr AFM sublattices with oppositely directed weak FM moments, exhibiting at low temperatures magnetic moment reversal and negative magnetization. It was found that the EB is positive below T_comp and negative above T_comp due to weak ferrimagnetic behavior of $\mathrm{LuFe_{0.5}Cr_{0.5}O_3}$ allowing the magnetic moment reversal governed by a specific competition of the DM interactions between $\mathrm{Fe^{3+}}$ and $\mathrm{Cr^{3+}}$ ions.
Both, in the case of orthoferrite and ferrite-chromite ferrimagnets, the DM interactions were found to be essential for the possible mechanisms of EB.
The EB effect and an appearance of the Griffiths phase (GP) were found in half-doped cobaltite $\mathrm{Gd_{0.5}Sr_{0.5}CoO_{3-\delta}}$ ceramic sample exhibiting a significant quenched disorder due to the ion size mismatch between Sr and Gd ions. The disorder weakens the FM interactions between Co ions, leading to low Curie temperature T_C = 90 K and to a highly non-homogenous magnetic state above T_C. It was demonstrated that the EB exists for the entire temperature range below T_G = 225 K, in contrast to the limited low-temperature EB observed so far in perovskite cobaltites. The EB has a different nature in the FM cluster phase below T_C and in the GP in temperature interval $T_\mathrm{C} < T < T_\mathrm{G}$. The cooling field effect on EB was examined in the GP, and the size of FM clusters was determined to be equal to 6.5 nm.

O155 - Free energy landscape profiles of magnetic nanodots with different type of spatial asymmetry.

10. Micromagnetics and magnetization processes

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The magnetic vortex nucleation process is studied by micro-magnetic simulations in cylindrical permalloy nano-dots with various kind of spatial asymmetry. The vortex nucleation is symmetry breaking process, with two possible orientations of the vortex circulation (chirality) and two possible orientations of the out-of-plane magnetization of the vortex core (polarity). It is well known that spatial asymmetry in the dot geometry breaks the symmetry in vortex chirality, with consequent possibility of control of the vortex chirality by relative orientation of the external in-plane magnetic field and asymmetric perturbation. It was shown that spatial asymmetry might also lead to breaking the symmetry in the vortex core polarity[1]. This effect has dynamical origin and is related to particular topology of the total energy surface [2]. With the help of metadynamics algorithm it is possible to reconstruct the total energy surface in reduced space of few order parameters [3]. This work presents calculations of the total energy surface for cylindrical nano-dots with various kind of asymmetry. The comparison of the total energy maps helps to understand what kind of asymmetry enhance or suppress the effect of dynamical control of the vortex polarity.

Acknowledgement : We acknowledge the financial support to VEGA grant agency, grant No. VEGA-2/0150/18 and APVV grant agency, grant No. APVV-16-0068.

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O156 - Giant magnetoreactance in nanomagnetic structures

10. Micromagnetics and magnetization processes

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We outline the idea of sensing the magnetic field with a nanometer spatial resolution via using the effect of giant magnetoreactance (GMX) and we disscuss results of our micromagnetic studies of the GMX from nanomagnets. By analogy to giant-magnetoimpedance (GMI) sensors, we consider nanosystems of many domains magnetized perpendicular to the direction of the current that flows in a nonmagnetic substrate. The dynamical magnetic response to the alternating Oersted field (the mechanism of GMX) is different than in the majority of GMI structures of larger (micrometer) sizes, however. In the nanomagnets, in the low-field regime (below the field of FMR), the main response effect relates to the oscillations of the domain-wall positions. On the other hand, because of small cross-section area of nanomagnets, the dynamical contribution to the impedance does not overcome the static resistivity. Therefore, instead on the modulus of the impedance, we focus our study on the imaginary part of the impedance (the reactance). Upon shortly discussing the GMX of nanotubes [1] and nanostripes [2] with transverse magnetic anisotropy, we outline the effect in double-vortex containing magnetic structure (Fig. a), that, we have found to allow for achieving relatively large field sensitivity of asymmetric GMX [3]. Finally, we discuss the effect in a structure with a crystalline Co nanowire of the circular cross-section, whose many-domain magnetic structure (Fig. b) is obtained via relaxation from an uniformly-magnetized state. It relates to a single-peak curve of the transverse GMX (the field dependence of the reactance).

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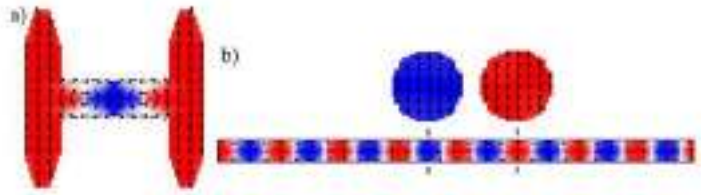

O157 - Magnetic reversal in perpendicularly magnetized antidot arrays with intrinsic and extrinsic defects

10. Micromagnetics and magnetization processes

Michal Krupinski[1] , *Pawel Sobieszczyk*[1], *Piotr Zielinski*[1], *Marta Marszalek*[1]
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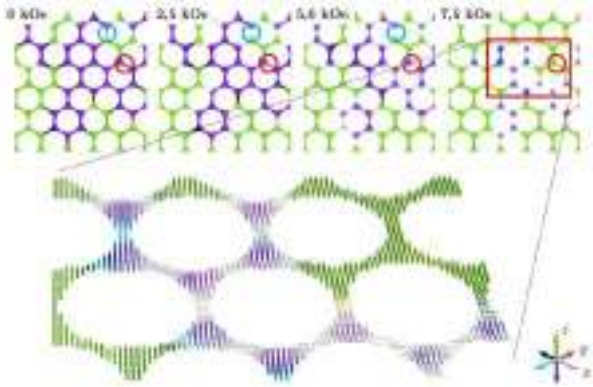
Defect are unavoidable in the large scale nanopatterned materials. Their density and character are key factors determining performance of magnetic storage devices, memories, magnetic sensors, as well as drug carriers in biomedicine based on nanostructures arrays i.e. magnetic antidot matrixes. Therefore, the influence of the defects on the magnetic reversal behavior should be understood well before the nanopatterned magnetic materials are used in these applications. The difficulty in studying of intrinsic and extrinsic defects lies in the inability to regulate their characteristics experimentally in a reproducible manner. The width of the defected edges, its roughness and composition are determined by the chosen patterning method and cannot be easily varied. Additionally, the experimentally measured parameters such as coercivity or effective anisotropy are a superposition of contributions from different defects, which often cannot be studied separately.

Here, we show that a significant progress in exploring this issue may be achieved by employing computational tools. For this purpose, we constructed a micromagnetic model for antidot arrays with perpendicular magnetic anisotropy, which accounts for intrinsic and extrinsic defects associated with the polycrystalline character of the material, including local oxidation, corrugations and defected edges of nanostructures. The predictions of the model were corroborated by the measurements obtained for Co/Pd multilayers patterned by nanosphere lithography supported by RF-plasma etching. After a careful selection of phenomenological parameters the model accurately reproduces the reversal behavior and domain pattern in the pristine material, and predicts magnetic parameters and reversal mechanism for hexagonally ordered arrays of antidots.

Different micromagnetic modeling approaches showed that magnetic properties and domain configuration of systems with perpendicular anisotropy are strongly determined by heterogeneity of nanostructure sizes, and edge corrugations, and that such imperfections play a key role in processes of magnetic reversal. The domain pattern simulations shed additional light on the details of magnetic reversal. In particular, an increase in the Néel domain walls, as compared to Bloch walls, was observed after increasing the number of defects. The simulations indicated also that a neck between two antidots can behave like a short nanowire with a width determined by the array period and antidot diameter. The evolution of the domain structures with the intensity of the external field was also visualized, and we predicted that the antidot lattice geometry connected with defected edges leads to the formation of structures, such as a network of magnetic bubbles (shown below), which are unstable in non-patterned flat films. Such structures are new in these systems and we show how they can be stabilized by edge corrugations.



Evolution of the domain pattern for an array with an antidot diameter of 185 nm and period of 350 nm. The red circle indicates the place where intrinsic defect is the source of edge nucleated removal, while the blue one indicates the place where transition from the Néel to the Bloch domain wall occurs. The map below shows details of a bubble-like structure stabilized by edge defects.

O158 - Magnetism You Can Rely On: A Materials-Science Based Solution to Stochastic Domain Wall Pinning

10. Micromagnetics and magnetization processes

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Proposed domain wall (DW) memory and logic devices rely upon the deterministic motion of domain walls through nanowires. However, their development has been hampered by the fact that DWs show exceptionally high levels of stochasticity in their pinning and depinning. Recent studies have shown that this stochasticity arises from Walker Breakdown phenomena, where DWs undergo periodic changes in their magnetisation structure at typical propagation fields, and thus that stochastic pinning is an intrinsic feature of DW behaviour [1].

In a previous theoretical work, we suggested that by doping small amounts of Rare earth elements into $Ni_{80}Fe_{20}$ to increase its Gilbert damping we can supress Walker Breakdown [2], thus eliminating the root cause of stochastic pinning/depinning effects, and creating devices with inherently reliable behaviours. In this presentation we present the first experimental validation of this approach.

We perform focussed magneto-optic Kerr effect (FMOKE) measurements of domain wall pinning/depinning at artificial defect sites in $Ni_{80}Fe_{20}$ nanowires doped with 0-10 % Tb. For the undoped $Ni_{80}Fe_{20}$ nanowires DW depinning field distributions (DFDs) exhibit multiple modes with a wide range of depinning fields, consistent with previously characterised stochastic behaviours [3] (Figure 1(a)). However, equivalent doped nanowires show much simpler quasi-deterministic, single mode DFDs (Figure 1(b)). We support these results with ferromagnetic resonance measurements of the doped-film's Gilbert damping constants, allowing us to estimate the DWs Walker breakdown fields in each device.

Our results illustrate the feasibility creating consistent, deterministic switching behaviour in nanowires devices through simple engineering of material properties, and ask broader questions about how gaining control of complex, dynamic magnetisation processes can supress stochastic behaviour.

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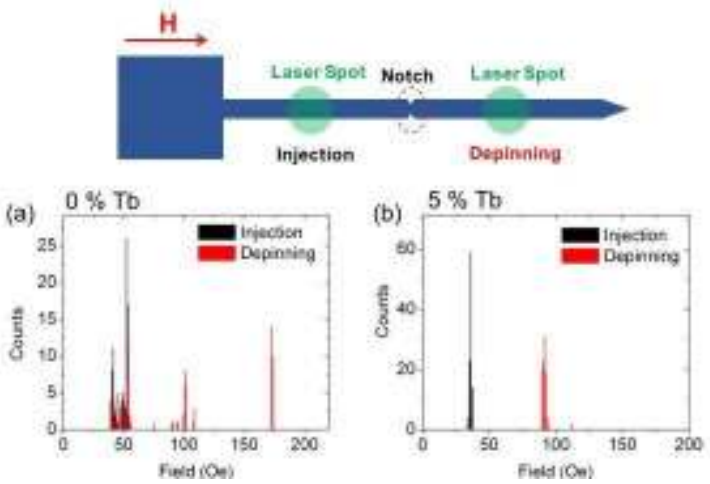
Figure 1. Injection and depinning distributions field measured for 100 nm deep double notch defects in $Ni_{80}Fe_{20}$ (20nm) nanowires doped with (a) 0 % and (b) 5 % Tb. Strongly stochastic behaviour is observed for the un-doped nanowire, while quasi-deterministic pinning is observed for the doped nanowire. A schematic of the experimental geometry is shown at the top of the figure.


H
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Depinning
Counts
Field (Oe)

O159 - Micromagnetic characterization of MnAl-C using trained neural networks

10. Micromagnetics and magnetization processes

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Micromagnetic simulations usually require a huge amount of computational resources depending on the size of the analyzed system. In this work we try to predict local coercive fields of MnAl-C using trained neural networks. We are using the python Keras library with a convolutional network [1]. The training data consists of finite element micromagnetic simulations, computing the coercive fields of small selections of Electron Backscatter Diffraction (EBSD) Data of a large MnAl-C slice (Fig. 1a). Here the input for the network is the pixelized selection with azimuth and elevation information of the magnetically easy axis of the current grain. The model is created using an automated meshing procedure from preliminary work [2]. We simulated the demagnetization curve of around 600 random unique selections of 20 pixel edge length of a full 600 pixel times 400 pixel EBSD dataset (180 µm times 120 µm, Fig. 1a). A single selection has about 300k finite elements (Fig. 1b) and the calculation time with a single Intel® Core™ i7-4600M CPU @ 2.90GHz is about 1.5 h, depending of course on the magnetic configuration (Fig. 1c). The computed switching fields range from 0.45 T/μ_0 to 3.3 T/μ_0 with a mean of 1.98 T/μ_0 (Fig. 1d). Data augmentation done by image transformation is increasing the amount of input data, assuming axisymmetric hysteresis properties and a mirrored negative and positive hysteresis curve. The layer structure of the neural network is manually adapted with a 10-fold validation to improve and optimize the output. 10% of the created simulation dataset is used for testing only and not included in the training set.
Results show, that using a single EBSD data set and around 600 computed selections, an accuracy of 84% can be achieved for predicting the 20% percentile of the lowest local coercive fields. This number could be improved by increasing the training data with different EBSD datasets. By using a trained neural network the time to result for predicting local coercive fields in MnAl-C can be reduced to a couple of seconds, compared to hours as in the micromagnetic finite element simulation.

Acknowledgment: The authors gratefully acknowledge the financial support of the Austrian Science Fund (FWF), Project: I 3288-N36 and the German Research Foundation (DFG), Project: 326646134.

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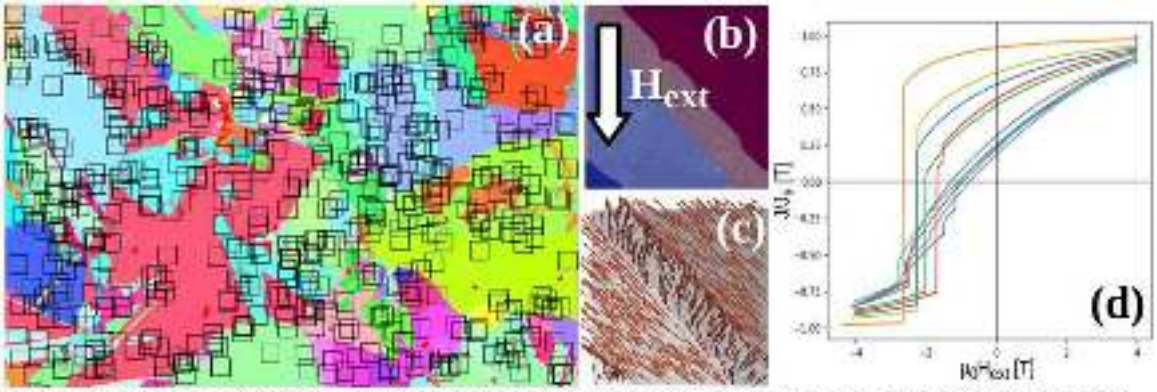

Fig. 1: (a) Inverse pole figure map of MnAl-C with random selections for training local coercive fields; (b) Example mesh of single selection; (c) Magnetic states during magnetization reversal; (d) Typical demagnetization curves of several selections

O161 - Resolving the elastic bath through fast spin switching probes the nature of spin

10. Micromagnetics and magnetization processes

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As electronic devices grow smaller and smaller, their components get more sensitive to novel effects. One of these effects is what the engineering community identified and later named magnetostriction. Although it has been investigated quite extensively over the years, there still are many aspects which remain to be clarified. One example is the dynamical regime of this effect [1]. Indeed, what is generically investigated, is the equilibrium deformation of a magnetic isotropic solid in the linear regime which is encoded in the Lamé parameters under a constant external magnetic field. As one tries to probe the dynamical regime, a quantitative description is much harder.

Whatever the details, the dynamics of any such Magneto-Elastically coupled (ME-coupled) material can be cast in Hamiltonian form, from which the equations of motion follow. From these equations of motion (EOM), we then obtain the coupling between the tensorial deformations and classical vector spins, as well as the corresponding constraints. We focus on how to solve the EOMs numerically using a symplectic integration scheme [2], thereby preserving the symmetries and consistently solving the constraints of the model. We apply this approach to the study of the magnetization (or more precisely the Néel order parameter) switching behavior under an external spin transfer torque (STT) for the case of the antiferromagnetic (AF) phase of NiO. As a useful check, we compare our results to a complementary Lagrangian approach, that we have also developed in recent work [3].

This example allows us to evaluate the influence of the coupling between the magnetic and the mechanical degrees of freedom on the switching behavior of the Néel order parameter. Since in an AF, the net magnetization is - close to - 0, identifying relations between the deformations and the magnetization can be done much more easily, since background magnetic effects are absent. This would be a great new testing ground for experimental investigation techniques on magnetic AF materials, which are notorious for displaying a broad spectrum of behavior, that challenge traditional approaches [4]. We show, in particular, how new kinds of symmetries, that either mix commuting and anticommuting degrees of freedom, or extend Hamiltonian mechanics to phase spaces of odd dimension (known under the name of Nambu mechanics), can provide insight into the constraints that are useful into controlling such materials.

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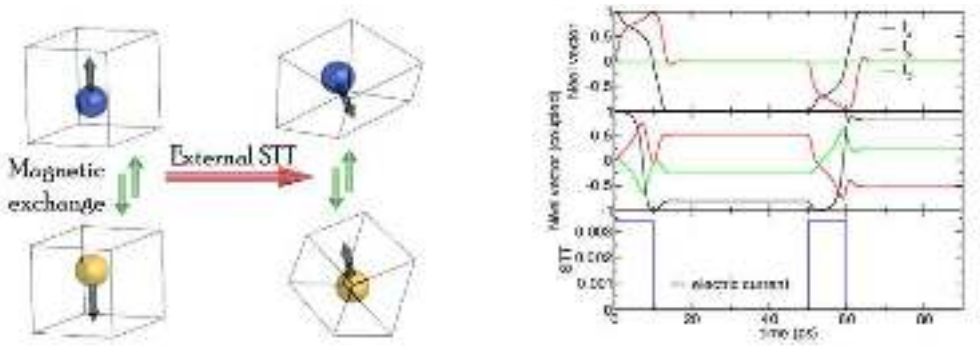

Figure 1: Magnetization switching for an AF under STT pulses : uncoupled vs. M-E coupled + stress

O162 - Skyrmion Confinement and Controlled Motion in Magnonic Antidot Lattices

10. Micromagnetics and magnetization processes

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Magnetic skyrmions are topologically protected nano-meter sized chiral spin textures which can exist e.g. in thin heavy metal/ferromagnet heterostructures due to the asymmetric Dzyaloshinskii-Moriya exchange interaction. As was proven theoretically and experimentally skyrmions can be manipulated by electric current via spin transfer and spin orbit torque. Skyrmions have higher current induced mobility compared to magnetic domain walls which makes them a promising candidate for future spintronic applications such as low dissipation magnetic information storage devices, skyrmion racetrack memories as well as logic devices.

Skyrmions in thin films have been observed to achieve a transverse velocity when displaced by an in-plane DC current exploiting the spin Hall effect. In real experiments on homogeneous samples the skyrmion motion is randomized by the thermal diffusion and presence of pining centers. The observation that edges of the sample and defects repel skyrmions led to idea to use magnetic antidot lattice as a medium with well defined and robust control of skyrmion motion.

We study theoretically the skyrmion motion driven by the short in-plane current pulses in the presence of a magnetic antidot array. Antidots are defined as circular holes etched in the thin CoFeB magnetic layer organized in a square superlattice. Since the antidots repel the skyrmion the antidot superlattice creates an effective potential of attractive valleys located between each four neighbouring antidots. Our calculations are based on the micromagnetic model as well as on the modified Thiele equation which significantly reduces the computational time while keeping the reasonable level of accuracy. We demonstrate that skyrmion transport between individual valleys can be controlled by applying a rectangular current pulse with adequate amplitude and duration. Resulting from the interplay between antidot potential and skyrmion Hall effect skyrmions can be manipulated in the longitudinal and even in the transversal direction with respect to the current flow. We indentify two mechanisms determining the final position of the skyrmion: i) the skyrmion is directly driven by the applied current to the desired valley, ii) after the current pulse is switched off, due to the energy relaxation the skyrmion uncoils down the antidot wall to the desired valley. We calculate a maps showing the regions of the current pulse parameters which correspond to the identical final positions of the skyrmion after the pulse is switched off. Starting from a bottom of a valley, our calculations show that just by applying an adequate current pulse in the horizontal direction it is possible to move the skyrmion to almost all of the neighbouring valleys horizontally and vertically. Therefore, by using the sequence of electrical current pulses, the magnetic antidot arrays can be used as a medium for well controlled skyrmion motion, whereby the results make a step towards skyrmion based devices.

O163 - The role of vortex-antivortex pairs in the magnetization reversal of patterned thin films

10. Micromagnetics and magnetization processes

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A detailed understanding of the magnetization reversal process is important both in fundamental research on magnetic materials and in applications, e.g., for data storage devices [1,2]. In this work, by applying an in-plane magnetic field during Magnetic Force Microscope (MFM) measurements, we analyzed the magnetization reversals along the long and short axes of micropatterned Permalloy thin film samples, respectively. The evolution of the domain-wall clusters (shown in Fig. 1) and the transfer of the magnetic flux across the domain walls were investigated by observing the nucleation and annihilation of vortex-antivortex pairs inside the walls. It is found that in order to let the flux pass through the domain wall, the domain wall undergoes switching of its magnetization orientation by transporting a vortex between the cluster knots along its axis. Furthermore, the experimental findings were evaluated by micromagnetic calculations. Based on the resulting magnetic energies within the whole sweep range of the applied field, it is concluded that the demagnetization and exchange energies dominate the Zeeman energy at small applied fields. This restricts the nucleation and annihilation of vortex-antivortex pairs inside the walls near the remanent state of the sample.

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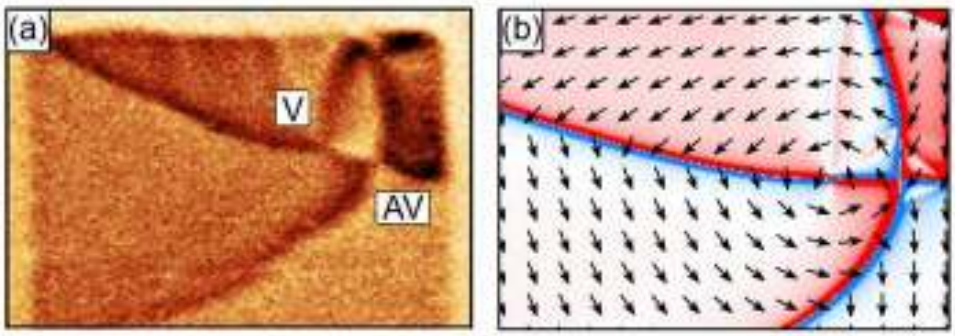

Fig. 1 Nucleation of a vortex-antivortex pair in a domain wall cluster in (a) MFM and (b) micromagnetic calculations.

11. Nanomaterials, patterned films, nanoparticles and molecular magnetism

O164 - An ‘all-in-one’ synthesis technique to prepare functional nanocomposites in different forms

11. Nanomaterials, patterned films, nanoparticles and molecular magnetism

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Functional nanocomposites, where the individual components themselves are complex systems belonging to the family of strongly correlated electron oxide systems, are both interesting as well difficult systems to study. The difficulty lies as much in the synthesis of pure phase nanocomposites as in the understanding of the cross-correlated electronic and magnetic properties. An easy way to synthesize nanocomposites is to physically mix the two phases. However, a simple physical mixing of the two phases leads to clustering and aggregation of the individual phases on the micron scale that is often detrimental to the physical properties of the nanocomposites. A second method is to use pre-formed nanoparticles of one phase and grow the second phase around these pre-formed nanoparticles. Such a synthesis method yields better homogeneity than physically mixed samples, but some level of clustering and aggregation is still present.

In the present paper, we report an ‘all-in-one’ modified sol-gel synthesis technique in which both the phases of the nanocomposite are formed during the same time. This is a bottom-up approach that reduces clustering and aggregation of the individual phases to the minimum possible, yielding true homogeneity on the nanoscale. In addition to nanoparticles, this technique can also be used to prepare thin films by a suitable modification of the precursors, solvents, and chelating agents used. We will demonstrate the synthesis technique for different nanocomposites such as the multiferroic $Pb(Zr,Ti)O_3$-$CoFe_2O_4$ and magnetic $LaFeO_3$-$CoFe_2O_4$. The physical properties of these functional nanocomposites will also be discussed.

We thank Stiftelsen Olle Engkvist Byggmästare (grant number: 188-0179), Carl Tryggers Stiftelse för Vetenskaplig Forskning (grant number KF:17:18), Swedish Research Council (VR starting grant number: 2017-05030), and the Royal Physiographic Society of Lund (the Märta and Eric Holmberg Endowment) for financial support.

O165 - Dynamic cantilever magnetometry of individual maghemite mesocrystals

11. Nanomaterials, patterned films, nanoparticles and molecular magnetism

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Self-assembled mesocrystals of magnetic nanoparticles are 3 dimensional periodic arrangements of magnetic nanoparticles. Like other types of metamaterials, magnetic mesoscrystals are especially interesting due to the extra degree of control allowed by the engineered mesostructure. In particular, these ordered nanomaterials may create a novel multi-functional system that is different from that of the individual building units. Future applications could range from magnetic storage media to plasmonic or optoelectonic devices.

Due to their small size and inherently delicate nature, until now, magnetic measurements have been performed on large ensembles of mesocrystals rather than on individual specimens. Interpretation of such measurements on the ensemble can be complicated by sample-to-sample inhomogenities in size, shape, and orientation or even by interactions between mesocrystals.

Here, we present magnetic measurements of individual maghemite mesocrystals using sensitive dynamic cantilever magnetometry (DCM). For the measurements, each mesocrystal has been removed from its substrate and attached to the apex of an ultra-soft cantilever via a mechanical micromanipulator. The cantilevers response to the forces arising from the magnetic moment of the mesocrystal in an externally applied field allows to extract information on magnetic properties such as blocking temperature or anisotropy.

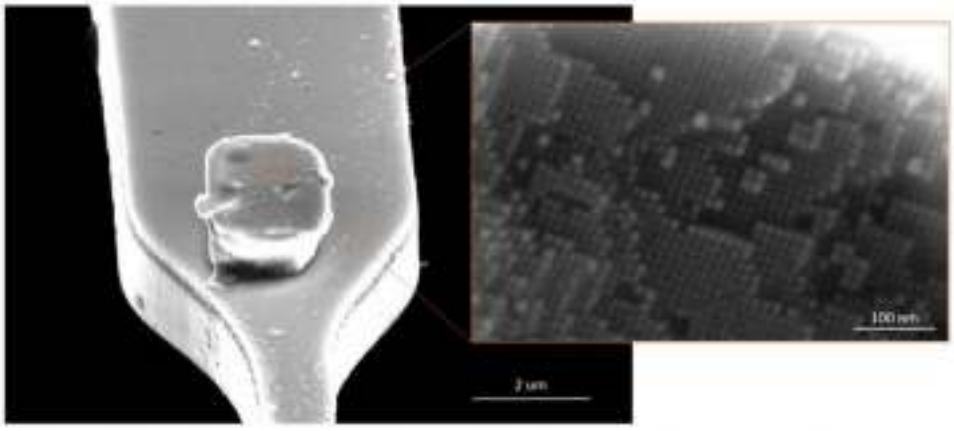

Figure 1: Individual mesocrystal attached to a cantilever. A close-up of the structure is shown in the inset

O167 - Engineering Three-Dimensional Magnetic Nanowires by Focused Electron Beam Induced Deposition

11. Nanomaterials, patterned films, nanoparticles and molecular magnetism

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The development of novel strategies to grow tailored three-dimensional (3D) magnetic nanostructures is paramount for the implementation of these objects in applications such as magnetic data storage, logic and sensing [1]. Ferromagnetic nanowires (NWs) and nanotubes (NTs) are particularly exciting and could play a crucial role in future technologies. One approach that has been recently explored is the Focused Electron Beam Induced Deposition (FEBID) of magnetic transition metals by the electron-beam induced decomposition of organometallic precursors. The growth of two-dimensional (2D) FEBID structures has been widely explored in the past, and is able to produce as-grown high purity deposits for functional devices [2]. On the other hand, the transition to 3D objects with nanoscale lateral dimensions is challenging, as the metal content of the deposit degrades quickly when decreasing the diameter of the object below 100 nm [3].

Here we report two recent approaches we have followed to optimize the magnetic properties of 3D Co and Fe FEBID NWs. Firstly, non-standard growth procedures have been adopted to produce heterostructures in the form of core-shell Co@Pt and Fe@Pt NWs [4], where the Pt shell also grown by FEBID acts as a protective coating upon oxidation. Later, this architecture has been adapted to fabricate Co FEBID NTs on Pt templates, which are currently under study [5]. Second, high-vacuum thermal annealing has been successfully carried out used to increase metal purity, crystallinity and magnetic induction of 3D magnetic FEBID deposits [6].

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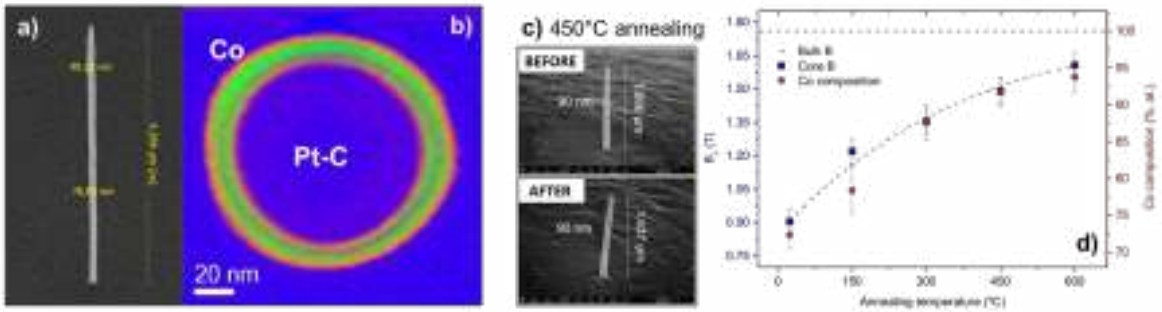

a) 3D FEBID Co NT grown on a Pt-FEBID template. **b)** Cross section of the Co NT. **c)** 3D Co-FEBID NWs before and after 450°C annealing. **d)** Dependence of magnetic induction and Co content with the annealing temperature.

O168 - Exchange bias coupling in Fe3O4/CoO magnetic nanoparticles with different morphologies

11. Nanomaterials, patterned films, nanoparticles and molecular magnetism

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Exchange bias (EB) coupling is an exciting phenomenon that takes place when an antiferromagnetic (AFM) material is associated to a ferromagnetic or ferrimagnetic (FiM) one. This interface effect induces a unidirectional anisotropy in the ferro- or ferrimagnetic material. EB results in a shift of the hysteresis loop along the field axis and, in some cases (e.g. nanostructures), an increase in coercivity [1,2]. Researches on nanosystems and in particular on core-shell nanoparticles (NP) have increased for the last few years [3,4]. In this type of systems, the presence of EB helps to gain magnetic stability at room temperature.

Thanks to this stability, NP exhibiting EB can be used in a variety of applications, such as storage medias but also permanent magnets or mediators for therapeutics. On top of that, core-shell NP constitute an excellent model for the study of nanomagnetism and EB.

The main question to address is: how can the AFM material influence the FiM one, leading to an overall enhancement of the magnetic anisotropy? The EB phenomenon is influenced by a certain number of parameters, such as the AFM and FiM materials, their relative fractions, anisotropies and the NP size/shape. Many studies show the magnetic consequences of the size variation of an AFM shell surrounding a FiM core [3-5]. However, to understand more precisely the EB phenomenon, it is interesting to study the core-shell FM@AFM system but also an AFM core surrounded by a FiM shell. On top of that, studying different NP morphologies such as raspberry-like or Janus-type can help understanding the EB mechanisms and obtaining particles with a high effect.

In this work, two materials were associated: FiM magnetite Fe_3O_4 and AFM cobalt oxide CoO. Seeds of both materials were prepared by a thermal decomposition route. The second material was grown on these seeds using the same route. Different NP morphologies were prepared (Fig. 1): core-shells, raspberry-like and Janus-type. This synthesis allowed us to obtain monodisperse pristine NP (core size: 7-8 nm) with a good control on the shell size (2-10 nm). Two types of core-shell nanoparticles were studied: magnetite cores with different CoO shell thicknesses, and CoO cores with a size-varying magnetite shell. Rapsberry-like and Janus particles were prepared from magnetite seeds with a magnetization saturation of about 70 emu/g. The magnetic properties of these systems were studied and exchange bias coupling was proven present. An increase of coercivity and remanence was observed for 8 nm Fe_3O_4 cores with CoO shells. This work is promising for the understanding of EB into nanosystems, but also to tailor nanoparticles with a strong control on their magnetic properties in view of practical applications.

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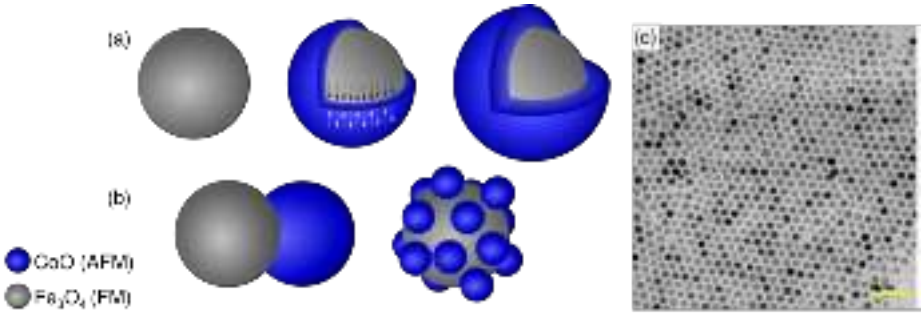

Figure 1. schemes of the different synthesized NP: (a) pristine magnetite, core-shells with different shell sizes (spin ordering schematized by arrows), (b) Janus-type and raspberry-like. (c) TEM image of pristine magnetite NP with 8 nm average size (scale bar is 50 nm).

O169 - FePd nanoparticles by solid-state dewetting for magnetic hyperthermia

11. Nanomaterials, patterned films, nanoparticles and molecular magnetism

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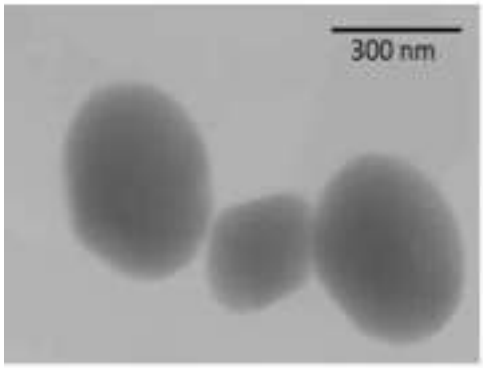
Magnetic particles of controlled size have raised a broad technological interest in different areas such as catalysis, photonics, biomagnetism and, in general, for fabricating multifunctional magnetic systems. Solid-state dewetting is a promising thermally activated bottom-up method to pattern magnetic thin films into nanoparticles on a large scale. In dewetting method, the spontaneous agglomeration of a metallic thin solid film on a substrate into an assembly of particles with defined shape and size is a controllable process by means of different factors (i.e. annealing parameters, substrate and film composition and thickness. Here, magnetic FePd particles from a continuous film are obtained. The starting Fe_xPd_{100-x} thin films are deposited on selected substrates (SiO_2 and Si/MgO) by rf-sputtering (film thickness about ranging from 7 to 100 nm) with nominal compositions (x = 70 and 80). To promote dewetting, the as-deposited thin films are subsequently submitted to a furnace annealing in vacuum atmosphere at selected temperatures (ranging from 700°C to 875°C) and for different time (up to 100 minutes). The dewetting process of FePd thin films has been carefully studied as a function of annealing temperature and annealing time. The process has been followed by acquiring scanning electron microscopy (SEM) images of annealed FePd samples to investigate the progressive steps of dewetting. This allows to analyze particle shape factors such as density, circularity and equivalent diameter. By finely tuning the annealing parameters and depending on film thickness, FePd nanoparticles with diameter varying in a wide interval (30 – 300 nm) have been obtained. After the dewetting process, the nanoparticles have been detached from the substrate by a sonication process and dispersed in deionized water. Isothermal magnetic hysteresis loops have been measured in the two different configurations (nanoparticles attached to the substrate and after their removal by sonication) by means of highly-sensitive magnetometety (AGFM and VSM) to understand the evolution of magnetic properties, i.e. coercivity, initial susceptibility and remanence during the particles formation in the dewetting process. Magnetic hyperthermia exploiting nanoparticles is currently a significant subject of research in the field of tumor treatment. A major issue preventing clinical applications lies in the difficulty of obtaining reproducible measurements of the specific absorption rate (SAR), i.e. of the amount of heat that is released by the magnetic nanoparticles submitted to an alternating electromagnetic field usually in the range of a few hundreds of kHz and with amplitudes of a few tens of mT. Here, this parameter has been accurately evaluted by performing optical thermometric measurements both in adiabatic and isothermal conditions, by applying a r.f.(up to 400 kHz) magnetic field of intensity up to 35 mT. 3D micromagnetic modelling of magnetization reversal process and hysteresis behavior is also performed to provide an interpretation of the experimental results.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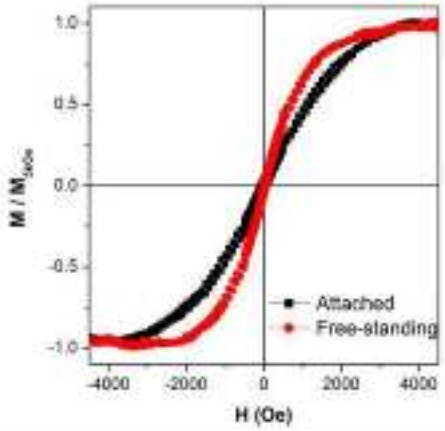
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O170 - Ferromagnetism at room temperature in nanoparticles of Sn(1-x)CexO2

11. Nanomaterials, patterned films, nanoparticles and molecular magnetism

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Semiconductor oxides are materials with different possibility for applications, such as catalysis, solar cells and magnetic devices. In point of view from the point of functional materials, SnO_2 and CeO_2 oxides have been reported in several experimental studies, the presence of ferromagnetism at room temperature [1,2], although they do not have concentration of ions with unpaired spins in layers *d* or *f* [3]. This magnetic behavior becomes the magnetic oxides very interesting for studies of fundamental physics and applications in spintronic devices. In this work, we investigate the influence of different cerium concentrations on the structural, optical and magnetic properties of the nanoparticles of $(Sn_{(1-x)}Ce_x)\ O_2$ with x = 0, 0.01,0.05, 0.1, 0.3, 0.5, 0.7 and 1 synthesized at 750° C by the Pechini method. Using the X-ray diffraction (XRD) technique and high resolution transmission electron microscopy (HRTEM) we observed the formation of the tetragonal phase and the stabilization of the orthorhombic phase of SnO_2 (O-SnO_2) at room temperature for x = 0. Using the Rietveld refinement analyzes, it was found that the addition of different concentrations of Ce resulted in a change in strain and / or defect generation, favoring the stabilization of 42% of the O-SnO_2 phase for the sample at the nominal concentration of 50 mol% of Ce.The presence of oxygen vacancies was observed by X-ray photoemission spectroscopy (XPS), since we identified the two oxidation states of Ce (III and IV). These oxidation states were confirmed by photoluminescence technique (PL), in which an emission band was observed in the visible region associated with defects.The magnetization measurements as a function of the magnetic field and temperature show that NPs of $(Sn_{(1-x)}Ce_x)O_2$ exhibit a ferromagnetic behavior at room temperature resulting from the magnetic moments alignment in small regions of samples. The dependence of the coercivity with the temperature of the samples was investigated, exhibiting an anomalous behavior in the region of low temperatures. This behavior was observed only in samples in which the orthorhombic phase is present, as a consequence, may be associated with a decrease in the effective anisotropy constant due to effects of surface. Our results suggest that the presence of monoionized oxygen vacancies on the surface of the nanoparticles are responsible for the ferromagnetic behavior at room temperature.

This work was partially financed by the Brazilian agencies FAPESP (grants 2017/24995-2 and 2013/07296-2) and CNPq

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O171 - First-principles studies of spin-electric coupling in molecular magnets without inversion symmetry

11. Nanomaterials, patterned films, nanoparticles and molecular magnetism

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The efficient manipulation of the quantum states of molecular magnets by an electric field is highly desirable in order to use molecules for spintronics and quantum information processing. There are two classes of molecules that are most promising for a spin-electric coupling (SEC) which does not reply on spin-orbit interaction: frustrated triangular single molecule magnets (SMMs) with antiferromagnetic exchange, and molecular helices. Frustrated triangular SMMs, such as Cu3, are characterized by a ground state consisting of two dubly degenerate S=1/2 -states with opposite chirality. It has been proposed theoretically [1] and later verified by ab-initio calculations [2] that the lack of inversion symmetry in these triangular SMMs allows an external electric field to couple these two chiral spin states. The lack of inversion symmetry in helical molecules is also the fundamental feature behind the SEC in this class. This type of SEC has been demonstrated experimentally only very recently in {Fe3] triangular SMM [3] and in MnPhOMe molecular helix [4]. In this work, following this recent development, we have studied the SEC in the {Fe3} SMM and compared it with other triangular SMMs Cu3, V3 and V15, discussing advantages and disadvantages. We will also discuss the electric modulation of the exchange coupling by an external electric field in in MnPhOMe molecular helix.

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O172 - Insights into magnetite bulk, surface and nanoparticles by first-principles

11. Nanomaterials, patterned films, nanoparticles and molecular magnetism

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The author has chosen not to publicise the abstract.

Field 5

Field 6

O173 - Intermolecular Magnetic Interactions in Phthalocyanine Dimers

11. Nanomaterials, patterned films, nanoparticles and molecular magnetism

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Organic molecules like porphyrins and phthalocyanines and their superstructures like 1D chains or dimers, are highly appealing in the emerging field of molecular spintronics. These systems are candidates as building blocks for novel molecular size devices, which would bring up remarkable benefits like reduction of power consumption and increase in magnetic storage density.
I will present theoretical studies of the magnetic properties of dimers of manganese phthalocyanine (MnPc) both bare and with atomic axial ligands like Cl and H. The calculations were performed by means of *ab initio* Density Functional Theory (DFT) including the dispersion interaction. We observe a significant ferromagnetic coupling between the Mn centres in the dimer, which decreases by 20% when a H atom is adsorbed on the Mn, and is reduced to less than 10% when a Cl atom is axially adsorbed. The magnetic coupling is almost fully quenched by depositing the dimer on the ferromagnetic substrate Co(001). The magnetic coupling within the dimer, i.e. between the two phthalocyanines molecules, takes place through a superexchange path involving electrons in the nitrogen atoms π net and the 3d electrons of the Mn centres. By analysing the electronic structure of the two molecules in the dimer, we show that the superexchange loop is altered when H and Cl are adsorbed on the dimer, or when the dimer is chemisorbed on the Co surface. In both cases the magnetic interaction between the molecules is strongly affected, or is practically quenched. This chemical tuning of the magnetic coupling can be exploited in the design of nanodevices for molecular electronics and spintronics, where the molecules need to be anchored to a support.

O174 - Magnetic and structural properties of one-dimensional arrays of endofullerene single-molecule magnet

11. Nanomaterials, patterned films, nanoparticles and molecular magnetism

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Rare-earth-based endofullerene nanomagnets belong to the group of single-molecule magnets (SMMs) [1], a class of molecules that exhibits intrinsic magnetic bistability at low temperatures. One such example is $Dy_2ScN@C_{80}$ which magnetic hysteresis and significant remanent magnetization with a relaxation rate of about 1 h at 2 K [2].

Here we present the first study of SMMs packed inside single-walled carbon nanotubes (SWCNTs). The study was performed on SWCNTs filled with one-dimensional chains of endofullerene $Dy_2ScN@C_{80}$ SMMs using high-resolution transmission electron microscopy (HRTEM), X-ray magnetic circular dichroism (XMCD), and ab initio calculation [3]. X-ray absorption measurements reveal that the orientation of the encapsulated endofullerenes differs from the isotropic distribution in a bulk sample, indicating a partial ordering of the endofullerenes inside the SWCNTs. The effect of the one-dimensional packing was further investigated by *ab initio* calculations performed for the structural analog $Y_2ScN@C_{80}$, demonstrating that for specific tube diameters, the encapsulation is leading to energetically preferential orientations of the endohedral clusters. In the case of endofullerene SMMs, a preferred direction of the endohedral units implies alignment of the molecular anisotropy axis and magnetic ordering. Therefore, these results demonstrate the feasibility of forming ordered and well protected one-dimensional spin chains that could be addressed through the creation of SMM/SWCNT hybrid devices. Additionally, element-specific magnetization curves reveal a decreased magnetic bistability of the encapsulated $Dy_2ScN@C_{80}$ SMMs compared to the bulk analog.

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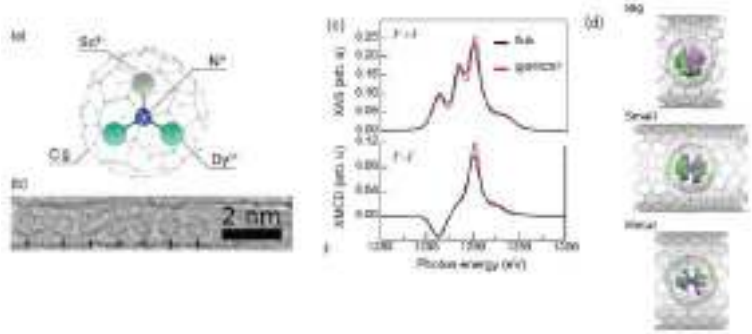

(a) Ball-and-stick model of $Dy_2ScN@C_{80}$. (b) HRTEM image of a one-dimensional array of $Dy_2ScN@C_{80}$ endofullerenes inside a SWCNT. For clarification, the dashed lines give the position of the walls of the SWCNT, and the arrows point to the circular endofullerenes. (c) A comparison of the normalized total absorption and XMCD spectra from the two systems. The temperature was set to 2 K, and an external magnetic field of 6.5 T was applied parallel to the X-ray beam and the surface normal of the samples. The data was normalized to the integrated total absorption over the displayed energy range. (d) Superposed subset of optimized structures where Y site is captured in light green and Sc site in purple.

O175 - Magnetic Properties of Aerosol Fe87.5Cr12.5 Ferrite Nanoparticles Generated by Spark Ablation

11. Nanomaterials, patterned films, nanoparticles and molecular magnetism

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Magnetic nanoparticles (NPs) have been a developing topic over the last years due to the wide variety of applications such as cancer therapy, data storage and environmental remediation. Here we present a structural and magnetic characterization of aerosol FeCr ferrite NPs produced by spark ablation [1], a method capable of generating particles with a narrow size distribution (<10%) and good control of the surface coverage. High-Resolution Transmission Electron Microscopy (HRTEM) reveals similar lattice parameters as magnetite spinel structure (Fe_3O_4) and Pair Distribution Function (PDF) measurements point in the same direction. XPS studies indicate the presence of a mixture of Fe(II), Fe(III) and Cr(III) species, with no metallic Fe. Furthermore, TEM analysis shows homogeneously mixed particles with an 87.5 to 12.5 Fe-Cr ratio. Magnetic properties of different coverages and particle sizes (10 - 50 nm) were studied by the use of SQUID magnetometry. The low coverage systems (with 3% coverage) of 10 nm particles exhibit SPM behaviour with a blocking temperature T_B =58 K and little to no coercivity (<75 Oe) present at room temperature. At a particle size of 30 nm, hysteresis is still detected at temperatures up to 400 K. X-ray Magnetic Circular Dichroism (XMCD) measurements show a ferromagnetic coupling between the Cr and Fe. Furthermore, comparing Cr substituted Fe_3O_4 with pure Fe oxide NPs demonstrate that the inclusion of Cr results in a much broader hysteresis which does not close between +/-5 T at 2 K and significantly larger coercivity at low temperatures.

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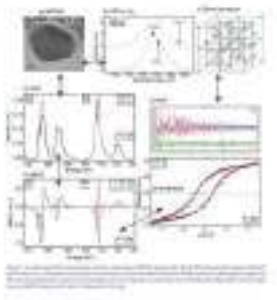

O176 - Magnetism and electronic structure probed by x-rays: polyoxopalladates as molecular model systems

11. Nanomaterials, patterned films, nanoparticles and molecular magnetism

Carolin Schmitz-Antoniak , *Natalya V. Izarova[1], Maria Stuckart[1, 2], Alevtina Smekhova[1], Detlef Schmitz[3], Paul Kögerler[1, 2]*

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Polyoxopalladates (Fig. a) form a new class of molecular materials, which gained a lot of interest due to their various possible applications e.g. as noble metal-based catalysts or spin qubits. Furthermore, with their well-defined and tunable morphology and ions coordination, polyoxopalladates can be considered as model systems for basic research as well, which is the focus of this contribution.
As shown in Fig. b,c, we investigated (i) the X-ray absorption near-edge structure (XANES) to monitor changes in the electronic structure, (ii) X-ray magnetic circular dichroism (XMCD) for the determination of effective spin and orbital magnetic moments, and (iii) X-ray magnetic linear dichroism (XMLD) for a refined analysis of crystal field splittings of the metal ion centers and their magnetic characteristics. Charge transfer multiplet calculations supported the interpretation of specific spectral changes.
Using three selected examples, we show how sensitive electronic and magnetic properties depend both on the direct coordination symmetry and even on the environment on a next-nearest neighbours length scale. Modifications of crystal fields were experimentally realised by different approaches including occupation of different sites (centre vs. dodeca-palladium(II) oxide shell) [1], capping groups [2], and hydrogenation and re-oxidation [3]

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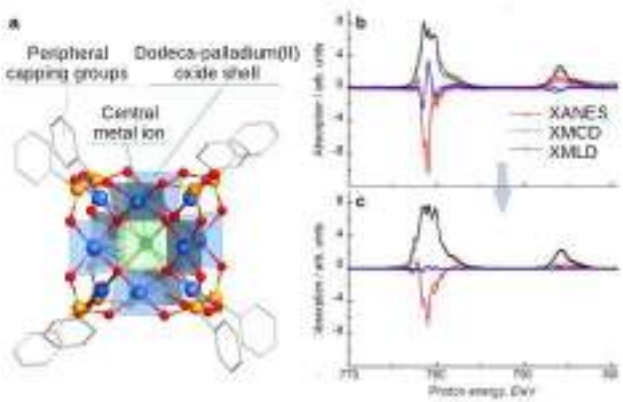

a: molecular structure of polyoxopalladates; **b-c**: example of XANES, XMCD, and XMLD spectra from which electronic and magnetic properties have been deduced [3].

O177 - Memory Effect & Growth of Glassy Magnetic Phase in Nanocrystalline La0.4(Ca0.5Sr0.5)0.6MnO3 Compound

11. Nanomaterials, patterned films, nanoparticles and molecular magnetism

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Doped perovskite manganites have been an attractive and active field of research for the past two decades due to its interesting fundamental properties as well as technological applications in various ways. [1] General formula of doped system is $R_{1-x}B_xMnO_3$, where R is rare-earth elements & B is divalent elements. [1] A detail and systematic study of magnetic properties for nanocrystalline $La_{0.4}(Ca_{0.5}Sr_{0.5})_{0.6}MnO_3$ (LCSMO) compound have been presented here. The nanocrystalline sample has been prepared by well-known sol-gel method. Results reveal that, doping (half) with higher ionic size bivalent element (Sr), at 'B' site of parent charge ordered $La_{0.4}Ca_{0.6}MnO_3$ (LCMO) compound, induces glassy magnetic phase at lower temperature. Memory effect (Fig. (a)) [2], Relaxation (Fig. (b)) [2], & exchange bias (EB) (Fig. (c)) [3] study substantiate the glassy nature of the compound.

In memory effect, short-term interim stops (1 hour) have been taken at T_{stop} = 20 K, 50 K, 80 K, 100 K, 200 K, 220 K, 240 K during cooling sequence (from 300 K to 3 K) in presence of 100 Oe external magnetic field (H) and during the heating cycle, while temperature ramping rate & H kept unchanged, it exhibits deeps at the respective stops except at T_{stop} = 200 K, 220 K, 240 K (as these temperatures are above the spin freezing temperature (T_f)). Thus, below T_f (200 K) existence of glassy magnetic phase is noticed. [2]

In addition to that, low temperature (T = 5 K) EB measurement exhibits positive & negative shifts of the loop and it corroborates the presence of glassy magnetic phase in the system. [3]

Moreover, magnetization as a function of time has also been taken at temperatures T = 5 K & 30 K. Data have been recorded in zero field cooled protocol and fitted with stretch exponential function, $M(t) = M_0 - M_g \exp(-t/\tau)$. Here, β is the stretching exponent ($0 < \beta < 1$ for glassy systems) & estimated β values (shown in Table I) again confirm the presence of glassy magnetic phase at lower temperature. [2]

Doping with higher ionic radius element 'Sr' at 'B'-site of parent LCMO, changes the tolerance factor & average 'A'-site ionic radius ($\langle r_A \rangle$) slightly, but, the size disorder parameter (σ^2), defined as,
$\sigma^2 = \Sigma x_i r_i^{\,2} - \langle r_A \rangle^2$,varies significantly (Table II). Therefore, remarkably high value of σ^2 in LCSMO, compared to LCMO is responsible for breaking the long-range magnetic ordering and gradually increases the disorder in LCSMO compound. [4] Thus, the presence of intrinsic defects, like uncompensated surface spins, pinning centers along with high size disorder parameter in nanostructured LCSMO, are esponsible for the development of glassy magnetic phase at low temperature.

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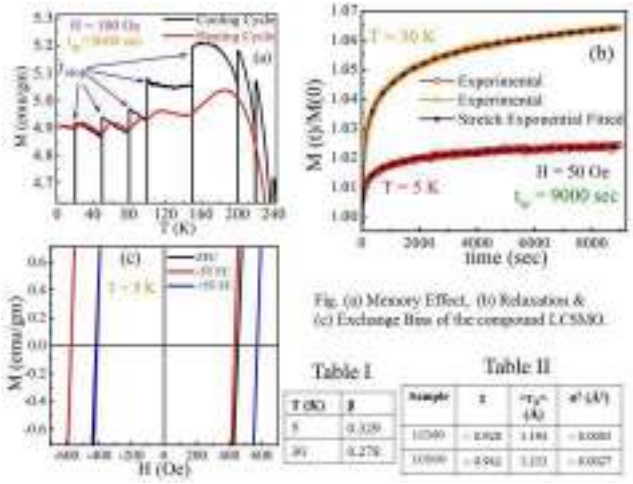

Fig. (a) Memory Effect, (b) Relaxation & (c) Exchange Bias of the compound LCSMO.

Table I

T (K)	β
5	0.320
30	0.270

Table II

Sample	x	$\sim r_A$ (Å)	σ^2 (Å^2)
LCSMO	0.925	1.191	0.0001
LSMO	0.950	1.223	0.0027

O178 - Microstructure and magnetism of Ni0.5Zn0.5Fe2O4/MWCNTs nanocomposites

11. Nanomaterials, patterned films, nanoparticles and molecular magnetism

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Nowadays, spinel ferrite nanoparticles (SF-NPs) are intensively studied due to their wide applications. Moreover, the combination of magnetic SF-NPs and carbon nanotubes (CNTs) into nanohybrids sensitive to the chosen synthesis method may expand their potential applications and make them highly attractive for new material development [1-2].

In present work we used the $Ni_{0.5}Zn_{0.5}Fe_2O_4$ ferrite nanoparticles (NFZO) synthesized via co-precipitation method [3]. The as-prepared NFZO and funcionalized multi-walled carbon nanotubes (MWCNTs) were used to prepare NZFO/MWCNT nanocomposites with the 2 wt % of NFZO. First MWCNTs were dispersed in ethanol using ultrasonic waves. Next, the ethanol solution of NFZO was slowly dropped into MWCNTs solution under continuously magnetic stirring. After that, the whole system was heated up to 60 °C and maintained for 4 h. Finally, the material was filtered and dried. The calcination was carried out under argon protection at 300°C. The structure, composition and morphology of the nanocomposites were characterized with X-ray diffraction (XRD), transmission electron microscopy (TEM) and photoemission spectroscopy (XPS). The magnetic properties were investigated with the use SQUID magnetometer.

The synthesis of the nanocomposites was proved. XRD patterns confirmed the crystalline structures of the NZFO/MWCNTs nanohybrids as compared to pure NZFO as well as MWCNTs. The TEM image before calcination process (Fig.1a) reveals the presence of agglomarated NPs with an average crystallites size of $d_{cryst} \approx 12 \pm 3$ nm which are attached by electrostatic interaction to nanotubes. The average internal diameter of nanotubes is about $d_{int} \approx 8 \pm 1.5$ nm whereas the external one about $d_{ext} \approx 21 \pm 4.1$ nm. After calcination no significant change within morphology was noticed.

The comparison of XPS spectra of studied nanomaterials reveals the domination of MWCNTs contribution. The analysis of core levels performed after surface cleaning by Ar^+ beam (1.5keV) for 45min. was effectively done. The distribution of Fe^{3+} cations over A-tetrahedral and B - octahedral sites is retained independently from calcination process. However, the percentage contribution of pure Fe clusters is sensitive to calcination.

The hysteresis loops of the NFZO/MWCNTs were investigated at 2K, 100K and 300K up to 7T (Fig.1b) and exhibit typical for SF-NPs thick S-shape. Moreover, at low temperature small hysteresis with low coercivity (H_C) is observed suggesting rather ferrimagnetic behaviour, whereas for T ³ 100K the possible existence of superparamagnetic (SPM) state with almost zero H_C and negligible remanence may occur (Fig.1c). The SPM is also confirmed by typical AC susceptibility frequency dependent variation of blocking temperature T_B and can be analyzed similarly like in NFZO by the use of Vogel- Fulcher relation [3]. The observed drastic reduction in saturation magnetization (M_S) for nanocomposites as compared to pure NFZO is due to large NFZO-MWCNTs dilution ratio. However, the calcination process leads to slight increase of M_S probably caused by pure Fe cluster separation confirmed by XPS.

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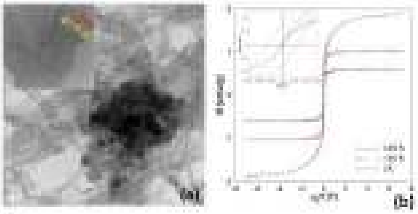

(c)

Hysteresis loops											
NiCoO				NiCoO/MWCNTs				NiCoO/MWCNTs calcined at 300°C			
	5K	100K	300K		5K	100K	300K		5K	100K	300K
M_s [emu/g]	[illegible]	[illegible]	[illegible]	M_s [emu/g]	[illegible]	[illegible]	[illegible]	M_s [emu/g]	[illegible]	[illegible]	[illegible]
M_r [emu/g]	[illegible]	[illegible]	[illegible]	M_r [emu/g]	[illegible]	[illegible]	[illegible]	M_r [emu/g]	[illegible]	[illegible]	[illegible]
H_c [kOe]	[illegible]	[illegible]	[illegible]	H_c [kOe]	[illegible]	[illegible]	[illegible]	H_c [kOe]	[illegible]	[illegible]	[illegible]

Fig. 1. (a) TEM image; (b) hysteresis loops for non-calcined NiCoO/MWCNTs nanocomposites and (c) comparison between magnetic parameters for NiCoO/MWCNTs nanocomposites not calcined and calcined at 300°C.

O179 - Pre-ordered Precursors Reduction: an effective route to synthesize highly ordered L10 particles

11. Nanomaterials, patterned films, nanoparticles and molecular magnetism

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Chemically ordered $L1_0$ magnetic alloys have attracted a special attention in the last decades due to their peculiar physical properties and excellent chemical stability, which arise from the particular arrangement of the atoms that alternate in composition along the *c*-axis direction of the *fct* unit cell. Despite the $L1_0$ phase is stable at low temperature below the order/disorder transition temperature $T_{O\text{-}D}$, high processing temperatures (700 – 800 °C) are usually required to increase the atomic mobility and favor the formation of the superstructure. Lowering the ordering temperature is therefore a critical issue for achieving the ordering in all the alloys whose low $T_{O\text{-}D}$ hinders the formation of the $L1_0$ phase by ordinary thermal processes.

In this work, a synthetic strategy, called *Pre-ordered Precursors Reduction* (*PPR*) [1-3], exploiting the use, as starting materials, of crystal salts consisting of an ordered arrangement of pure elements on alternating atomic planes, is proposed as an effective and versatile method to obtain $L1_0$ alloy particles at lower ordering temperatures (Figure 1). For such a purpose, a systematic work as a function of the processing temperature (*T*) and reaction time (*t*) was performed to synthesize $L1_0$ MPt binary alloys (M = Fe, Co, Ni) by thermal decomposition in a reductive atmosphere of layered $M(H_2O)_6PtCl_6$ crystal salt precursors. The three alloys present different $T_{O\text{-}D}$ (FePt: 1350 °C, CoPt: 825 °C, NiPt: 630 °C) resulting in a different driving force for ordering. In particular, the very low $T_{O\text{-}D}$ of NiPt makes the synthesis of such a system extremely challenging, and only few studies are mentioned in the literature using prolonged and high-temperature multi-step thermal treatments.

The pre-ordered structure of the starting salt leads to the formation of chemically ordered nuclei, which strongly affect the subsequent formation to the $L1_0$ phase that occurs at much milder conditions than usual. Almost fully ordered FePt nanoparticles were indeed obtained at T = 400 °C and t = 2 h. Higher temperatures (600 °C) and longer reaction times (8 h) were necessary to obtain almost fully ordered CoPt particles due to the lower $T_{O\text{-}D}$ of such alloy. Moreover, despite the low $T_{O\text{-}D}$ of the NiPt alloy, partially ordered $L1_0$ nanoparticles were obtained at T = 350 °C (t = 2h) and an almost fully ordered phase was achieved at 600 °C (t = 2 h). The pre-ordering strategy, which is commonly applied to obtain $L1_0$ thin films by alternating layer deposition, was applied at the atomic scale by taking advantage of the perfect order that is naturally found in a crystal. The results indicate that, by properly choosing the starting salt, the *PPR* method could be used to synthesize $L1_0$ binary magnetic alloys, including those with a low $T_{O\text{-}D}$, such as the $L1_0$-FeNi alloy ($T_{O\text{-}D}$ ~ 320 °C), which is nowadays considered one of the most promising materials for next geenration critical element free permanent magnets.

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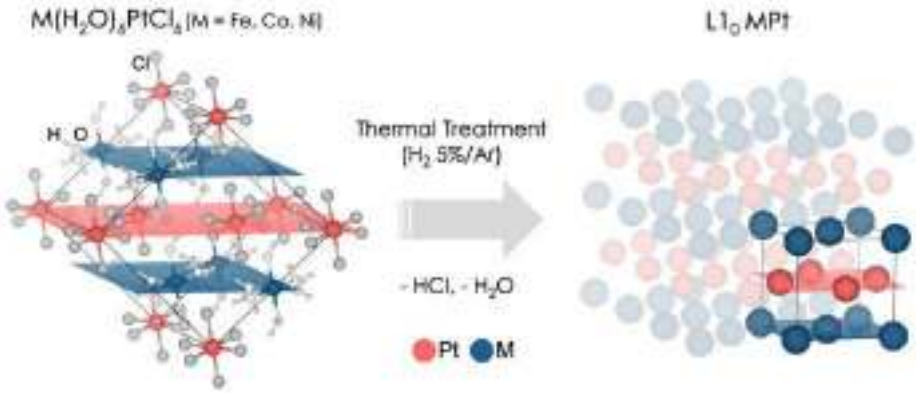

Figure 1. Schematic illustration of the *Pre-ordered Precursors Reduction* strategy exploited for the synthesis of chemically ordered MPt alloys (M = Fe, Co, Ni).

O180 - Strong emergence of magnetic disorder in orbital free moment GdCu2 antiferromagnetic nanoparticles.

11. Nanomaterials, patterned films, nanoparticles and molecular magnetism

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Rare Earth intermetallics exhibit a *rich variety of magnetic structures and crystal-field effects* [1]. A typical family of these Rare Earth intermetallics are RX_2 systems (R = Rare Earth, X = non-magnetic metal) such as GdX_2. Gd^{3+} has a high magnetic moment ($J = 2$, $\mu_{eff} = 7.94\ \mu_B$) but no crystal field effect ($L = 0$). If, for example, $X = Al$, the behaviour is ferromagnetic in bulk, with $T_C = 170$ K. But if $X = Cu$, *the* alloy becomes antiferromagnetic, with $T_N = 41$ K. *Therefore, this possibility of drastically modifying the magnetic (moment) structure by changing X is one of the main advantages of these alloys*.

A *promising research line consists on investigating the influence of milling (i.e. reducing the size of the nanograins) in the magnetic behaviour of* GdX_2 *alloys* [2]. In this work, *we have undergone a profound study of milled* $GdCu_2$ *alloys* with milling times 0.5 - 5 hours, thereby obtaining magnetic nanoparticles (MNPs) reaching sizes down to 7 nm. X-Ray Diffraction has confirmed that all samples displayed the same crystalline structure (*Imma*) as in the parent bulk alloy, with lattice parameters $a = 4.331(2)$ Å, $b = 6.896(3)$ Å and $c = 7.3499(1)$ Å. However, the milling process introduces an increasing strain factor (reaching up to $\eta = 0.90(7)$ %).

AC-susceptibility measurements performed by SQUID magnetometry demonstrate that, as milling time increases, the antiferromagnetic phase coexists with a growing magnetic disorder, causing the appearance of a freezing transition below $T_f = 28$ K, much higher that that in the $TbCu_2$ nano-alloy counterpart, with $Tf = 15$ K [3, 4]. This transition causes the appearance of magnetic irreversibility in the thermal variation of DC-magnetisation. In particular, we observed that for milling times greater than 2 h (NP size below 9 (1) nm), the AFM order was completely destroyed. AC-susceptibility measurements revealed that these samples behave like a Spin Glass (SG) system with low δ values (below 0.014), as is typical for SG systems [3].

As the core crystal structure is barely affected by the milling time, this rising magnetic disorder can be mainly attributed to the size reduction. In this way, as $GdCu_2$ samples become nano-sized, the magnetic interactions between Gd^{3+} ions (RKKY interactions) get randomised due to the increasing disorder of magnetic moments on the surface of these nanoparticles, although lattice strain should not be discarded.

AcknowledgementsThis work has been supported by the MAT2017-83631-C3-R grant. EMJ thanks the “Beca de Colaboración” BOE-B-2016-33433 granted by the “Ministerio de Educación, Cultura y Deporte” and the “Beca Concepción Arenal” BOC-133-09-07-2018 granted by the Gobierno de Cantabria.

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O181 - Structural and Magnetic properties of Cr-Substituted ε-Fe2O3 Nanoparticles

11. Nanomaterials, patterned films, nanoparticles and molecular magnetism

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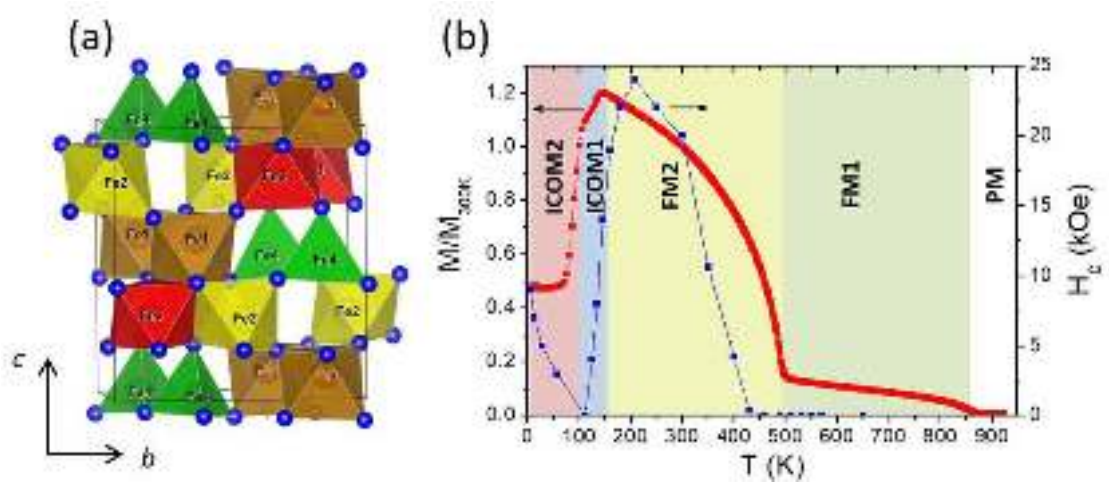
The epsilon phase of Fe_2O_3 being much less studied than other iron (III) oxide polymorphs, has received unprecedented attention in the last few years due to its unique physical properties, including giant coercivity (up to 2 T at room temperature), magneto-electric coupling [1], and millimeter-wave ferromagnetic resonance. ε-Fe_2O_3 has four non-equivalent Fe^{3+} sites in the non-centrosymmetric *Pna2₁* structure (Fig. 1 a). Its frustrated structure provides a rich magnetic phase diagram. It presents four different magnetic structures between 4 K and 900 K (see Fig. 1 b): 2 incommensurate magnetic orders (ICOM2 and ICOM1) below 150 K, and 2 collinear ferrimagnetic orders along [100] (FM2 and FM1) between 150 K and the Curie temperature at 850 K [2].

In this work, a series of Cr doped ε-Fe_2O_3 nanoparticles (~20 nm) confined in silica matrix has been prepared by sol-gel method. The *Pna2₁* structure of ε-Fe_2O_3 is rather robust against the substitution of Fe by Cr. The structure evolution across the FM2/FM1 transition at ~480 K (hard-soft transition) is carefully studied by synchrotron X-ray diffraction in order to gain insight on the presence of orbital moment related with the unusual properties of the super-hard magnetic phase. Macroscopic magnetic measurements showed that Cr doping has a strong impact on both the low and high temperature magnetic properties. So, the quenched orbital moment magnetic phase (ICOM1) is strongly favored by Cr doping. Synchrotron x-ray absorption studies (XAS) have confirmed the Cr^{3+} state (isovalent substitution) of chromium cations. These results, together with some neutron measurements suggest a key role of the spin-lattice coupling and magnetic anisotropy in this complex polar system.



O182 - Symbiotic, low-temperature synthesis of LaFeO3-CoFe2O4 magnetic nanocomposites

11. Nanomaterials, patterned films, nanoparticles and molecular magnetism

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Magnetic nanocomposites, where the individual components themselves are complex systems belonging to the family of strongly correlated electron oxide systems, are both interesting as well difficult systems to study. The difficulty lies as much in the synthesis of pure phase nanocomposites as in the understanding of the cross-correlated electronic and magnetic properties. An easy way to synthesize nanocomposites is to physically mix the two phases. However, a simple physical mixing of the two phases leads to clustering and aggregation of the individual phases on the micron scale that is often detrimental to the physical properties of the nanocomposites. A second method is to use pre-formed nanoparticles of one phase and grow the second phase around these pre-formed nanoparticles. Such a synthesis method yields better homogeneity than physically mixed samples, but some level of clustering and aggregation is still present.

In the present paper, we report a modified sol-gel synthesis technique in which both the phases of the nanocomposite (in our case, $LaFeO_3$ (LFO) and $CoFe_2O_4$ (CFO)) are formed during the same time. This is a bottom-up approach that reduces clustering and aggregation of the individual phases to the minimum possible, yielding true homogeneity on the nanoscale. We will also show, how, contrary to naïve expectations, the LFO and CFO phases help each other during the synthesis process during which the CFO crystals act as nucleation points for the LFO phase. The formation of CFO proceeds with an exothermic reaction, and the heat produced is sufficient to crystallize the LFO phase, so that pure phase nanocomposites are formed at a temperature as low as 250 ^{o}C, without the need for further annealing at higher temperatures. This is quite remarkable because most oxides belonging to the family of strongly correlated electron oxides (including pure LFO) require annealing at higher temperatures (~500 ^{o}C) for complete crystallization. In turn, the LFO phase acts as a matrix, and prevents the growth of the CFO nanoparticles in the nanocomposite, as evidenced by the fact that pure CFO (in the absence of an LFO matrix) formed using the same synthesis technique yields particles with a larger size as compared to the particle size of CFO in the LFO-CFO nanocomposites. We will present details of this symbiotic synthesis process along with the physical properties of the LFO-CFO nanocomposites.

We thank Carl Tryggers Stiftelse för Vetenskaplig Forskning (grant number KF 17:18), Swedish Research Council (VR starting grant number: 2017-05030), Stiftelsen Olle Engkvist Byggmästare (grant number: 188-0179), and the Royal Physiographic Society of Lund (the Märta and Eric Holmberg Endowment) for financial support.

O183 - Two-step magnetization reversal in sharply diameter-modulated bisegmented cylindrical nanowires

11. Nanomaterials, patterned films, nanoparticles and molecular magnetism

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Cylindrical nanowires, NWs, are promising curved nano-objects that offer new capabilities arising from their revolution symmetry such as circular geometry-mediated phenomena and topologically non-trivial magneto-chiral structures [1] with innovative technological application for domain-wall-based devices in new-generation spintronics [2]. An emerging interest addresses the reversal process in NWs with modulations in diameter or composition (multilayer) enabled by their fine-tuned electrochemical growth, where the transition regions determine the pinning/depinning mechanism for the propagating domain wall, DW. Advances recently reported in multisegmented Ferromagnetic/Metal NWs (i.e., magnetization ratchet) and diameter modulations (including anti-notched NWs), have shown promising results [3], although only modest difference in diameters (i.e., 110 to 130 nm) was considered.

Here, we combine electrodeposition and atomic layer deposition, ALD, techniques to enable a larger difference in diameter and a more abrupt transition between the segments to enhance the pinning and facilitate the control over the DW motion. For an optimized identification of the process, we consider a simplified case of bisegmented NWs. Hexagonal dense arrays of bisegmented NWs with two well defined diameters have been grown by electrodeposition inside of engineered pores of anodic alumina templates prepared by an advanced combination of mild anodization in oxalic acid, pore widening and controlled ALD. Subsequently, SEM, EDS, XRD and HRTEM techniques were used to determine their geometry (i.e., 40 and 80 nm diameter, 5 micron long, 105 nm hexagonal lattice constant), composition (Ni and $Fe_{50}Co_{50}$) and structure (*fcc and bcc* cubic) characteristics [4].

The magnetic behavior was investigated in a VSM under 1.5 T maximum applied magnetic field as a function of its angle with the NW axis. The angular dependence of coercivity and remanence suggests a magnetization reversal by propagation of transverse wall. The figure shows a typical axial loop with reduced remanence ascribed to the significant magnetostatic interactions among NWs in spite of their dominant longitudinal shape anisotropy. The two maxima observed in the Anisotropy Field Distribution, AFD, together with the bi-valuated susceptibility denote a magnetization reversal taking place by DW propagation in two steps ascribed each to the individual segments with different diameter, the wall being pinned at the diameter transition. A systematic analysis of the First Order Reversal Curves, FORC, was successfully conducted where the splitting of the interaction field in the diagram into two branches around two different values of coercive field is correlated to the segments of different diameter. Bi-segmented nanowires engineered with a sharply defined diameter modulation are proved to magnetize nearly independently, which constitutes a key point for the development of novel ultrahigh-density data storage devices based on 3D NW arrays.

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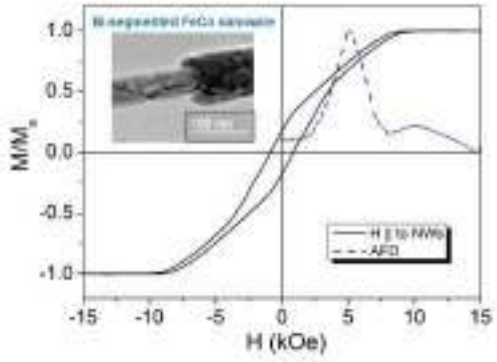

Figure. Axial hysteresis loop of a bi-segmented FeCo nanowire array presenting a two-steps susceptibility and the corresponding Anisotropy Field Distribution, AFD. Inset shows a HRTEM image of the nanowire taken at the geometrical modulation.

12. Spin-orbit and topology driven phenomena

O184 - Analytical modeling of skyrmion-extended defect interaction

12. Spin-orbit and topology driven phenomena

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The performance of skyrmion-based spintronic devices is affected by the presence of defects in the materials. We present an analytic model for describing the interaction of skyrmions with defects in ultrathin films. The starting point is a Gaussian-like potential of interaction between a defect and a point defect. From this potential, other expressions for the interaction between skyrmions with extended defects, such as line-segments, infinite lines, crossing lines, etc., are found. The dynamics of skyrmions in the presence of such defects, under the driving of polarized current is studied. We consider several types of torques acting over the skyrmion, either coming from the spin transfer torque with in-plane polarized electrons in the ferromagnet (J_f) or from spin Hall-effect induced polarized currents coming from a heavy-metal substrate (J_h). The rewriting of Thiele's equation in the complex plane shows a natural way for expressing all the torques simultaneously into a single vector field, allowing for a complete description of the system with a reduced number of parameters. This expression has a simple geometrical interpretation. For the different types of extended defects we consider, we find the conditions for which dynamic regimes of pinning, guiding, accelerating, or arranging skyrmions by defects can be established. In particular, expressions for the threshold driven current-density to pin or depin skyrmions in such defects, the position of the critical points, as well as the guiding conditions along long defects are found.

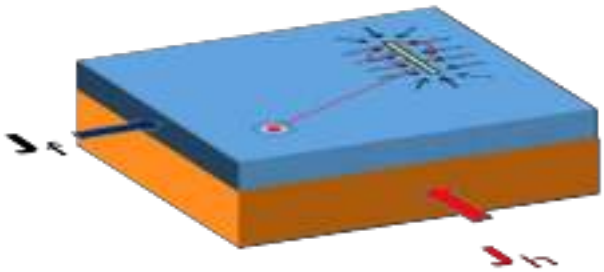

Figure 1. Sketch of the studied system considering a skyrmion (red dot) moving through a defect (segment) whose force over the skyrmion can be modelled by a vector field (black arrows). The driving currents J_f and J_h are also shown.

O185 - Antiferromagnetic skyrmions in room-temperature synthetic antiferromagnetic multilayers

12. Spin-orbit and topology driven phenomena

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Magnetic skyrmions constitute localized magnetic textures, behaving as single particles in two-dimensional systems and featuring specific topological properties. They have been identified as extremely promising for applications in both memory and computing devices, as well as of fundamental interest [1]. A major research effort on materials has been done in the last couple of years to stabilize them successfully at room temperature with sizes down to 100 nm, most often by designing magnetic multilayers combining perpendicular magnetic anisotropy, Dzyaloshinskii-Moriya (DM) interaction and heavy-metal layers [2]. The DM interaction promotes a unique chirality for the magnetic texture of the skyrmions, which allows, in combination with spin-orbit torques generated in neighboring heavy-metal layers, their efficient current-induced motion up to 100 m/s [3]. Future skyrmion research aims at reaching the room-temperature stabilization of even smaller skyrmions as well as their more efficient motion with spin-orbit torques, in order to meet the level of expectations they have raised.
To reach these objectives, ferrimagnetic materials have been experimentally studied and have provided very promising results [4]. Likewise, synthetic antiferromagnetic (SAF) systems have been theoretically proposed to allow the desired skyrmions properties [5]. In this work, we therefore explore how to obtain experimentally such small and mobile skyrmions in sputter-deposited SAFs. First, we show how we have obtained SAFs hosting chiral magnetization textures, and how we have biased them in order to stabilize antiferromagnetic skyrmions at zero field and at room temperature [6]. We then detail our imaging experiments, based on advanced magnetic force microscopy, aiming at characterizing the properties of these antiferromagnetic skyrmions, together with the modelling of their expected small but measurable dipolar fields. We also discuss size and velocity aspects, as predicted from micromagnetic simulations fed with the experimental magnetic parameters measured in our experimental multilayers. Finally, we also describe some experimental results showing that the electrical measurement of chiral magnetization textures in SAF systems is feasible [7].

French ANR grant TOPSKY (ANR-17-CE24-0025), DARPA TEE program grant (MIPR#HR0011831554) and EU grant SKYTOP (H2020 FET Proactive 824123) are acknowledged for their financial support.

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O186 - Chiral skyrmion auto-oscillations under spin transfer torque

12. Spin-orbit and topology driven phenomena

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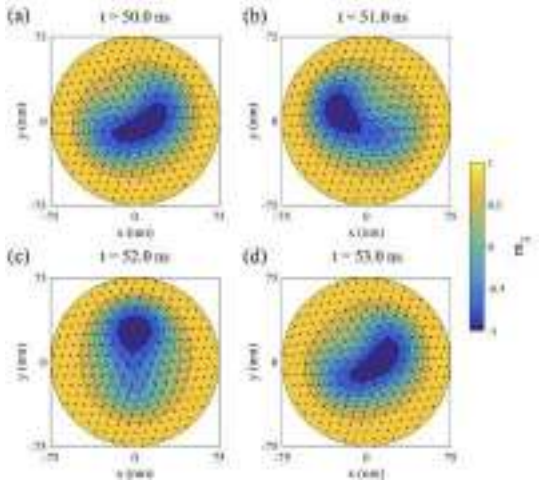
A skyrmion can be stabilized in a nanodisc geometry in a ferromagnetic material with perpendicular anisotropy and Dzyaloshinskii-Moriya interaction (DMI). We apply time independent and spatially uniform spin-torque across the disc particle and observe numerically that this is set in a steady rotational motion around a point off the nanodisc center. This phenomenon is very different than oscillations reported in previous studies where non-uniform or time-dependent torques were applied. The sustained rotation of the skyrmion which is reported here is obtained in a very simple system which is easier to realize. The skyrmion oscillations are robust with respect to varying parameters within a large range, such as the polarized current, the DMI parameter, the external field, the disc size, or the damping constant. The figure shows four snapshots from a complete cycle of the rotation of the skyrmion.

We give a theoretical description of the emerging auto-oscillation dynamics based on the coupling of the rotational motion to the breathing mode of the skyrmion. It is already known that excitation of the breathing mode through the spin current gives rise to oscillations of the magnetization perpendicular to the disc. In addition, we show here that the breathing mode is accompanied by associated oscillations of the in-plane magnetization components. The simultaneous oscillations of the perpendicular and the in-plane components of the magnetization are due to the fact that these are associated with conjugate variables in the Hamiltonian formalism for the Landau-Lifshitz equation. We show that the combined oscillations of the perpendicular and in-plane magnetization components are crucial for the emergence of skyrmion auto-oscillations in the form of combined rotation and breathing. We thus argue that the achievement of auto-oscillations in this simple set-up is due to the chiral symmetry breaking.

In order to show the technological relevance of the phenomenon, we demonstrate injection locking of our skyrmion oscillator when a small AC current with a frequency close to the resonant frequency is used. This is the first step towards synchronization of multiple oscillators, which would enhance the output power and narrow down the obtained linewidth.

We finally explain general arguments showing that chiral symmetry breaking enables dynamical behavior of solitons and can give rise to stationary states in ferromagnets with Dzyaloshinskii-Moriya interaction. The skyrmion auto-oscillations is an example of such a dynamical stationary state. A further example is given by a traveling domain wall solution for the Landau-Lifshitz equation in uniaxial ferromagnets. Its profile and velocity crucially depend on the chiral symmetry breaking and are thus very different than the well-known Walker traveling domain wall. Our methods pave the way in order to find and study further dynamical stationary states in DMI ferromagnets.


(a)
t = 50.0 ns
(b)
t = 51.0 ns
(c)
t = 52.0 ns
(d)
t = 53.0 ns

O187 - Creation of magnetic skyrmions by surface acoustic waves in Co/Pt/Ir trilayer films

12. Spin-orbit and topology driven phenomena

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Skyrmion, nanometric topological spin texture, gives rise to various unique physical phenomena and offers great possibilities for applications. Especially, because of ultralow current driven motion of skyrmion, skyrmion is considered as a promising candidate for an information bit in new magnetic storage devices [1,2]. Recently, the formation of Neel-type skyrmion at and above room temperature is reported in multilayer thin films in which magnetic metal is sandwiched by two heavy metals due to interfacial Dzyaloshinslii-Moriya interaction (iDMI) originating from the breaking inversion symmetry at the interface [2,3]. This has accelerated the research on the development of skyrmion-based storage devices. In order to realize these devices, efficient and practical means to create skyrmions are highly demanded. So far the creation of skyrmions has been demonstrated by employing local spin-orbit torque arising from an electric current flowing in multilayer films processed into special shapes with a notch or a constriction [3,4]. However, in these methods, the position where skyrmions are created is limited at a specific position of the multilayer films and relatively large current density is required

In this presentation, we demonstrate a novel approach for the creation of skyrmion, focusing on the interplay between the spins and strain resulting from surface acoustic waves. A stack of Pt/Co/Ir was deposited on $LiNbO_3$ substrate and surface acoustic waves were excited by using interdigital transducers (IDTs). We used a Kerr microscope in polar geometry to observe magnetic structures. When the surface acoustic wave is excited in the ferromagnetic state, skyrmions appear in the Pt/Co/Ir film, which indicates surface acoustic waves create skyrmions (Fig. 1). To clarify the mechanism for the skyrmion creation induced by surface acoustic waves, we performed micromagnetic simulation and found that an inhomogeneous torque arising from surface acoustic waves via the magnetoelastic coupling create a pair of Néel and antiskyrmion-like structure, which subsequently transforms to Néel skyrmion due to the instability of antiskyrmion-like structure in the iDMI systems. We also investigated the wavelength dependence of the number of created skyrmions in both experiment and simulation; the creation efficiency of skyrmions are maximum when the size of skyrmion is comparable to the size of an inhomogeneous torque. Our results offer a novel guiding principle for a means to create skyrmions in ultrathin films.

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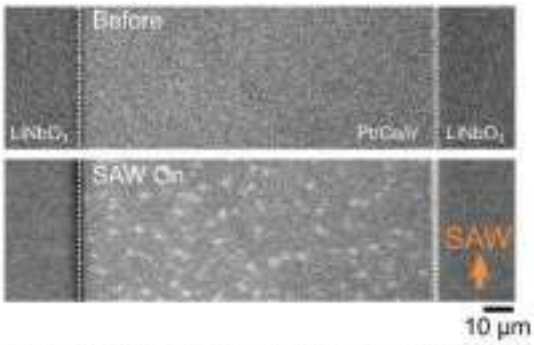

Fig. 1 Polar Kerr magnetic images for creation of skyrmions by surface acoustic waves.

O188 - Current-driven domain wall motion along ferrimagnetic stacks

12. Spin-orbit and topology driven phenomena

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Recent experimental observations [1] show that current-driven domain wall (DW) motion can reach velocities as fast as 1km s^{-1} along stacks formed by two antiferromagnetically coupled ferromagnetic bilayers on top of a heavy metal (HM). The dragging mechanism, resulting in a vanishing DW tilting, allows fast and synchronous tracking of DWs, even along curved paths [2,3]. More recently, it has been also found that under certain conditions a linear relationship between domain wall speeds and current magnitudes also occurs in the case of certain ferrimagnetic (FiM) alloys, where spins interact antiferromagnetically [4,5].

Based on these promising experimental results, here we provide a full micromagnetic (mM) analysis of the current-driven DW dynamics in HM/FiM stacks (Fig. 1(a)), also extendable to other antiferromagnetically coupled systems. Our micromagnetic model treats the FiM as constituted by two sublattices coupled by means of an additional interlattice exchange, and differing in their gyromagnetic ratios and temperature behavior. Other interactions are accounted for differently within each sublattice, depending on the considered physical characteristics. Micromagnetic simulations are also supported by an extended one-dimensional model (1DM) that, differently from previous approaches based on effective parameters [4,5], also considers the FiM as formed by two coupled sublattices with experimentally definite parameters. This is rather important, since according to recent experimental evidence [6] the characteristic parameters of the material, such as gyromagnetic ratio or Gilbert damping constant, are not needed to diverge to account for the magnetization dynamics, contrarily to what it was suggested in the literature [4,5]. Therefore, such approach permits to infer results not achievable from the mentioned effective models that can be of relevance to understand future experimental results. Examples of the current-driven DW motion along these HM/FiM stacks are shown in Fig. 1(b) and (c) for different current and temperatures. Additionally, realistic conditions are also considered in our study, which allow us to describe experimental observations. Our results confirm the alignment of the magnetization with the direction of the electric current as responsible for the linear increase of DW terminal velocities with current. This alignment is remarkable when the angular moment compensation of sublattices occurs in these FiM alloys, at a temperature (T_A) close but not equal to the magnetization compensation temperature (T_M).

Moreover, we have also studied the current-driven DW motion along curved HM/FiM stacks, which is found to be dissimilar to that along straight ones, with different speeds depending on the DW type. Our methods and results will be of relevance to understand future experimental results and also for the development of DW-devices based on ferrimagnetic stacks.

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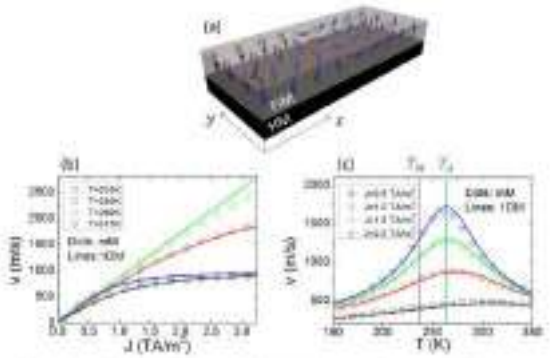

Fig. 1 (a) Scheme of the HM/FM stack. (b) DW velocity as a function of the injected current density along the HM at different temperatures along a perfect sample. (c) DW velocity as function of the temperature for different current densities. Dots are micromagnetic results and solid lines 1DM predictions.

O189 - Dynamically controlling Dzyaloshinskii-Moriya Interaction: a route towards skyrmion chirality switch

12. Spin-orbit and topology driven phenomena

Titiksha Srivastava[1] , *Marine Schott[1, 2], Roméo Juge[1], Viola Krizakova[2], Mohamed Belmeguenai[3], Yves Roussigné[3], Anne Bernand-Mantel[2, 4], Laurent Ranno[2], Stefania Pizzini[2], Salim-Mourad Cherif[3], Andrey Stashkevich[3], Stéphane Auffret[1], Isabelle Joumard[1], Willy Lim[1], Olivier Boulle[1], Gilles Gaudin[1], Mair Chshiev[1], Claire Baraduc[1],* ***Hélène Béa***[1]

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Electric control of magnetism is a prerequisite for efficient and low power spintronic devices. More specifically, in heavy metal/ferromagnet/oxide heterostructures, voltage gating has been used to locally and dynamically tune magnetic properties like interface anisotropy or saturation magnetization [1,2]. Moreover, in these non-centrosymmetric structures, Dzyaloshinskii-Moriya Interaction (DMI) [3,4] gives rise to non-collinear spin textures. Therefore, the magnetic bubbles observed in these systems have Néel type domain wall of a specific chirality, determined by the sign of DMI: these skyrmions or skyrmionic bubbles, which are promising to code information bits, are envisioned for memory, logic and neuromorphic devices.

The effect of electric field on DMI has been challenging to achieve and measure in ultrathin films. Here, we study Ta/FeCoB/TaO_x trilayers where we have optimized thicknesses and interface quality by using wedges of both FeCoB and the top Ta to create a gradient of oxidation at FeCoB/TaO_x interface. Using Brillouin Light Spectroscopy (BLS), we demonstrate in this system 130% variation of DMI parameter D with electric field E and an unprecedented electric field efficiency for DMI $\beta_{DMI}=\Delta D/E=600$ fJ/Vm [5]. To compare with the long time (hour timescale) BLS measurements giving direct estimation of DMI, we have used faster (minute timescale) polar-Magneto-Optical-Kerr-Effect (p-MOKE) microscopy to determine DMI from the equilibrium domain size in demagnetized state (see Fig1a). In that case, a lower efficiency is obtained but with linear behaviour. These results are consistent with ionic migration mechanism for long time scale effects and pure charge effects for shorter time scale effects and a Rashba origin for the DMI [6].

The efficient DMI manipulation with voltage thus establishes an additional degree of control over skyrmionic and spin-orbitronic devices. We anticipate that a sign reversal of DMI with electric field is possible, which would lead to a chirality switch (see Fig1b-c). This dynamic engineering of DMI sets the foundation towards programmable skyrmion based memory or logic devices.

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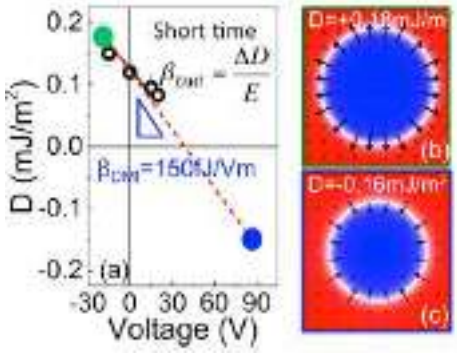

Figure 1: (a) Evolution of DMI coefficient under gate voltage measured by p-MOKE microscopy using the equilibrium size of domains in demagnetized state. (b-c) Micromagnetic simulation of skyrmionic bubble in the case of magnetic parameters corresponding to -20V (experimental values, green point on (a)) with positive DMI (b) and in the case of +88V (extrapolated from experimental values, blue point on (a)) with negative DMI. A switch of chirality is thus expected with voltage.

O190 - Dynamics of magnetostatically coupled skyrmions in cylindrical nanodots

12. Spin-orbit and topology driven phenomena

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Magnetic skyrmions are robust particle-like nanosize magnetization configurations with non-zero topological charges. The skyrmions attracted considerable attention due to their promising application in spintronics and information recording technologies. The skyrmion topological charges manifest themselves in non-trivial skyrmion spin dynamics. There are low-frequency skyrmion excitation modes related to motion of the skyrmion positions such as the gyrotropic (translation) modes [1, 2].

In this talk we focus on the low frequency dynamics of magnetic skyrmions in magnetostatically coupled cylindrical nanodots [3]. We consider the particular cases of the dot pairs and linear chains of the dots. Individual skyrmions in the dots (with thickness about of 1 nm and radius about of 100 nm) are assumed to be stabilized by an interplay of the isotropic exchange and Dzyaloshinskii-Moriya exchange interactions, magnetic anisotropy and magnetostatic interactions. We consider the dipolar and quadrupolar interactions between moving skyrmions in the dots as a prevailing mechanism responsible for the dynamic interdot magnetostatic coupling. We show that the skyrmion dipolar moments do not depend, whereas the quadrupole moments depend strongly on the internal skyrmion magnetization configuration. This is manifested in the dynamic properties of the coupled skyrmion dot arrays. We calculate the frequency dispersion relations of the collective skyrmion gyrotropic excitations for the skyrmions differing by internal structure and polarity and discuss the found differences. We show that accounting the magnetostatic interaction between the skyrmions removes degeneracy of the gyrotropic frequencies existing for isolated skyrmions and allows distinguishing the Bloch and Neel skyrmionic configurations by their dynamic response to external stimuli.

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O192 - Isolated zero field sub-10 nm skyrmions in ultrathin Co films

12. Spin-orbit and topology driven phenomena

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Due to their exceptional topological and dynamical properties, magnetic skyrmions – localized stable spin structures on the nanometer scale – show great promise for future spintronic devices [1]. For such applications it is envisioned to use isolated skyrmions with diameters below 10 nm that are stable at zero magnetic field and at room temperature [2]. Despite finding skyrmions in a wide spectrum of materials, the quest for a material with these envisioned properties is still ongoing.

Here we show that zero field isolated skyrmions with diameters smaller than 5 nm coexist with 1 nm thin domain walls in Rh/Co atomic bilayers on the Ir(111) surface [3]. These spin structures are characterized by spin-polarized scanning tunnelling microscopy and can also be detected using non-spin-polarized tips due to a large non-collinear magnetoresistance (NCMR) [4] at the Fermi energy. We demonstrate based on a combination of density functional theory (DFT) calculations and atomistic spin dynamics simulations that sub-10 nm skyrmions are stabilised in these ferromagnetic Co films at zero field due to strong frustration of exchange interaction, together with Dzyaloshinskii-Moriya interaction and a large magnetocrystalline anisotropy. The experimentally and theoretically obtained zero-field skyrmion profiles are in good agreement. Using DFT calculations, we explain the experimentally observed NCMR by spin mixing of majority *d* and minority *p* states in the vicinity of the Fermi energy.

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O193 - Manifestation of exchange gap in topological insulator/magnetic insulator by transport measurement

12. Spin-orbit and topology driven phenomena

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Magnetic proximity effect (MPE) induced transport signatures of exchange gap opening in the band structure are reported for bilayer structure of Bi_2Se_3 thin films on thulium iron garnet (TmIG) of perpendicular magnetic anisotropy (PMA). Negative magnetoresistance (MR) was detected and attributed to an emergent weak localization (WL) effect superimposing on a weak antilocalization (WAL) one, which shows positive MR background. Thickness-dependent study reveals that the WL originates from the time-reversal-symmetry breaking of topological surface states by interfacial exchange coupling. Angular dependent measurements show that the weight of WL declined when the interfacial magnetization was aligned toward the in-plane direction, which is understood as the effect of tuning the exchange gap size by varying the perpendicular magnetization component. Clear evidence of anomalous Hall effect (AHE) of square loops and anisotropic magnetoresistance (AMR) characteristic, typifying a ferromagnetic conductor and the presence of an interfacial ferromagnetism driven by MPE will be presented. Coexistence of the MPE-induced ferromagnetism and the finite exchange gap in the band structure provides an opportunity of realizing zero-magnetic-field dissipationless transport in topological insulator/ferromagnetic insulator heterostructures.

O195 - Photocurrents in 3D topological insulators Hall bar and nanowire devices

12. Spin-orbit and topology driven phenomena

Nina Meyer[1] , *Thomas Schumann[1], Eva Schmoranzerová[2], Kevin Geishendorf[3], Gregor Mussler[4], Jakob Walowski[1], Petr Nemec[2], Andy Thomas[3], Kornelius Nielsch[3], Detlev Grützmache[4], Markus Münzenberg[1]*

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Topological Insulators (TI) open up a new route to influence the transport of charge and spin in a surface film via spin-momentum locking [1,2]. It has been demonstrated experimentally [2] that illuminating a TI by circularly polarized light can result in excitation of a helicity-dependent photocurrents.

The photocurrent measurements were performed on $(Bi, Sb)_2Te_3$ thin films Hall bar structures and Bi_2Se_3 core-shell nanowires. We illuminate the TIs with visible laser light (785nm) for both kinds of samples and measure the photocurrent between two gold contacts. The position of the laser light can be changed in two directions parallel to the surfaces of the sample. At every laser spot, the polarisation of the exciting beam is changed periodically while measuring the photocurrent. Due to the polarisation dependence, the different contributions of the photocurrent at each position are separated and are displayed as spatially resolved 2D maps.

We detect in both cases a polarization dependent photoinduced current depending on the position of the laser light, consistent with results at room temperature reported by McIver et al. [2]. The helicity-dependent current can be switched by the lights polarization properties but is weak. For the Hall bar structure, a lateral accumulation of spin polarization at the TIs edges due to the spin Nernst effect is found [3]. For the nanowires, the interaction between nanowire and Au contact due to the Schottky effect and a constant spin polarized current far off the contacts is found.

We acknowledge funding through DFG priority program SPP "Topological Insulators" and DAAD PPP Czech Republic "FemtomagTopo".

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O196 - Role of the impurity potential in the gap opening at the Dirac point of topological insulators

12. Spin-orbit and topology driven phenomena

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A combination of nontrivial bulk band topology and robust ferromagnetic order makes magnetically doped topological insulators (TIs) most promising quantum materials for realizing the quantum anomalous Hall effect (QAHE). Because the spin of the surface electrons aligns along the direction of the magnetic-impurity exchange field, only magnetic TIs with an out-of-plane magnetization are thought to open a gap at the Dirac point (DP) of the surface states, resulting in the QAHE. Using a continuum model supported by atomistic tight-binding and first-principles calculations for transition-metal doped Bi_2Se_3, we show that a surface-impurity potential generates an additional effective magnetic field which spin polarizes the surface electrons along the direction perpendicular to the surface. The predicted gap opening mechanism results from the interplay of this effective field and the in-plane magnetization that shifts the position of the DP away from the Gamma-point. This effect is similar to the one originating from the hexagonal warping correction to the band structure but is one order of magnitude stronger. Our calculations show that in a doped TI with in-plane magnetization the impurity-potential-induced gap at the DP is comparable to the one opened by an out-of-plane magnetization.

O197 - Spin Hall effects in Non-Collinear Antiferromagnets

12. Spin-orbit and topology driven phenomena

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The detection and manipulation of electron spin currents is a key focus in spintronics. It is commonly believed that the spin Hall effect (SHE) is a relativistic spin-orbit coupling derived (SOC) phenomena where electrical current can generate transverse spin currents. In heavy metals SOC breaks the spin rotational symmetry, thereby resulting in SHE.

However, spin rotation symmetry can also be broken without relying on the SOC as, for example, in non-collinear magnetic textures. Such an effect was first proposed and experimentally reported in thin films of Mn_3Ir [1]. Recently, it was predicted [2] that the non-collinear antiferromagnet phase of hexagonal Mn_3Ge may also possess a large spin Hall angle.

In this work we study the SHE in two phases of Mn_3Ge - the cubic phase and the hexagonal phase - and show experimentally first indications of an SHE in this compound. Measurements are carried out using a highly sensitive optically detected ferromagnetic resonance (OFMR) technique[3].

Spin Hall effect without SOC may prove useful in future spintronic devices without the incorporation of heavy metals.

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O198 - Spin-Orbit Coupling in Graphene-MoS2 Hybrid Structures: An X-Ray Absorption Spectroscopy Study

12. Spin-orbit and topology driven phenomena

Adriana I. Figueroa[1] , *Ivan Fernandez Aguirre*[1, 2], *Regina Galceran*[1], *Lorenzo Camosi*[1], *Pierluigi Gargiani*[3], *Manuel Valvidares*[3], *Kevin Garello*[4], *Subir Parui*[4], *Cédric Huyghebaert*[4], *Salim El Kazzi*[4], *Jiongjiong Mo*[4], *Sergio O. Valenzuela*[1, 5]

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Spintronics is one of the vast prospects for applications of 2-dimensional materials. In particular, the combination of graphene with materials with large spin-orbit coupling (SOC) is offering new opportunities of achieving control and manipulation of spin transport in hybrid structures. A large enhancement in SOC of graphene interfaced with semiconducting transition metal dichalcogenides (TMDCs) has been predicted [1]. Experiments focusing on spin relaxation anisotropy have recently confirmed that the large SOC and spin–valley coupling in a semiconducting TMDC can be imprinted in graphene [2]. However, such measurements are indirect since they do not provide quantitative information about the SOC enhancement, while the mechanisms responsible are yet to be fully understood and, as a result, are not totally controlled. One of the experimental techniques that allows for a direct detection and measurement of SOC is x-ray absorption spectroscopy (XAS). We have used XAS to probe the electronic states of Graphene/MoS_2 structures in order to investigate SOC proximity effects. Analysis of the core-level spin-orbit split branching ratio [3] at the Mo XAS $L_{2,3}$ edges allowed us to quantify the change in SOC in the Mo 4*d* states in contact with graphene. Moreover, evidences of strong interlayer hybridization between the Mo 4*d* states and graphene *p* orbitals are observed, which is highly relevant to understand the mechanisms by which the SOC in graphene is enhanced in these heterostructures.

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O199 - Spin-orbit magnetic state readout with favorable miniaturization

12. Spin-orbit and topology driven phenomena

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Modern computing and memory are scaled to tens of nanometers in lateral dimensions driven by the favorable miniaturization of transistor technology (Moore's Law). Such a favorable miniaturization, so far missing in spintronics, is an essential requirement for proliferation of spin logic (*1*) and memory (*2*). Magnetoresistance effects have been hitherto used in magnetic state detection(*3*), but they suffer from unfavorable miniaturization and do not generate an electromotive force that can be used to drive a circuit element for logic device applications.

Here, we demonstrate the favorable miniaturization of the spin-orbit-based readout of a magnetic state. Sketch in Fig. 1(a) illustrates the spin-to-charge conversion device used for in-plane magnetic state detection. The charge current (I_C^{app}) is applied to inject the spin current (I_S) into the Pt T-shaped nanostructure. The inverse spin Hall effect in Pt converts this spin current to a negative or positive transverse charge current (I_C^{ISHE}) depending on the magnetization state of the CoFe electrode. Consequently, in-plane magnetization reversal will lead to a sign change of the transverse voltage, which we normalize to the applied charge current (I_C^{app}). Figure 1(b) plots as a function of the magnetic field. The two magnetization configurations of the electrode are clearly distinguished by the sharp resistance jump at the switching fields. We define the spin Hall signal as the difference in the resistance between the two magnetization orientations ($2\Delta R_{ISHE}$).

We show that the spin-to-charge conversion using ISHE allows us to independently enhance the spin Hall signal (needed to read the in-plane magnetization) and the output current (needed for cascading circuit elements) with downscaling of different device dimensions[see Fig. 1(c)], which are necessary conditions for implementing spin-based logic such as the MESO logic (*1*). We exploit these unveiled scaling laws to obtain giant spin Hall signals (0.3 Ω) at room temperature [Fig. 1(b)], which arise from the small dimensions and high resistivities of Pt (ρ_{Pt}) and CoFe (ρ_{CoFe}) [see definition of parameter G in Fig 1(c)], whereas the effective spin-to-charge conversion rate remains constant for the CoFe/Pt system. We show that it is possible to further increase the spin Hall signal to the values needed to operate the MESO logic with the proper choice of materials, making it a real candidate for post-CMOS computing.

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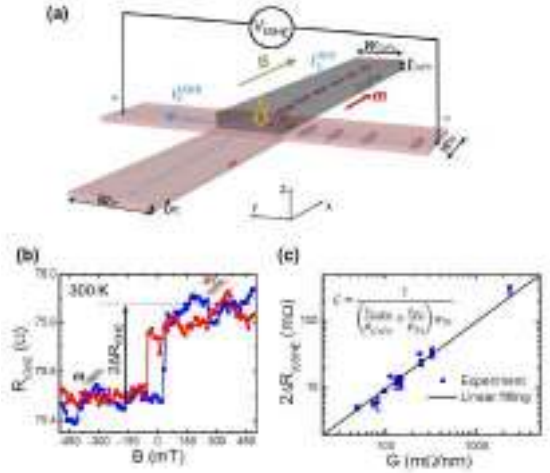
(a)
(b)
300 K
2ΔR_HE
B (mT)
(c)
Experiment
Linear fitting
G (mΩ/nm)

O200 - Tailoring spin-orbit phenomena in Dirac material heterostructures

12. Spin-orbit and topology driven phenomena

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Dirac materials such as graphene (Gr) and topological insulators (TIs) are known to have unique electronic and spintronic properties. Having similar linear energy band spectra with massless 2D Dirac fermions, these materials differ significantly in their intrinsic value of spin-orbit coupling. We combine Gr and TIs in van der Waals heterostructures[1], aiming to utilize both the excellent spin transport properties of graphene[2] and the strong spin-orbit interactions in the TI bulk and surface states[3] in a single device.

By performing spin transport and precession measurements supported by ab initio simulations, we discover a strong tunability and suppression of the spin signal and spin lifetime due to the interaction of Gr and TI electronic bands. In addition, our theoretical calculations of the hybridized band structure predict the emergence of a novel spin texture in graphene with a strong anisotropy in lifetime of carriers with in-plane and out-of-plane spin polarization, promising for spin switch and spin filtering applications.

Finally, we investigate the nature of the spin relaxation processes in Gr-TI heterostructures considering both Elliott-Yafet and D'yakonov-Perel' mechanisms. This allows us to estimate the induced spin-orbit coupling strength in Gr of 1.1 meV, which is nearly an order of magnitude higher than the pristine graphene value, showing the rich potential of such heterostructures for the spin-to-charge conversion applications and possible realization of the quantum spin Hall effect in graphene.

Overall, these findings[4] in graphene-topological insulator heterostructures could open interesting opportunities for exploring exotic physical phenomena and new device functionalities governed by topological proximity effects.

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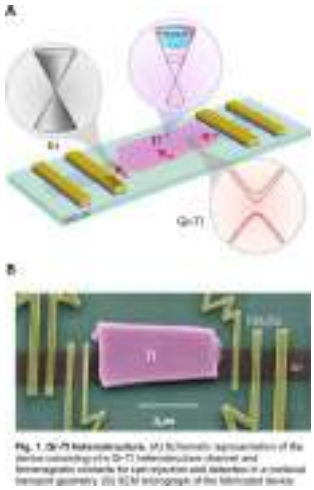

O201 - Thermoelectric detection and counting of individual skyrmions in Co|Ru|Pt multilayer nanowires

12. Spin-orbit and topology driven phenomena

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The detection by electrical means of single skyrmions is a key requirement both for future devices and fundamental studies. So far, skyrmions have been electrically detected by their signature in the anomalous Hall effect (AHE) [1]. While AHE detection is limited to Hall crosses, here we show that the anomalous Nernst effect (ANE) [2], the thermoelectric analogue of the AHE, allows non-invasive detection, counting and characterization of individual skyrmions in complete nanowires at room temperature.

We use a combined ANE – *in situ* magnetic force microscopy (MFM) setup to identify the ANE signature of individual skyrmions in Co|Ru|Pt multilayer nanostrips. First, a set of skyrmions is nucleated by a current pulse through the wire. Then, MFM is used to characterize the number, size, and spatial distribution of the skyrmions. A transverse thermal gradient from a microheater induces an ANE signal proportional to the out-of-plane magnetization of the wire, which is electrically detected. To derive the ANE signature of individual skyrmions, the stray field of the MFM tip is used to delete individual skyrmions one by one and the respective ANE signals are compared. We demonstrate the ANE based detection and counting of individual skyrmions and study the field dependence of the ANE signature of individual skyrmions. This new non-invasive tool could prove useful for applications and for fundamental studies of the topological Nernst effect.

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O202 - Topological and anomalous Hall effect in thin films of Mn(2-x)PtSn

12. Spin-orbit and topology driven phenomena

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Spin chirality in metallic materials with non-coplanar magnetic order gives rise to a Berry phase induced topological Hall effect. The effect is of particular interest in tetragonal Heusler compounds with D_{2d} symmetry, owing to the recent discovery of antiskyrmions in $Mn_{1.4}Pt_{0.9}Pd_{0.1}Sn$ [1]. In that context, we recently observed a topological Hall resistivity up to 1.2 μΩcm in sputtered high-quality $Mn_{1.5}PtSn$ thin films below a spin reorientation transition temperature of 185 K (Figure 1) [2].

Here, we demonstrate our systematic investigation of the topological and anomalous Hall effect for a variety of stoichiometries and thicknesses in sputtered high-quality $Mn_{2-x}PtSn$ (x=0-0.5) thin films, ranging from 120 nm to 20 nm. By changing the Mn content we are able to tune the magnetization as well as the spin reorientation, which in turn affect the topological and anomalous Hall effect. Additionally, we present in the temperature evolution of the Hall effects that the topological Hall resistivity is of comparable size to that of the anomalous Hall resistivity up to the spin reorientation transition temperature. We conclude, that tuning of the topological Hall effect opens the possibility for more in-depth studies of the non-coplanar spin textures in tetragonal Heusler compounds.

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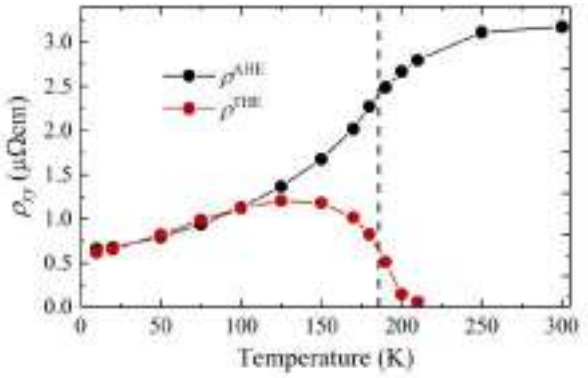

Figure 1. Anomalous and topological Hall resistivities as a function of temperature in 104-nm-thick $Mn_{1.5}PtSn$ film.

13. Magneto-optics and magnetoplasmonics

O203 - Design of Narrow Linewidth Magneto-Optical Resonances in Ni Nanodisk Arrays on SiO2/Au bilayers

13. Magneto-optics and magnetoplasmonics

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Systems consisting of ordered ensembles of noble metal nanostructures can support ultra-narrow surface lattice resonances (SLRs). These modes circumvent optical losses in noble metals offering resonance widths below 5 nm [1]. In ordered arrays of magnetic nanoparticles, optical losses are larger. The width of the SLR mode in optical and magneto-optical spectra of such lattices is ~ 100 nm [2]. Here, we demonstrate that narrow linewidth and intense magneto-optical resonances can be attained by placing Ni nanodisk arrays within the optical near field of surface plasmon polaritons (SPPs) that propagate along a SiO_2/Au interface.

We fabricated our samples by e-beam lithography of Ni nanodisks with a diameter of 200 nm and a thickness of 70 nm on top of 5 – 60 nm SiO_2/150 nm Au bilayers. The nanodisks were ordered into square arrays with periodicities ranging from 350 nm to 500 nm. Figure 1(a) shows an exemplary magneto-optical Kerr spectrum of one of the samples. For comparison, we also depict the magneto-optical signal of an identical Ni nanodisk array on a glass substrate. In the latter geometry, a relatively broad SLR mode produces a Kerr angle of about 5 mrad at 870 nm. For nanodisks patterned onto the SiO_2/Au bilayer, we measure a narrow (FWHM = 30 nm) and three times more intense magneto-optical resonance at λ_1 = 710 nm, in addition to the weaker SLR mode at λ_2 = 955 nm. The wavelength of the narrow resonance corresponds to that of a propagating SPP mode in the SiO_2/Au bilayer. As previously demonstrated for noble metal disks [3], this mode hybridizes with localized surface plasmons. As a result, an intense electric dipole is induced on the Ni nanodisks over a narrow wavelength range. Via spin-orbit coupling [4], this produces a strong magneto-optical Kerr effect. Finite-difference time-domain (FDTD) simulations of electric field distributions at λ_1 and λ_2 confirm this scenario (Figs. 1(b) and 1(c)). Our results open up a new route towards low-loss magnetoplasmonics with applications in biosensing, non-reciprocal optoelectronic devices, and localized all-optical magnetic switching [5].

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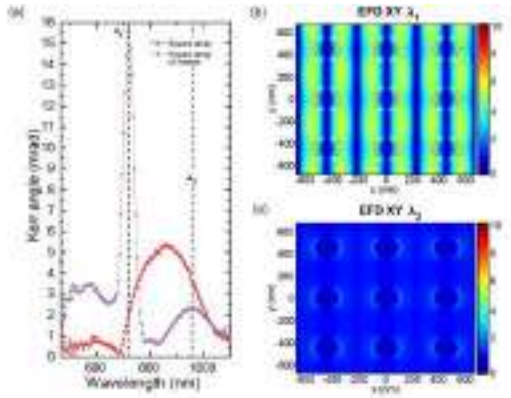

Fig.1 (a) Magneto-optical Kerr angle spectrum of a Ni nanodisk array on a glass substrate (red disks) and on a 10 nm SiO_2/150 nm Au bilayer (violet diamonds). (b),(c) Electric field distribution (EFD) at λ_1 and λ_2 of the Ni nanodisk array on SiO_2/Au. The XY monitor in the simulations is located right above the Ni nanodisk array.

O204 - Enhanced magneto-optic activity in Bi:YIG/Au hybrid nanostructures

13. Magneto-optics and magnetoplasmonics

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Magnetoplasmonics allow to explore the influence of the strong localization of light, induced by resonant plasmonic structures, on the response of adjacent magneto-optically active materials. In this work, we study the enhancement of the magneto-optic activity of bismuth-substituted yttrium iron garnet films, induced by localized surface plasmons in embedded gold nanoparticles [1]. The latter is achieved with the aid of a combination of magneto-optic Kerr effect spectroscopy operating in the longitudinal topology (Fig. 1), and reflectance spectroscopy. In order to gain insight into the exact origin of the magneto-optic response of the hybrid structure, we performed far-field simulations, as well as we analyzed computationally the underlying mesoscopic near-field mechanism. The far-field simulations reproduce very well the features of the measured magneto-optic response in the spectral vicinity of the relevant plasmonic resonances. The near-field computations reveal a transverse resonant magneto-optically induced field at a spectral position close to the main plasmon resonance. The exploration of the origin of the plasmon-induced effects on the properties of the adjacent magneto-optic materials, as well as the near-field mapping of the enhanced magneto-optically induced fields, can have a high impact on the engineering of hybrid magneto-plasmonic structures. Furthermore, our results pave the way to an on-demand design of the magneto-optic response of similar hybrid structures [2].

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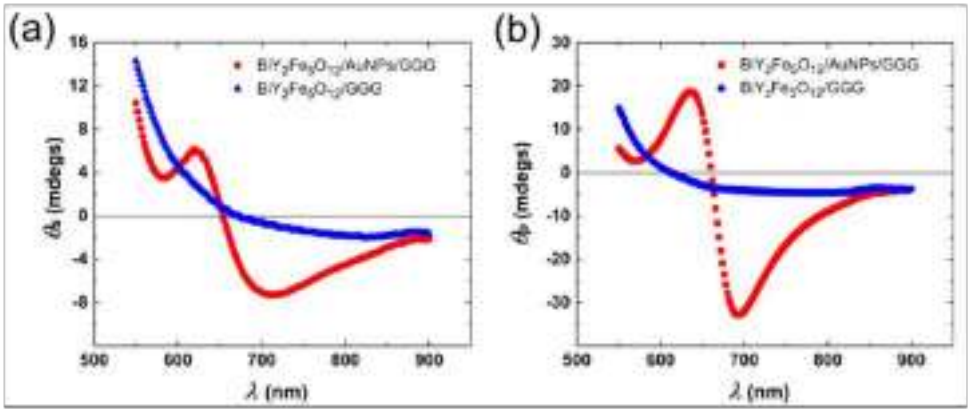

Figure 1. Experimental plot of the Kerr rotation as a function of wavelength, recorded for the samples with (red - solid symbols) and without (blue - solid symbols) Au nanoparticles for: (a) s- and (b) p- polarized incident light.

O206 - Impact of correlation effects on the magneto-optical Kerr effect in transition metals

13. Magneto-optics and magnetoplasmonics

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The magneto-optical Kerr effect (MOKE) is a well-established tool for investigating the properties of magnetic systems. Originating from the subtle interplay between magnetic order and spin-orbit coupling, a proper theoretical description of MOKE requires an appropriate framework. Such a scheme has been worked out by Huhne [1] on the basis of the fully relativistic spin-polarized Korringa-Kohn-Rostoker method [2]. To allow for the treatment of substitutionally disordered systems, the approach has been combined with the coherent potential approximation (CPA) alloy theory. The extended scheme gives access to the configurationally averaged optical conductivity tensor and this way to the corresponding complex Kerr angle. The additional combination with Dynamical Mean Field Theory (DMFT) [3] allows in particular to investigate the influence of correlation effects on the MOKE in disordered systems. Corresponding results for pure Ni, Fe and Co as well as disordered Co_xPt_{1-x} alloys are presented and compared with experimental data.

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O207 - Light scattering from a magneto-optical grating

13. Magneto-optics and magnetoplasmonics

Ioan-Augustin Chioar[1] , *Merlin Pohlit[1], Richard M. Rowan-Robinson[1], Wilhelm O. Redl[1], Spyridon D. Pappas[2], Agne Ciuciulkaite[1], Evangelos Th. Papaioannou[2], Björgvin Hjörvarsson[1], Vassilios Kapaklis[1]*

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We have explored the use of a magneto-optical diffraction grating, in the form of a YIG ($Y_3Fe_5O_{12}$) continuous film, as a mean of controlling light with mesoscale magnetic textures. Combining state-of-the-art Kerr microscopy with spectrally-tunable modern magneto-optical diffractometry [1], we have experimentally investigated, in both real and reciprocal space, the connection between the magnetic domain structure developed in an otherwise unpatterned magnetic film and the resulting scattering pattern of the transmitted light.

After gradually reducing an externally applied in-plane magnetic field from saturation, the sample develops a periodic stripe-like magnetic domain structure at remanence that is aligned with the diminishing field. The resulting pattern is characterized by alternating stripe domains, see Figure 1(a), with both in and out-of-plane magnetic components and a typical domain size of a few micrometers. The existence of a periodicity for the out-of-plane magnetic component opens up the possibility of using the film as a magneto-optical diffraction grating within the visible range. For incident light linearly-polarized along the stripe direction, the Faraday rotation yields a polarization profile of the transmitted light characterized by a uniform distribution along the direction parallel to the stripes and a periodic phase reversal texture along the corresponding orthogonal direction [2,3]. The interference pattern resulting from the latter gives rise to magnetic Bragg peaks, in good agreement with the Fourier transform of the real-space magnetic domain texture recorded with Kerr microscopy. At remanence, first and third order Bragg peaks have been detected, see Figure 1(b). The absence of even-ordered peaks is attributed to the symmetry in domain size distribution. Nevertheless, by applying a magnetic field within the sample plane, one domain orientation is favored in the detriment of the other, ultimately biasing the spatial distribution between opposite magnetic domains and enabling the build-up of even-ordered peaks, see Figure 1(c).

These results highlight the potential of controlling the scattering of light within the visible regime by employing and tailoring meso-scale magnetic textures. Embracing a scattering perspective, the presented case can serve as a cornerstone study that can further facilitate and inspire the design of meso-scale devices with magnetically-reconfigurable optical functionalities.

Acknowledgements

We acknowledge the Deutsche Forschungsgemeinschaft through the Collaborative Research Center under SFB TRR 173: SPIN+X Project B07.

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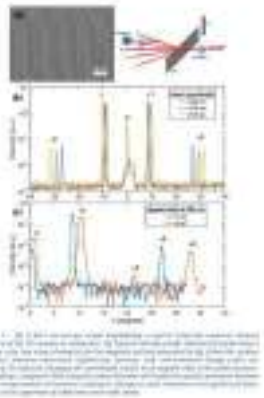

O208 - Magnetic modulation of surface plasmons in magnetoplasmonic nanoparticles

13. Magneto-optics and magnetoplasmonics

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The active modulation of the optical response of plasmonic nanoparticles (NPs) by means of an external magnetic field, i.e. magnetoplasmonics, can trigger interesting innovations in the design of optical switches, modulators or more efficient refractometric sensors [1]. The enhancement of this magnetic modulation is a challenging goal in magnetoplasmonics.Some examples of nanostructures have been already proposed in the literature: nickel nanodisks [2] and Au-Co-Au sandwich nanostructures [3**]** showed the most promising results. Nevertheless, these materials have higher optical losses related to inter-band transitions with respect to noble metals, leading to a broader plasmonic resonance, while a sharp resonance is preferable for applications. In our work we propose colloidal chemistry as an alternative nanofabrication tool with respect to the more widely employed lithographic methods, exploiting the possibility to control the size and the composition of the NPs, as well as the low cost and mild conditions needed. To characterize the magnetoplasmonic properties of the NPs we used Magnetic Circular Dichroism (MCD). In a previous work we demonstrated that small magnetic field-induced energy shifts of the plasmonic modes in simple Au NPs are easily detectable by MCD [4]. Nevertheless, the MCD signal of Au NPs is too small for applications in devices. In this work, we propose two approaches to enhance the magneto-optical signal, based on two classes of materials.
The first approach involves the preparation of hybridized magnetoplasmonic NPs, by alloying Au with magnetic metals (Fe, Co or Ni) and exploiting the interaction between the conduction electrons of Au and the spin polarized electrons of magnetic metals to increase the magnetic modulation. Recently, we measured the MCD spectrum of AuFe nanoalloys prepared by laser ablation [5] and the MCD signal was roughly one order of magnitude higher than that of pure Au NPs (Figure 1A). Motivated by these promising results we exploited colloidal chemistry approaches to synthesize AuM (M = Fe, Ni) alloy NPs. We found that the control of the metal composition of the NPs is crucial to boost the magneto-optical signal.
The second approach consists in the use of a new emerging class of plasmonic material, n-doped Indium-Tin-Oxide (n-ITO) NPs, which display a sharp plasmonic absorption in the Near-Infrared region of the spectrum [6]. Thanks to their low peak width and to the lower electron effective mass of n-ITO with respect to Au, the magnetic modulation of surface plasmons in n-ITO NPs is at least one order of magnitude higher than in noble metals NPs, as we found from MCD investigations (Figure 1B), paving the way for the use of heavily doped semiconductors for magnetoplasmonics.
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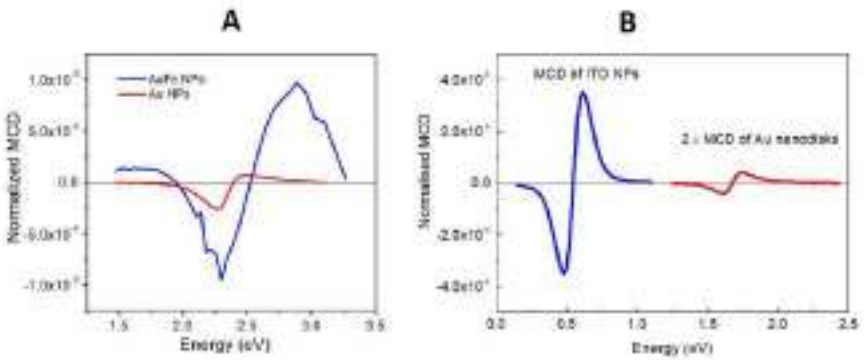

Figure 1: MCD signal of AuFe alloy NPs, compared to pure Au NPs (A), and of n-ITO compared with that of Au nanodisks (B). The MCD signal is normalized to the extinction maximum and to the applied magnetic field.

O209 - Magneto-optical effects quadratic in magnetization - Voigt and XMLD

13. Magneto-optics and magnetoplasmonics

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We report investigations of x-ray magneto-optical effects quadratic in magnetization using first-principle calculations and experimental data on bcc Fe, fcc Ni and fcc and hcp Co. By means of polarization analysis the Voigt rotation and ellipticity of linearly polarized synchrotron radiation is measured for Fe, Ni and Co films at the all L_2 / L_3 and M_2 / M_3[4-6] edges upon transmission/reflection. The same spectra are calculated using first-principle calculations and solving Fresnel equations using multi-layered Yeh's formalism [1]. On the basis of ab initio calculations it is shown that the x-ray Voigt effect follows sensitively the amount of spin polarization of the 2p core or 3p semi-core states. The effects like core-level spin-orbit splitting vs . core exchange splittings are reflected in the spectra. The x-ray magnetic linear dichroism is obtained from calculated intensity spectra in reflection and transmission. A highly anisotropic XMLD signal at the L_2 / L_3 as well as M_2 / M_3 (with lower intensity [4-6]) edges is observed, which origin is analyzed in detail. The XMLD anisotropy is shown to be a consequence of the cubic crystal-field split density of 3d states, which are selectively probed by transitions from the spin-orbit and exchange-split 2p/3p levels. The relation between the asymmetry of XMLD is related to the 2*Voigt rotation [2,3]. The general model calculations employing just the DOS of the electronic structure to construct those spectra are determined.

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O210 - Plasmonic Nanoantennas: Toward the Optical Readout of Magnetic Field at the Nanoscale

13. Magneto-optics and magnetoplasmonics

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Metallic nanostructures supporting localized surface plasmons are able, thanks to their shape, size and composition, to collect, enhance and confine the external electromagnetic field carried by the incident light. The use of the magnetic field can add an extra functionality, leading to optically-controlled nanomagnetism or, on the other side, making it possible to probe the magnetic field around the nanostructures [1].
Through a proper combination of nanostructured plasmonic surfaces with magnetic materials, magnetoplasmonic nanoantennas can be realized. The plasmonic nanostructures can focus the electromagnetic field in nanometric hotspots around themselves, and by assembling the magnetic material in these points we aim at tailoring light-matter interactions at the nanoscale.
As a magnetic material we chose magnetic nanoparticles (MNPs) because of the ease in tuning their properties by varying nanoparticles’ size and composition, acting on basic synthetic parameters. The synthesis is performed by thermal decomposition of organometallic precursors, a method that leads to a colloidal solution of nanoparticles with a narrow size distribution [2], capped with oleic acid and oleylamine. The nanostructured surfaces are realized through soft lithographic techniques (i.e. hole-mask colloidal lithography using polystyrene nanospheres) [3]. The magnetic nanoparticles are then assembled on the plasmonic surfaces exploiting the soft-soft interactions between gold and the apolar chains that cap the MNPs (**Fig. 1**).

Performing UV - visible spectroscopy the displacement of the gold plasmonic peak in the presence of ferrite MNPs is monitored (**Fig. 2**). In fact, they can locally modify the refractive index causing a redshift of the peak.Using a homebuilt Magnetic Circular Dichroism apparatus (MCD), tuning both incident light wavelength and applied field magnitude, a bidimensional map of these two parameters is obtained. In the MCD spectrum reported below (**Fig. 3**), we can see that decreasing the external magnetic field the magneto-optical signal due to the plasmon first decreases in a linear fashion as expected, and then inverts, while the shoulder at higher energy, due to the MNPs, stays until the field is high enough to saturate them [4, 5]. A proper rationalization of the behavior of the plasmonic signal is still in progress and will require further investigations, what we hypothesize is that the MNPs at the disks' sides may generate a local magnetic field that opposes to the external one (as sketched in **Fig. 4**) inducing an inverted plasmonic signal (the effect of the MNPs on top of the disks is negligible as they are located far from the nanoantennas’ hotspot). For this reason, it is possible to see the nanoantennas as a local probe of the magnetic field at the nanoscale.

This work has been financed by the EC through grant 737093 — FEMTOTERABYTE — H2020-FETOPEN-2016-2017.

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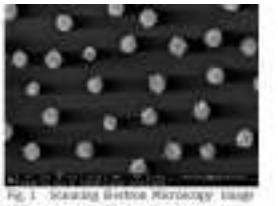

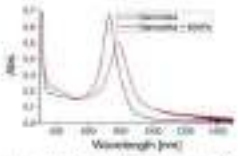

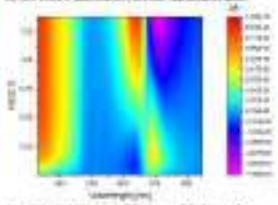

14. Multifunctional magnetic materials: magnetic shape memory materials, multiferroics including artificial/composite multiferroics, and perovskites

O211 - Determining large voltage response of magnetoelectric composite by anisotropic magnetoresistance

14. Multifunctional magnetic materials: magnetic shape memory materials, multiferroics including artificial/composite multiferroics, and perovskites

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Voltage-based magnetoelectric composites, consisting of both magnetostrictive as well as piezoelectric elements, offer an energy-efficient scalable approach to control nanomagnets. In such a composite, the magnetization can be controlled by the strain induced in the piezoelectric element via the Villari effect. Ferromagnetic resonance has been widely used to quantify the magnetoelectric coefficient of various composites consisting of thin magnetic films on bulk macroscopic piezoelectric substrates. However, advanced magnetoelectric device applications require the study of magnetoelectric effects in scaled nanostructures. Yet, a deeper understanding of the magnetoelectric coupling at the nanoscale is still missing. Here, we report on an investigation of the magnetoelectric coupling of a Ni-$PbZrTiO_3$ (Ni-PZT) magnetoelectric composite (Figure 1, left) by anisotropic magnetoresistance (AMR) measurements. A 1-µm-wide Ni stripe was patterned on top of a PZT mesa, formed by etching 100 nm deep into PZT to reduce the mechanical clamping of the structure. Two needle-shaped 4-µm-wide Au gate-electrodes with 750-nm-wide gaps with respect to the Ni stripe were used to generate voltage-controlled strain in the PZT. Additional Au contact pads (two voltage and two current contacts) were patterned on the waveguide to measure the anisotropic magnetoresistance (Figure 1, right) of the device as a function of an applied dc voltage and the angle of the external magnetic field. Upon the application of a dc voltage to the electrodes, electric fringing fields are generated in the PZT mesa, which in turn induce strain in the PZT that is transferred to the adjacent Ni stripe. The strain modifies the magnetoelastic anisotropy field in the Ni by the Villari effect. The anisotropy field depends on both the components of the strain tensor as well as the direction of the magnetization. This complex interplay translates into a modulation and/or a shift of the anisotropic magnetoresistance curve. To determine the effects of different strain components in such a scaled geometry under different voltage schemes, an in-depth finite-element simulation study has been performed. AMR characterization was then carried out under the most uniform and largest strain configuration to determine the magnetoelastic coupling. The observed variation of the anisotropic magnetoresistance with applied field allowed us the quantification of the magnetoelastic coefficient in such Ni/PZT nanostructures. We determined a value of 5800 (A/m)/V which is considerably larger than previously reported values for macroscopic devices [1]. This demonstrated the large potential of nanoscale ME composites for low-voltage spintronic applications such as the manipulation of nanomagnets, etc.

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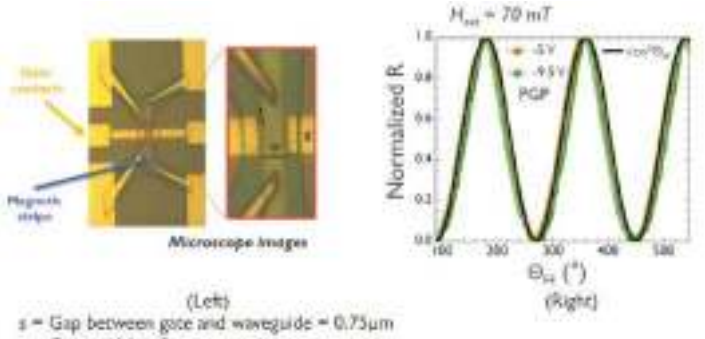
Funding Sources: the European Union’s Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No 794354 and within the FET-OPEN project CHIRON under grant agreement No. 801055.



s = Gap between gate and waveguide = 0.75μm
g = Gate width = 2μm
w = Ni waveguide width = 1μm

Figure 1: (Left) Schematic of the AMR Device. (Right) Perpendicular AMR measurements vs the angle of the external magnetic field at different bias voltages.

O212 - Dzyaloshinskii – Moriya interaction and phase transitions in multiferroics with cycloidal structure

14. Multifunctional magnetic materials: magnetic shape memory materials, multiferroics including artificial/composite multiferroics, and perovskites

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Multiferroics, multifunctional materials with coexisting ferroelectric and ferromagnetic order, suggest promising advances in new generation spintronic technologies. Coexistence of several exchange interactions in multiferroics often results in competition between non – collinear spin orders leading to stabilization of incommensurate spin structures [1]. These configurations can arise either directly from competing exchange interactions, or through the influence of the ferroelectric polarization on the spin arrangement via a Dzyaloshinskii – Moriya interaction (DMI) as in the case of bismuth ferrite.

In this talk, we focus on high temperature multiferroic BiFeO3 and incommensurate cycloidal spin structure being the ground state of BiFeO3. We explore the mechanisms responsible for non – collinear spin ordering and manifestation of DMI on magnetic and ferroelectric properties of BiFeO3 – like multiferroics, analyze the conditions required for stabilization of cycloidal magnetic states and highlight the differences between spin cycloids in single crystals and films. We show that in the case of the film additional magnetic anisotropy induced by the strains allocates cycloids with the definite directions of spin rotation. Until now, it was believed that polarization is linked with antiferromagnetic order throughout the plane of spin rotation, namely it was considered that polarization always lies in the cycloid spin rotation plane. Due to the action of epitaxial strains spin rotational plane of the cycloid deviates from the plane containing intrinsic spontaneous polarization. We show that the properties of cycloidal structures and conditions of phase transitions into another magnetic state depend on the sign and the strength of the induced

magnetic anisotropy related to epitaxial growth processes, strains, electrostriction, magnetostriction etc.

In the films, spin cycloid can be destroyed or transformed into another antiferromagnetic state even when magnetic or electric fields are absent. These results are consistent with the recent experiments on BiFeO3 films grown on the different substrates. Measurements through nuclear resonant scattering, Raman and Moessbauer spectroscopy [1] showed that spin modulation can be modified, transformed to ordering patterns, destabilized and also suppressed due to compression and stretching deformations; the mismatch between film and substrate. We also explored spin reorientation phase transition under the action of strain and magnetic fields exemplified on (110) – oriented BiFeO3 film. Peculiarities of phase diagrams are discussed.

Progress in strain engineering allows technological control of the multiferroics symmetry by variations of mismatch parameters that can lead to anharmonic deformations of cycloid, violations of planar character of spin rotation, modifications of magnetic and magnetoelectric properties and the conditions required for cycloid destruction. Strain control of cycloidal state suggest opportunities for the straintronics devices taking advantage of finite size effects in multiferroic films.

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O213 - Electric and magnetic chiralities in multiferroic textures

14. Multifunctional magnetic materials: magnetic shape memory materials, multiferroics including artificial/composite multiferroics, and perovskites

Jean-Yves Chauleau[1, 2] , *T. Chirac[1], S. Fusil[3], V. Garcia[3], W. Akhtar[4], I. Gross[4], B. DKhil[5], M. Bibes[3], V. Jacques[4], N. Jaouen[2], M. Viret[1]*

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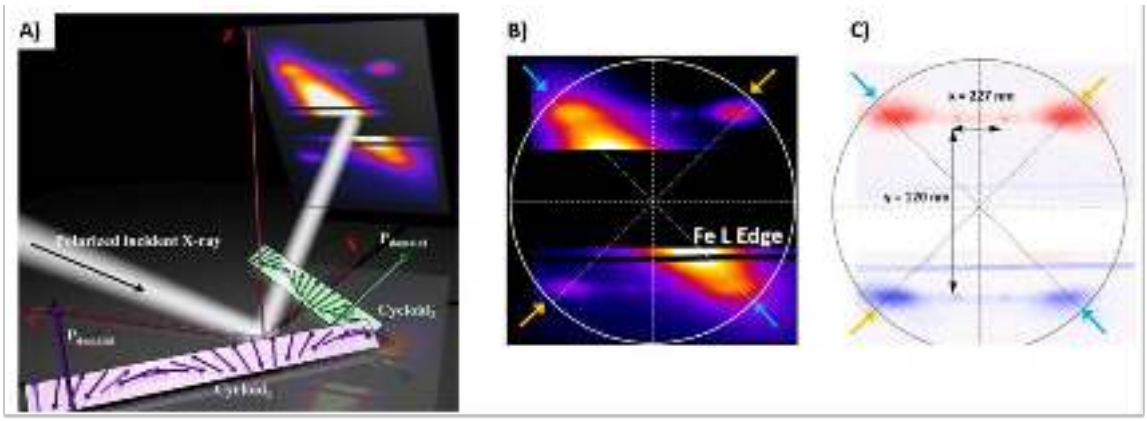
Nowadays, magnetic chirality has become a topic of utmost importance considering the ever-growing interest in static and dynamic properties of topological magnetic structures such as magnetic skyrmions and domain walls and their possible implications in future high-density data storage devices [1]. One effective way of inducing chiral magnetic structures is to consider magnetic systems showing a dominant Dzyaloshinskii-Moriya interaction (DMI) [2]. On the other hand, electric polar skyrmions have just been evidenced in peculiar $PbTiO_3/SrTiO_3$ heterostructures [3], opening new horizons for complex topological phases.
Some classes of material can exhibit several ferroic orders. They are commonly known as multiferroics. Among these materials, the ones that simultaneously show ferroelectricity (FE) and (anti)ferromagnetism (AF) associated to a large magnetoelectric coupling are of particular interest due to their envisioned relevant implications in tomorrow's performant information technologies. Magnetoelectric coupling in AF-FE multiferroics is a promising route to effectively induce and manipulate antiferromagnetic chiral distributions. Nowadays, Bismuth ferrite [4] ($BiFeO_3$) is without doubt the most prototypical multiferroics as it is the only known material which presents these two ordered phases well above room temperature.

In this work, we investigate concomitant electric and antiferromagnetic textures in $BiFeO_3$ thin epitaxial layers [5] using soft x-ray resonant elastic diffraction [6]. This approach provides, a unique access to antiferromagnetic chirality. In addition, our study reveals an unexpected chiral winding of the electrical order parameter in ferroelectric stripe patterns.



Antiferromagnetic order by X-ray resonant magnetic diffraction. (A) Schematic representation of the experimental configuration. (B) diffraction diagram at the Fe L edge (707.5 eV). (C) corresponding circular dichroic patterns

O214 - Electrical control of morphology in heterostructures: a new mechanism for magneto-electric coupling?

14. Multifunctional magnetic materials: magnetic shape memory materials, multiferroics including artificial/composite multiferroics, and perovskites

Giovanni Vinai[1] , ***Federico Motti***[1, 2], *Valentina Bonanni*[1, 2], *Aleksander Yu. Petrov*[1], *Stefania Benedetti*[3], *Christian Rinaldi*[4, 5], *Mattia Stella*[4], *Matteo Cantoni*[4], *Damiano Cassese*[6], *Stefano Prato*[6], *Thomas Forrest*[7], *Francesco Maccherozzi*[7], *Sarnjeet Dhesi*[7], *Giorgio Rossi*[1, 2], *Giancarlo Panaccione*[1], *Piero Torelli*[1]

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Converse magnetoelectric coupling in artificial multiferroics is generally modeled through three possible mechanisms [1]: charge transfer, strain mediated effects or ion migration. Here we dicuss the role played by electrically controlled morphological modifications on the ferromagnetic response of a multiferroic heterostructure, specifically Fe_xMn_{1-x} (FeMn) ferromagnetic films on piezoferroelectric PMN-PT [001] substrates.
The substrates present, in correspondence to electrical switching, *fully reversible* morphological changes at the surface [2], to which correspond reproducible and reversible modifications of the ferromagnetic response of the FeMn films.
Topographic analysis by atomic force microscopy shows the formation of surface cracks (up to 100 nm in height) upon application of a sufficiently high positive electric field (up to 6 kV cm^{-1}), which disappear after application of a negative electric field of the same magnitude. Correspondingly, *in-operando* XMCD spectroscopy at Fe $L_{2,3}$ edges shows modifications of the hysteresis loop, with different effects depending on the zone probed on the surface. Furthermore magnetic domain rotation, mainly by 90°, was observed by XMCD-PEEM following the ferroelectric polarization switching, accompanied by crack formation on the surface. Finally, MOKE microscopy allowed us to observe a variation in magnetic anisotropy and to correlate it to the morphological change.
We thus have shown [3] that this morphologic parameter, rarely explored in literature, directly affects the ferromagnetic response of the system. Its proof of electrically reversible modification adds a new possibility in the design of electrically controlled magnetic devices.

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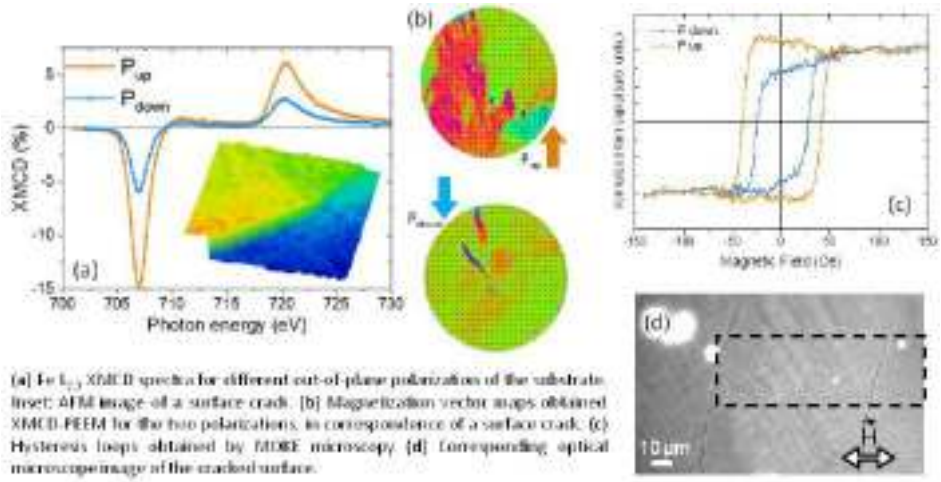

(a) Fe $L_{3,2}$ XMCD spectra for different out-of-plane polarization of the substrate. Inset: AFM image of a surface crack. (b) Magnetization vector maps obtained XMCD-PEEM for the two polarizations, in correspondence of a surface crack. (c) Hysteresis loops obtained by MOKE microscopy. (d) Corresponding optical microscope image of the cracked surface.

O215 - Engineering the microstructure of ferromagnetic shape memory thin films by post growth treatments

14. Multifunctional magnetic materials: magnetic shape memory materials, multiferroics including artificial/composite multiferroics, and perovskites

Francesca Casoli[1] , *Milad Takhsha Ghahfarokhi*[1], *Simone Fabbrici*[1], *Lucia Nasi*[1], *Giovanna Trevisi*[1], *Riccardo Cabassi*[1], *Federica Celegato*[2], *Paola Tiberto*[2], *Franca Albertini*[1]

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Ferromagnetic shape memory Heuslers show multifunctional properties arising from a strong coupling between magnetic, thermal and mechanical degrees of freedom. Within this class of compounds, Ni_2MnGa is a model system, which shows a martensitic phase transformation from a cubic $L2_1$phase (austenite) to a lower symmetry phase (martensite) by decreasing temperature.
We have investigated the possibility of modifying the martensitic microstructure in Ni-Mn-Ga films with thickness between 75 and 200 nm, grown by r.f. sputtering on MgO(100) or Cr/MgO(100). Films were grown in the temperature range 200 - 400 °C, with different growth parameter (i.e., sputtering rate, sputtering power) and composition $Ni_{54}Mn_{22}Ga_{24}$.
A multiscale magnetic and structural study was performed by means of several techniques: AFM, SEM, TEM, XRD were used for characterizing microstructure, while the magnetic properties were studied by MFM, Lorentz microscopy, AGFM and SQUID magnetometry.
The $L2_1$austenitic phase grows epitaxial at high temperature both on MgO(100) and Cr/MgO(100). The martensitic phase, which is stable at room temperature, has a monoclinic 7M incommensurated structure. Both the phases are ferromagnetic, but the martensitic phase shows higher magnetocrystalline anisotropy. The martensitic microstructure is made of complex arrays of differently oriented hierarchical twin microstructures, i.e., X-type and Y-type, where the easy-magnetization directions are respectively out-of-plane and in-plane [1]. Controlling the orientation and organization of X- and Y-type twins in epitaxial films and nanostructures could pave the way towards multifunctional applications such as thermomagnetic actuation [2], magnetic storage [3] and magnetic anisotropy dependent properties in fluids [4].
We have focused on microstructure/magnetic pattern engineering by post-growth treatments such as post-annealing, stress, annealing in magnetic field. Through these post-growth treatments, a variety of martensitic patterns (i.e. orientation and spatial organization of the martensitic twin variants) were obtained, demonstrating that it is possible to engineer the magnetic patterns and strongly influence the magnetization processes (Figure 1). The intimate link between magnetic and structural degrees of freedom and the flexible twin-within-twin martensitic structure makes epitaxial Ni-Mn-Ga films a unique platform for the precise control of the magnetic configuration from the atomic to the macro-scale also by means of easy and suitable post-growth treatments.

Figure 1: Large scale SEM-BSE images showing different microstructures in as-grown (left) and post- annealed (right) films.

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O216 - First observation of structural and magnetic properties of novel multicomponent perovskites

14. Multifunctional magnetic materials: magnetic shape memory materials, multiferroics including artificial/composite multiferroics, and perovskites

Johan Cedervall[1] , *Pedro Berastegui*[1], *Premysl Beran*[2, 3], *Mikael S. Andersson*[4, 5], *Roland Mathieu*[4], *Martin Sahlberg*[1]

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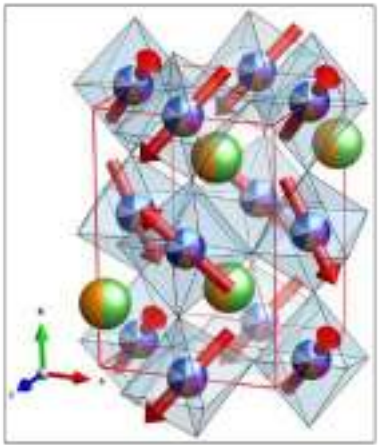
Multicomponent alloys, also called high entropy alloys (HEA) or complex solid solutions, of five or more elements in equiatomic or near equiatomic ratios can lead to unexpected improvements of the material properties. Many results indicate that the mechanical properties can be considerably enhanced, but also novel magnetic properties and superconductivity have been reported. The high entropy concept has also been transferred into other compounds e.g., oxides, carbides, nitrides and borides. Most focus on the studies have been focused on thermal stability and mechanical properties, even though high concentrations of magnetic atoms or ions exists in the alloys. However, a few examples of HEAs with excellent soft-magnetic properties, e.g. the CoCrFeMnNi HEA, and also magnetocaloric properties in HEAs based on rare earth elements. When it comes to other multicomponent systems, the magnetic properties are often overlooked.

In this study, a complex perovskite, $La_{0.5}Nd_{0.5}(Ti_{1/7}Cr_{1/7}Mn_{1/7}Fe_{1/7}Co_{1/7}Ni_{1/7}Cu_{1/7})O_3$, has been synthesised with a high entropy approach. It crystallises in the orthorhombic space group *Pnma* and at 900 K it undergoes a phase transition to the trigonal space group *R*-3*c*. The magnetic properties, including the magnetic structure have been evaluated for the first time for multicomponent perovskites. The neutron diffraction study reveals a canted, uncompensated, antiferromagnetic configuration with magnetic moments on the Mn, Fe, Cr and Ni ions at 10 K, shown in the figure below. The magnetic moment is found to be 1.04(2) μB per magnetic *B*-atom, which is consistent with the theoretical value of 1.7 μB calculated from the spin-only values of the magnetic moments of Cr^{3+}, Mn^{4+}, Fe^{3+} and Ni^{3+}. The total magnetic moment, from both neutron diffraction and magnetometry, is found to be about 0.1 μB/f.u., at 10 K.



O217 - Magnetically Addressable Shape-memory and Stiffening in a Composite Elastomer

14. Multifunctional magnetic materials: magnetic shape memory materials, multiferroics including artificial/composite multiferroics, and perovskites

Paolo Testa[1, 2, 3] , *Robert Style*[2], *Jizhai Cui*[1, 3], *Claire Donnelly*[1, 3], *Peter Derlet*[3], *Eric Dufresne*[2], *Laura Heyderman*[1, 3]

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The author has chosen not to publicise the abstract.

Field 5

Field 6

O218 - Magnetoelectric and Multiferroic properties of Mn4Ta2O9 and Fe4Ta2O9

14. Multifunctional magnetic materials: magnetic shape memory materials, multiferroics including artificial/composite multiferroics, and perovskites

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We report some of our recent work on the corundum related honeycomb magnets $Mn_4Ta_2O_9$ and $Fe_4Ta_2O_9$. The Mn member of this family – a linear magnetoelectric – exhits a remarkably anistropic magnetization, with the appearance of a weak ferromagnetic component well within the antiferromagnetically ordered state. Powder neutron diffraction indicates that the magnetic structure comprises of antiferromagnetically coupled ferromagnetic chains of Mn^{2+} spins aligned along the trigonal *c* axis, in contrast to that reported in other isostructural members of this family. Magnetic measurements performed under a period electric field indicate that the magnetoelectric response is also anisotropic, with this coupling along the trigonal *c* axis and that perpendicular to it having different signs. On the other hand, $Fe_4Ta_2O_9$ is seen to exhibit a series of magnetic transitions, many of which are coupled to the emergence of ferroelectric order, making it the only genuine multiferroic in this material class. We suggest that the observed properties arise as a consequence of an effective reduction in the dimensionality of the magnetic lattice, with the magnetically active Fe^{2+} ions preferentially occupying a quasi 2D buckled honeycomb structure. The low temperature *H*-*T* phase diagram of $Fe_4Ta_2O_9$ reveals a rich variety of coupled magnetic and ferroelectric phases, in similarity with that observed in the distorted Kagome systems.

O219 - Magnetoelectric coupling in BaTiO3 / CaMnO3 thin film heterostructures

14. Multifunctional magnetic materials: magnetic shape memory materials, multiferroics including artificial/composite multiferroics, and perovskites

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One route towards the development of multiferroic materials with strong magnetoelectric coupling is by exploring the break of time reversal and space inversion symmetries that occur at the interface between a magnetic and a ferroelectric material. The properties of each component of the heterostructures can be chosen within a large number of materials, allowing a better optimization of the desired properties. This engineered magnetoelectric coupling could reach values that are orders of magnitude larger than those typical of single phase multiferroics.

In this work the structural, electronic and magnetic properties of $BaTiO_3$/$CaMnO_3$ heterostructures grown on an $SrTiO_3$ substrate are investigated from first principles calculations. The most important effects to take into account when dealing with the electronic and magnetic properties of thin films of ferroelectric / magnetic heterostructures can be mechanical strain, charge transfer and interface effects. As a first step, we study how the confinement and the epitaxial tensile strain induced by an $SrTiO_3$ substrate affect the magnetic properties of $CaMnO_3$ thin films for both, MnO_2- and CaO-terminated surfaces. We find that when the film is CaO-terminated the magnetic structure remains equal to the bulk one (antiferromagnetic coupling between Mn nearest neighbours, i.e. GAF) whereas a MnO_2-terminated film favors an in-plane ferromagnetic coupling between Mn atoms. These results are contrasted with the obtained experimental results.

Finally, we also analyze the influence of the $BaTiO_3$ polarization switching by means of the charge transfer through the interface for different interface combinations, namely BaO-MnO_2 and TiO_2-CaO.

O220 - Microscopy of the coupling between electric and magnetic domains in multiferroic h-RMnO3

14. Multifunctional magnetic materials: magnetic shape memory materials, multiferroics including artificial/composite multiferroics, and perovskites

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Fundamental understanding of the cross-coupling between ferroic orders at the level of domains and domain walls is crucial and timely to envision the pathways for future systematic manipulation of multiferroic materials. Here, for the first time, we investigate the coupling between electric and magnetic domains and domain walls in h-*R*MnO_3 on the microscopic scale using optical second-harmonic generation microscopy. Up to now, it was known that coupling between electric and magnetic domains occurs at macroscopic length scales in this type-I multiferroic system where the different ferroic orders emerge independently [1]. The complexity of the system was described by the ferroelectric and antiferromagnetic order parameters – P and L, respectively –, and the combination F∼PL between both. Years later, it was shown on the microscopic scale that ferroelectric domains are topologically protected objects with six domain walls meeting at a single point. While the largest ferroelectric vortex domains are about tens of microns, the antiferromagnetic domains are about hundreds of microns in size. Moreover, they exhibit a completely distinct morphology. Such discrepancies between electric and magnetic orders disclosed a lack of understanding at the microscale and raised controversies debating the proposed coupling [1].
Here, we show experimentally how the two distinct domain morphologies of ferroelectric and antiferromagnetic orders merge into a single picture. At the level of the domain walls, our experiments reveal that always two of the three order parameters (P, L and F) change their sign simultaneously at every domain wall while the third one retains its sign. This observation uncovers a type of domain wall never observed before where P and F change their sign simultaneously while the sign of L remains constant. Hence, three different types of clamped domain walls are present in these compounds in the multiferroic phase. This allows us to establish the complete landscape of coupled domain walls in these materials. Our observations unveil that antiferromagnetic domains in these compounds possess an unexpected mixed morphology as a consequence of the different types of existent domain walls. On the one hand, they have an Ising-like morphology formed by clamped L/F and P/F domain walls. On the other hand, the antiferromagnetic domains also share the morphology of the ferroelectric vortex domains due to the clamping of P and L domain walls. Furthermore, this demonstrates the multiferroic nature of the topological defects in these compounds. Our work expands the existing understanding of the unique coupling nature between ferroic orders in hexagonal manganites. Furthermore, it demonstrates the – at first sight unexpected – intrinsic coupling of domains and domain walls in a type-I multiferroic.
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O221 - New insights in RMn2O5 multiferroics : rare earth and pressure influence

14. Multifunctional magnetic materials: magnetic shape memory materials, multiferroics including artificial/composite multiferroics, and perovskites

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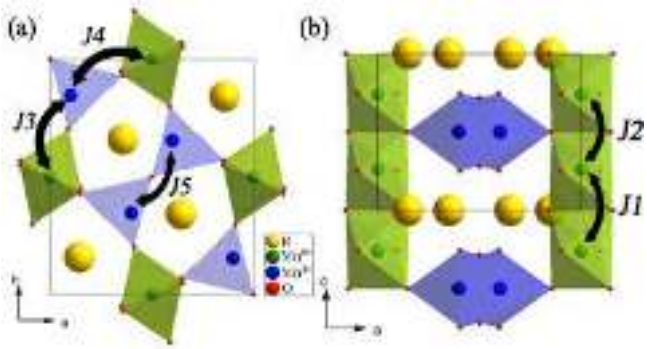
RMn_2O_5 materials (R being a rare earth) have long been presented as spin induced multiferroic family, where the electric polarization develops concomitantly with a magnetic transition at low temperature. What makes them particularly interesting lies in their singular properties: an electric polarization among the strongest reported so far (3600µC.cm-2 in GdMn2O5), a strong magneto-electric coupling (enabling a polarization flip under a magnetic field of 2T in $TbMn_2O_5$), and a magnetism that indicates a different fundamental mechanism than the standard Dzyaloshinskii Moriya Interaction. Indeed, among the universal properties of this RMn2O5 family is the quasi-colinear magnetic ordering in the (a,b) plane.

In this presentation, we will give an overview of universal properties of RMn2O5 that single them out from most of multiferroics : two valences, strong polarization, remarkable magneto-electric coupling and rare earth influence. We will present recent results that shed light on the underlying mechanism responsible for magneto-electric coupling in all the members of the family. Using neutron diffraction, we investigated several members of the series to unravel the common mechanism to the whole family : the exchange striction model.

We will also present results on a systematic study of magnetic ordering under high pressure with 5 members of the family investigated. One of the striking conclusion of this study is the presence of a universal magnetic phase at high pressure despite different room pressure magnetic order it originates from. This common high pressure magnetic phase stabilization can be explained by the combination of both X-ray diffraction under pressure and ab-initio calculations of super-exchange couplings.

Based on the mechanism revealed by neutron diffraction and the new magnetic high pressure phase, we will conclude this presentation by reporting the first case of pressure induced multiferroicity.



O222 - Phase field model for ferromagnetic domain evolution during martensitic transformation

14. Multifunctional magnetic materials: magnetic shape memory materials, multiferroics including artificial/composite multiferroics, and perovskites

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As the energy consumed by cooling systems is expected to increase over the next decades, mag-
netocaloric cooling systems are of high interest as they are a promising and more energy efficient
alternative to conventional vapor compression refrigerators. The most promising prototypes for mag-
netic cooling make use of materials exhibiting a giant magnetocaloric effect (MCE), such as Heusler
alloys. These materials undergo a first-order magnetic phase transition coupled with a structural
change, e.g., from cubic to tetragonal structure. The change in magnetization and structure re-
sults in larger entropy changes ΔS and therefore in larger adiabatic temperature changes ΔT_{ad} .
We propose a phase field model to simulate the magnetic domain evolution during the martensite
formation in, e.q. Heusler alloys. The model takes into account three order parameters η_1 , η_2 , and
η_3 for the martensite transformation, corresponding to a cubic to tetragonal phase transition. The
energy of the martensite transformation is described by a Landau-type formulation and is coupled
with micromagentic formulations for the description of the magnetic domain evolution. The three-
dimensional finite-element implementation of this model is straightforward and has been performed
within the MOOSE framework. The model is shown to be capable of reproducing the formation and
evolution of domains in magnetic materials under external magnetic field or mechanical loading.

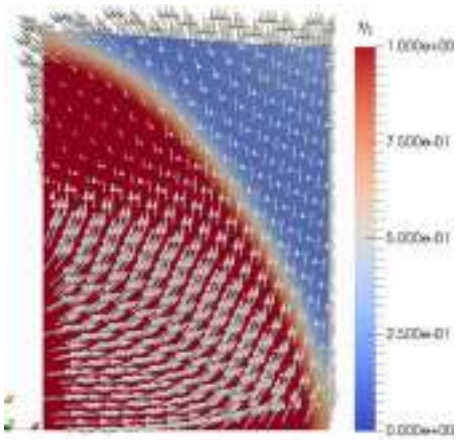

FIG. 1: Stress induced martensitic transformation and magnetic domain evolution.

O223 - Pressure-induced polymorphism in Mn2FeSbO6: in search of a polar magnet

14. Multifunctional magnetic materials: magnetic shape memory materials, multiferroics including artificial/composite multiferroics, and perovskites

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In the last decade, major efforts have been devoted to searching for polar magnets due to their vast potential applications in spintronic devices [1]. However, the polar magnets are rare because of conflicting electronic configuration requirements of ferromagnetism and electric polarization. Double-perovskite oxides with a polar structure containing transition metal elements represent excellent candidates for the polar magnet design. Herein, the crystal structure evolution of Mn_2FeSbO_6 (MFSO) was investigated at pressures reaching ~50 GPa by *in situ* synchrotron X-ray diffraction (XRD), Raman scattering, and *ab initio* calculation techniques. The XRD results reveal ilmenite- to perovskite-type phase transition at around 35 GPa. An additional intermediate phase, observed in the range of 31–36 GPa by Raman spectroscopy, but not the XRD technique (Fig. 1.), is proposed to represent the polar $LiNbO_3$ phase [2,3]. It is argued that this phase emerged due to the heating effect of the Raman-excitation laser. The $LiNbO_3$-type MFSO compounds, displaying an intrinsic dipole ordering, represent a promising candidate for multiferroic materials. The detected phase transitions were found to be reversible although a significant hysteresis was noticeable between compression and decompression runs. Moreover, a pressure-induced piezochromism, signifying a bandgap change, was discovered by the direct visual observations and corroborated by ab initio calculations. The present study benefits an efficient high-pressure synthesis of polar magnetic double-perovskite oxides in the future.

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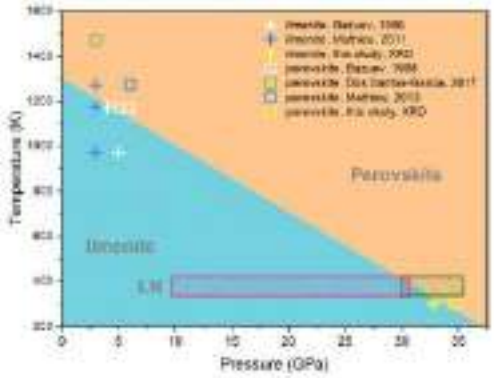

FIG. 3. Phase diagram of MFSO. The green shaded area represents the PT region of the metastable LN phase upon compression, and the pink shaded area represents the PT region of the metastable LN phase upon decompression, as determined in the course of Raman experiment.

O224 - Reversible domain-pattern transfer in a multiferroic rare-earth ferrite

14. Multifunctional magnetic materials: magnetic shape memory materials, multiferroics including artificial/composite multiferroics, and perovskites

Ehsan Hassanpour Yesaghi[1] , *Mads. C. Weber*[1], *Yusuke Tokunaga*[2], *Yasujiro Taguchi*[3], *Yoshinori Tokura*[3, 4], *Thomas Lottermoser*[1], *Manfred Fiebig*[1]

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Multiferroic materials show a variety of interesting effects beyond straightforward magnetoelectric coupling because of coexistence of complex forms of magnetic and electric order. Coupling of ferroic states at the level of domains and domain walls can be used for applications like inversion of domain patterns, that is reversing the direction of the order parameter in each domain but leaving the domain pattern unaffected. As another example, mainly in multiferroic heterostructures, a pattern is written in ferroelectric domains which can then be transferred to ferromagnetic domains for an easier read-out. To demonstrate some of these exotic effects, we use a single-phase multiferroic bulk system $Dy_{0.7}Tb_{0.3}FeO_3$ where a ferroelectric polarization is induced as a result of interaction of two magnetic sublattices of iron Fe^{3+} and rare-earth R^{3+} (R=$Dy_{0.7}Tb_{0.3}$) via exchange magnetostriction. The strong coupling of these three order parameters creates a variety of composite domains and domain walls. Using magnetooptic imaging, we first visualize all the coexisting ferroic domain patterns separately and then we demonstrate how we control the multiferroic interplay of coexisting domains using electric and magnetic fields. We then show that we can fully invert a ferromagnetic domain pattern using an electric field. Finally, we show that magnetic field erases a ferromagnetic domain pattern, yet simultaneously transferring it to the ferroelectric order. The reverse process is also possible in case of starting with a ferroelectric domain pattern and using an electric field. With this, for the first time, we demonstrate a full control over the magnetic and electric domain states in a bulk multiferroic compound which is a prerequisite for the technological application of multiferroics.

O225 - Self-assembled network of nanostructures in BiFeO3 thin films

14. Multifunctional magnetic materials: magnetic shape memory materials, multiferroics including artificial/composite multiferroics, and perovskites

Baptiste Colson[1] , *Victor Fuentes[1], **Zorica Konstantinovic**[2], Carlos Frontera[1], Jose Santiso[3], Felip Sandiumenge[1], Dorothée Colson[4], Anne Forget[4], Nenad Lazarević[2], Maja Šćepanović[2], Zoran Popović[2], Lluis Balcells[1], Alberto Pomar[1], Benjamín Martínez[1]*

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The tendency of some functional perovskite oxides towards self-organized growth and spontaneous nanostructuration, offers enormous potential for the implementation of new nanodevices. Among them, environment friendly multiferroic $BiFeO_3$ present an increasing interest due to large spontaneous polarization at room-temperature. In form of epitaxial thin films, functional properties of this multiferroic can be drastically modified due to presence of the structural strain induced by selected substrate. Additionally, substrate vicinity open new playground by inducing new metastable states with ordered nanostructures at the surface. Complex oxide thin films are often elastically strained and this lattice strain can, in some cases, select preferential growth modes leading to the appearance of different self-organized morphologies.

In this work we report on the controlled fabrication of a self-assembled network of nanostructures (pits and grooves) in highly epitaxial BiFeO3 thin films. As previously shown in the case of manganite thin films [1], the remarkable degree of ordering is achieved using vicinal substrates with well-defined step-terrace morphology. Nanostructured BiFeO3 thin films show mixed-phase morphology, exhibiting the giant ferroelectric polarization close to the theoretical limit. These particular microstructures open a huge playground for future applications in multiferroic nanomaterials.

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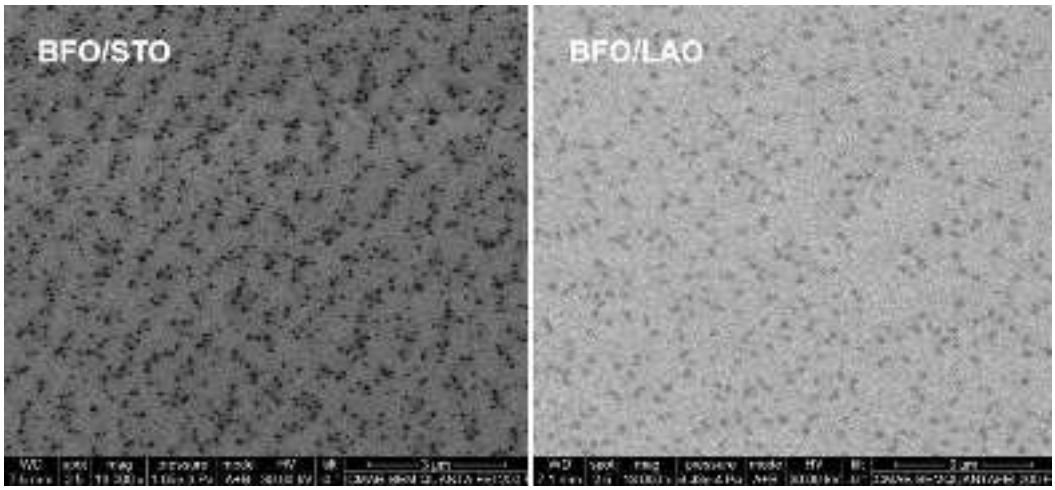

O226 - Strain and electric-field control of magnetism in iron oxide nanoparticle - BaTiO3 composites

14. Multifunctional magnetic materials: magnetic shape memory materials, multiferroics including artificial/composite multiferroics, and perovskites

Li-Ming Wang[1, 2, 3] , ***Oleg Petracic***[1], *Emmanuel Kentzinger*[1], *Ulrich Rücker*[1], *Jürgen Schubert*[4], *Stefan Mattauch*[5], *Alexandros Koutsioubas*[5], *Markus Schmitz*[1], *Xian-Kui Wei*[6], *Marc Heggen*[6], *Vanessa Leffler*[7, 8], *Sascha Ehlert*[7], *Thomas Brückel*[1]

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Ferrimagnetic iron oxide nanoparticle monolayers on top of ferroelectric $BaTiO_3$ (BTO) substrates were prepared and a magnetoelectric coupling effect was observed. Grazing incidence small angle X-ray scattering and scanning electron microscopy confirm a hexagonal close-packed supercrystalline order of the nanoparticle monolayers. We employed a magnetoelectric AC susceptibility setup as modification of a commercial superconducting quantum interference device magnetometer. The magnetoelectric coefficient shows two jumps at the BTO phase transition temperatures. Moreover, the magnetic depth profile of the nanoparticle monolayer was probed by polarized neutron reflectivity. The data recorded at various electric field values show that the electric field is able to alter the magnetism of the nanoparticle monolayer by a strain mediated magnetoelectric coupling effect. Moreover, we prepared BTO films by pulsed laser deposition (PLD) where iron oxide nanoparticles were embedded in the BTO films. We observe also for this system a magnetoelectric coupling between the BTO film and the NPs via strain and interface charge co-mediation. This is demonstrated by measurements of the magnetization as function of DC and AC electric fields.

L.-M. Wang, O. Petracic, E. Kentzinger, U. Rücker, M. Schmitz, X.-K. Wei, M. Heggen, Th. Brückel, *Strain and electric-field control of magnetism in supercrystalline iron oxide nanoparticle - BaTiO3 composite*s, Nanoscale **9**, 12957 (2017)

L.-M. Wang, O. Petracic, S. Mattauch, A. Koutsioumbas, X.-K. Wei, M. Heggen, V.Leffler, S. Ehlert, and Th. Brückel, *Magnetoelectric coupling in iron oxide nanoparticle - barium titanate composites*, J. Phys. D: Appl. Phys. **52**, 065301 (2019)

O227 - Transition from commensurate to incommensurate modulation in 10M Ni50Mn27Ga22Fe1 martensite

14. Multifunctional magnetic materials: magnetic shape memory materials, multiferroics including artificial/composite multiferroics, and perovskites

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Extremely mobile twin boundaries of Ni-Mn-Ga are essential for the existence of the magnetic shape memory effect or the magnetically induced reorientation of martensite. The highest mobility is found in 10M modulated martensite. The character of this phase is still under discussion. For different compositions, the 10M martensite was reported to have commensurate or incommensurate modulation [1-4] or to be nanotwinned [5, 6]. Both incommensurate and nanotwinned structure can result in similar apparent changes in the modulation vector. Considering the incommensurality approach, it has been shown, that the modulation vector changes gradually with temperature [1, 3].
Using neutron and X-ray diffraction experiments on single crystal of $Ni_{50}Mn_{27}Ga_{22}Fe_1$ alloy, we discovered the transition between incommensurate and commensurate modulated structure. We further observed that doping of the Ni-Mn-Ga alloy with Fe leads to accentuation of the modulation satellites of 10M martensite. This allows precise analysis of the transition between commensurate and incommensurate modulated structure and following its temperature evolution. We found that the transition exhibits thermal hysteresis around the room temperature. Owing to the hysteresis, the sample can be prepared in the commensurate or incommensurate state at the same temperature using appropriate heating/cooling procedure. Observed structural transition was confirmed by resistivity measurement and it is further analysed by magnetic measurements. The investigation whether the incommensurality is proper or only apparent caused by nanotwinning is the subject of ongoing research.

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O228 - Trirutiles as potential multiferroics: the case of Mn2TeO6

14. Multifunctional magnetic materials: magnetic shape memory materials, multiferroics including artificial/composite multiferroics, and perovskites

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Magnetoelectric (ME) multiferroic materials, which present simultaneously two coupled properties between ferromagnetism and ferroelectricity, have attracted much attention recently, not only owing to their application perspectives, e.g., next-generation magnetic RAM, but also for the rich physics associated with the understanding of this coupling. Inverse trirutiles are of particular interest here since ME properties have been reported in this family of compounds (*1*). Within this inverse trirutile system, Mn_2TeO_6 was first reported by Hund (*2*) and Fruchart *et al*. (*3*). The fact that the structure of Mn_2TeO_6 was not determined precisely in these earlier works motivated us to revisit its crystal and magnetic structures, along with its physical properties. Thanks to extensiveuse of different techniques performed in a largetemperature range (1.5K to 700°C), encompassing synchrotron (MSPD@ALBA, Spain), neutron (WISH@ISIS, UK and G4.1@LLB, France) andelectron diffraction experiments combined with physical properties measurements, the very complex behaviourof Mn_2TeO_6 was revealed.

Like other inverse trirutile compounds, the high-temperature (from 700 to 420°C) crystal structure of Mn_2TeO_6 is tetragonal. Below 420°C, however, as shown in Figure 1(a-c), the phase transforms to a monoclinic phase ($P12_1/c1$) is with a doubling along *b*-axis (a = 9.103 Å, b = 13.05 Å, c = 6.466 Å, beta = 90.03°). It is evidenced by the superlattice reflections on the electron diffraction and synchrotron powder diffraction at room temperature (Figure 1 middle). The refinement of the room temperature structure from synchrotron powder diffraction was carried out with an approach based on symmetry-adapted modes: the structural distortion is seen as a superposition onto the parent structure of symmetry breaking atomic displacements modes. Amongst the 7 basis modes that could be taken into account to describe the transition from tetragonal to monoclinic super-cell, a single one, the S_3 representation, is found to be of predominant amplitude and is also sufficient to get a satisfactory refinement. The structure of Mn_2TeO_6 can be understood therefore as a distorted inverse trirutile structure: with respect to the parent tetragonal one, the Mn/Te (2:1) lines of edge-sharing octahedra running along *a*are now slightly puckered (Figure 1 (b), the lines indicate by black arrows.). This distortion is attributed to cooperative Jahn-Teller effects of Mn^{3+}, which lead to both elongated (Mn(1) and Mn(3)) and compressed (Mn(2) and Mn (4)) octahedra (*4*).

Further cooling the sample, a hysteretic structural transition is observed spanning more than 50K, which leads to the coexistence of two monoclinic phases. A series of magnetic transitions are also observed between 48K and 22K, with magnetization, ehat capacity measurement and neutron diffraction. The latter one possibly involving a magneto-electric coupling (Figure 1 Right) (*5*).

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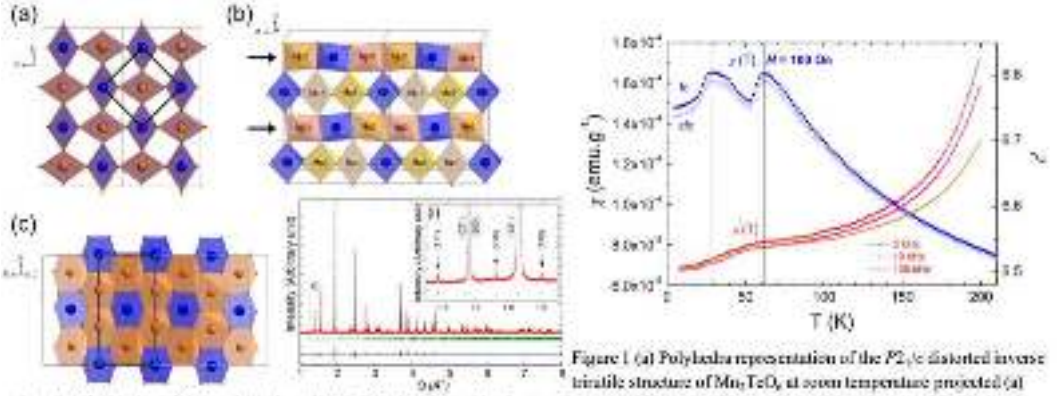

Figure 1 (a) Polyhedra representation of the $P2_1/c$ distorted inverse trirutile structure of Mn_2TeO_6 at room temperature projected (a) along [100], (b) along [001] and (c) along [011]. (Middle) Rietveld refinement of the synchrotron XRPD data of Mn_2TeO_6 at room temperature. The inset shows an enlarged view of the satellite peaks, indexed in the monoclinic structure. (Right) Zero field-cooling warming and field-cooling χ (T) curves of Mn_2TeO_6 and T-dependence of the dielectric constant (ε') at different frequencies from 5k to 1000 Hz

O229 - Unusual terahertz soft mode in multiferroic M-hexaferrite Ba(1-x)Pb(x)Fe12O19

14. Multifunctional magnetic materials: magnetic shape memory materials, multiferroics including artificial/composite multiferroics, and perovskites

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Hexagonal ferrites form a large class of materials characterized by hexagonal syngony and layered structure. Among other members of hexagonal ferrite family, M-type hexaferrites, i.e. compounds isostructural to magnetoplumbite ($PbFe_{12}O_{19}$), have the simplest unit cell containing 64 ions (Z=2). 24 iron ions within the unit cell are distributed over 5 distinct site-positions with 4-, 5- and 6-fold oxygen coordination. The most famous compound, $BaFe_{12}O_{19}$, is a broadly known hard magnetic material with magnetic subsystem that is stable down to the lowest temperatures, and widely used in device fabrication and engineering [1]. Properties of hexagonal ferrites show extremely high sensitivity to the doping and to the dopant content which results in strong variation of their properties (shift of AFM resonance, change of magnetization saturation, change of dielectric constant, etc.) or emergence of new effects, like quantum criticality in $BaFe_{12}O_{19}$ and bi-relaxor state in $Ba_{0.3}Pb_{0.7}Fe_{12}O_{19}$ [2]. Both subsystems, dielectric and magnetic, are dependent on the local environment of the atoms in the unit cell, which in turn is strongly affected by chemical composition: pure barium hexaferrite is a hard magnetic material with collinear structure [1], while strontium hexaferrite is known to have conical magnetic structure. We performed first detailed terahertz-infrared investigation of the barium-lead substituted compounds $Ba_{1-x}Pb_xFe_{12}O_{19}$ with x = (0,..., 1). Dielectric response of the samples was measured at frequencies 0.3-240 THz in the temperature interval 5-610 K using terahertz time-domain TeraView TPS 3000 spectrometer and infrared Fourier-transform spectrometer Bruker Vertex 80v. The influence of lead content on the terahertz electronic transitions within the fine structure of divalent iron was reported in [3]. In compounds with small concentrations of lead (x=0.1, 0.2), we discover an excitation that is not seen in the compounds with higher lead concentrations. The excitation is located at 1.05 THz at room temperature and softens down to 0.27 THz at 5 K. This softening is accompanied by an increase of the dielectric contribution of the excitation. Detailed analysis of the results revealed that the temperature evolution of the soft mode resonance frequency is rather unusual and follows a power law with the exponent 0.27: , T_c=3.3 K. Close value of the critical temperature (T_c=3 K) was found in undoped $BaFe_{12}O_{19}$ [4] where it was connected with the reconstruction of magnetic ordering. We assume that the specific temperature behavior of the observed excitation is connected with the change of the type of magnetic ordering from simple collinear antiferromagnetic to conical. Such switching could be driven by distortions introduced in the lattice by co-occupation of the 12-fold oxygen polyhedra with Ba and Pb ions, which provide lowering of the symmetry of 12k octahedra that is known to be responsible for the inclined spin directions.

The work was supported by Russian ministry of education and Science (Program 5-100).

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O230 - Visualization of antiphase boundaries and their effect on magnetic hysteresis in Ni-Mn-Ga compound

14. Multifunctional magnetic materials: magnetic shape memory materials, multiferroics including artificial/composite multiferroics, and perovskites

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Ni-Mn-Ga compound is considered as an example of magnetoelastic multiferroics combining ferromagnetism and ferroelasticity. It was found [1] that magneto-elastic properties are strongly influenced by the density of antiphase boundaries. The antiphase boundary (APB), i.e. planar defects occurring in ordered $L2_1$ Ni-Mn-Ga phase, is assumed to be disordered Ni-Mn-Ga phase in which the ferromagnetic interaction is weakened or even turned antiferromagnetic. However, the direct observation of antiphase boundaries is hindered by the fact that usual transmission electron microscopy (TEM) method provides no contrast on the boundary. The first observation of APBs was done using Lorenz TEM thanks to magnetic contrast arising from different magnetic properties of the boundary and bulk [2].

We demonstrate that APBs can be visualized by usual magnetic force microscopy (MFM) on the surface of the bulk crystals without need to resort to Lorenz TEM and very thin foil. The magnetic contrast arises due to different magnetic properties of APB core and surrounding, however, compared to LTEM the mechanism is different. In the case of 100 orientation of the surface the easy magnetization axis is in plane. The in-plane magnetization follows an easy axis and crosses randomly distributed APBs. On the APB the weak magnetic contrast is generated, which is then detected by magnetic force microscopy. The contrast from APB is bi-colored and weak compared to single color of magnetic domain wall and thus can be easily recognized. We provide a simple model of the arising contrast [3].

In perpendicular orientation of easy axis, the APB contrast is inundated by the contrast arising from magnetic domains walls. From the detailed analysis follows that most of the magnetic domain walls are pinned on the APBs. Moreover, in cubic austenite due to very low cubic magnetocrystalline anisotropy the APB contrast is hardly detectable as the overall magnetization direction is easily disturbed. We will correlate our results with recent observation of APB using LTEM [4].

Using newly developed method we were able to demonstrate the pinning of magnetic domain walls on the APBs, which is main coercivity mechanism in 10M martensite [5]. The increasing density of APBs obtained by heat treatment strongly enhances the magnetic coercivity which provides new functionality of the Ni-Mn-Ga magnetic shape memory alloys [6].

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15. Spin waves, magnonics, ultrafast magnetization dynamics and optically driven spin excitations

O231 - All-Optical Switching in Twisted Gd/Fe-Superlattices

15. Spin waves, magnonics, ultrafast magnetization dynamics and optically driven spin excitations

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Multicomponent magnetic systems can exhibit rich state diagrams and have great potential for future applications in data storage and communication. A prominent example for this class of materials is GdFe which features all-optical switching (AOS) of its ferrimagnetic ground state as well as a transient ferromagnetic state on sub-ps timescale [1]. In addition to GdFe alloys, well defined superlattices (SLs) of Gd and Fe can be grown by magnetron sputtering, with interfacial roughness down to 1-2 atomic layers, featuring additional non-collinear magnetic phases that have been identified, e.g. by neutron and X-ray scattering, optical MOKE measurements, and mean-field theory [2–4], see Fig. 1.
Due to the antiferromagnetic coupling between the Gd and Fe interfaces and their different Curie temperatures (in bulk: , T_C^{Fe} = 1043 K, T_C^{Gd} = 293 K) a compensation point T_{comp} exists at which both magnetic moments are equal and thus cancel out resulting in zero total magnetic moment. Below T_{comp}, the magnetic moments in Gd are larger than in Fe, while above T_{comp}, the magnetic moments align the opposite way. Under weak in-plane magnetic fields a collinear magnetic phase is realized with Fe magnetic moments aligned parallel ($T > T_{comp}$) or antiparallel ($T < T_{comp}$) to the external magnetic field. For magnetic fields above a critical value the collinear phase becomes unstable and a canted magnetic state occurs with an additional non-uniform magnetization distribution with the Gd layers – the so-called twisted state.
We present time-resolved soft X-ray MCD data in reflection on Gd/Fe SLs measured at the FemtoSpeX facility at BESSY II (Berlin, Germany). Our results obtained with 75 ps temporal resolution reveal complex magnetization dynamics after femtosecond photoexcitation as a function of X-ray photon energy, temperature, magnetic field amplitude and direction, excitation fluence, and scattering vector *q,* see Fig. 2. We observe transient changes of the XMCD contrast of more than 100% of the initial value, which can be attributed to diffraction effects or realignment of the twisted magnetic state. We support the XMCD data by static and pump-probe MOKE measurement to gain a deeper understanding of the static spin structure and the sub-ps magnetization dynamics.

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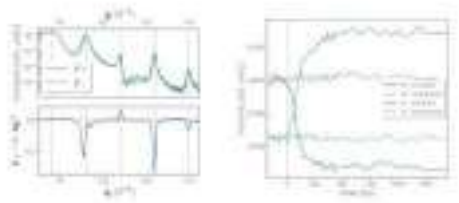

O232 - Composition dependent THz emission of spintronic TbFe/Pt layers

15. Spin waves, magnonics, ultrafast magnetization dynamics and optically driven spin excitations

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Bilayers of ferro-/ferrimagnetic (FM) thin films and nonmagnetic metal (NM) layers have been shown to be high power broadband THz emitters when excited by femtosecond laser pulses [1-2]. Amplitude and frequency of the emitted THz radiation depend on the film thickness, the electrical conductivity, the magnetic properties of the FM layer, and the spin-Hall conductivity of the NM layer and can, therefore, be tuned by changing the composition of the used layer stack [3]. However, so far the microscopic processes leading to the THz radiation and also the role of the magnetic states especially for more complex magnetic layers are not completely understood.

Here we report on a systematic study on the THz emission of magnetron sputter deposited 20 nm thick ferrimagnetic Tb_xFe_{1-x} ($0 \leq x \leq 1$) alloys combined with a 5 nm thick Pt layer [2]. Tb_xFe_{1-x} shows a great variety of different magnetic states depending on the composition, temperature, and applied magnetic field. Thus, it is an ideal candidate to investigate the role of the different magnetic states on the emitted THz radiation. The samples were characterized by SQUID magnetometry and THz emission pump probe experiments. Figure 1a shows the measured THz intensity with respect to the Tb content x of the Tb_xFe_{1-x}/Pt sample series. The measured THz radiation is mainly caused by the Fe electrons. The highest THz signals that can be observed for $0.03 \leq x \leq 0.15$ derive from the reduced electrical conductivity of these samples compared to the pure Fe/Pt bilayer. The decreased signal for higher x and also the local maximum for $x = 0.5$ can be attributed to the reduced Fe content and the in-plane magnetic moment of the Fe sublattice, which is schematically drawn in figure 1b. An inversion of the THz signal for $0.45 \leq x \leq 0.55$ (see figure 1c) can be explained by the inverted alignment of the Fe magnetic moments. Please note that the Tb net moment is dominating (aligned with the applied field) at room temperature and points opposite to the Fe moments. The small signals for high x are caused by the induced paramagnetic moments as the Curie temperature is already below room temperature.

Our study provides deeper insights into the role of complex magnetic materials used in spintronic THz emitters and will contribute to future optimized emitter designs.

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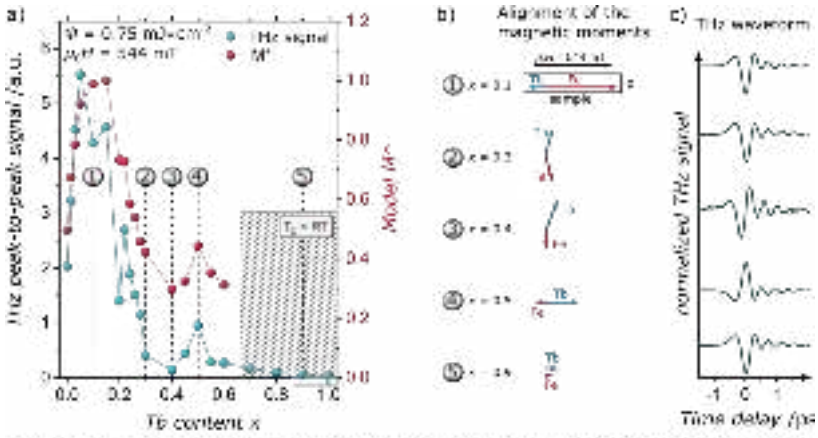
a)
b)
c)
THz signal
M²
Tb content x
Time delay /ps

O233 - Direct Imaging of Sub 200 nm Spin Waves in Yttrium Iron Garnet Films

15. Spin waves, magnonics, ultrafast magnetization dynamics and optically driven spin excitations

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Spin waves continue to be a topic of high interest in magnetism research. The idea of applying these in future computer technology strongly contributes to this interest [1]. This also creates a push towards smaller length scales in the field, for these applications to be competitive with current nanometer scale CMOS technology. The resolution of the commonly used optical spin wave measurement techniques (Brillouin light scattering, Kerr microscopy) is, however, limited to about 250 nm. Studies on spin waves below that limit are mostly done through all-electrical measurements, which do not offer spatial information.

Time-resolved scanning transmission x-ray microscopy (TR-STXM) can be used to directly image magnetization dynamics with a resolution in space and time of down to 18 nm and 10 ps. This technique has been utilized in the past for spin wave imaging down to 100 nm wavelength and below in metallic thin films [2]. However, due to the requirement of x-ray transparency, it has been a challenge to apply it to sample materials that need bulk single crystal substrates for film growth. Among these materials is yttrium iron garnet (YIG), which is, incidentally, very prominent in spin wave research due its very low magnetic damping.

Our group has experimented with various approaches to bringing the substrate down to x-ray transparent thickness. First results were obtained with a thin lamella prepared via a focused ion beam microscope (FIB) [3]. Since this restricts the possible geometries that can be studied, a more general approach was taken next. Through a combination of mechanical grinding and ion milling [4], x-ray transparent windows were created in the substrates of continuous 2 by 2 mm YIG thin films. Since the sample layout is very general, the technique can in principle be applied to almost all conceivable thin film sample geometries. Spin waves of wavelengths down to 100 nm, well below the optical limit, were directly imaged and their dispersion recorded for two different film thicknesses. In the thicker film the dispersion was found to show increasing influence of mode hybridization towards shorter wavelengths. Furthermore the limits of efficient excitation of ultrashort waves have been explored for the two thicknesses and two different wave sources.

In summary, this work shows direct images of down to 100 nm spin waves in YIG films and insights into their characteristics. It thus opens up a path to nanoscale imaging of spin wave phenomena in general thin film samples of YIG and other single crystal materials.

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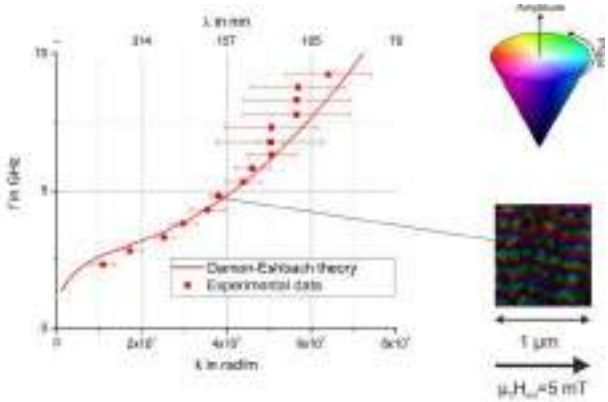

Dispersion of spin waves in Damon-Eshbach geometry in an 80 nm thick YIG film measured via TR-STXM. Exemplary image (phase/amplitude) of measured spin wave activity to the right of the diagram.

O234 - Directional emission of spin waves from a vortex core

15. Spin waves, magnonics, ultrafast magnetization dynamics and optically driven spin excitations

Sina Mayr[1, 2] , *Lukáš Flajšman*[3], *Simone Finizio*[1], *Aleš Hrabec*[1, 2], *Markus Weigand*[4], *Hermann Stoll*[5, 6], *Laura Jane Heyderman*[1, 2], *Michal Urbánek*[3], *Sebastian Wintz*[1, 7], *Jörg Raabe*[1]

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Spin waves could be used as signal carriers in future spintronic logic and memory devices with a potentially lower power consumption and improved miniaturization compared to the present charge-based CMOS technology [1]. Towards the goal of miniaturization, it was shown recently that isotropically propagating spin waves with ultra-short wavelengths can be generated by exploiting the driven dynamics of topological spin textures such as magnetic vortex cores [2, 3]. In this contribution, we show that it is even possible to achieve a directional emission of these waves when a static magnetic field is applied to the vortex structure. This field deforms the vortex core from a point-like source into a curved one-dimensional object (see Figure 1), while at the same time displacing it laterally. In particular, self-focusing effects of spin waves can be observed for certain combinations of magnetic field and driving frequency. This directional emission and self-focusing of spin waves from a vortex core opens a way for the directional propagation of spin waves without the need for additional patterning or waveguides.

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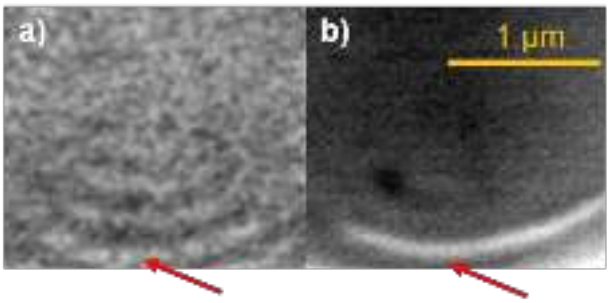

Figure 1. a) Normalized and b) absolute snapshot of a time-resolved scanning transmission X-ray microscopy measurement illustrating the directional emission of spin waves (f = 8.5 GHz) from a vortex core (indicated by the red arrows), the latter extending to a one-dimensional object upon static field excitation.

O235 - Enhanced demagnetization in CoPt due to spin-orbit coupling and intersite spin transfer

15. Spin waves, magnonics, ultrafast magnetization dynamics and optically driven spin excitations

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The development of laboratory-based higher harmonic generation (HHG) experiments with polarization control enables spectroscopy on magnetic systems in the extended ultraviolet spectral regime (XUV) with high temporal resolution. A unique feature of HHG spectroscopy is its broad spectral range allowing the simultaneous measurement of different elements in a complex sample system[1]. This makes it possible to measure the spin dynamics of the different elements individually and to investigate the interplay between these elements. The investigation of the interplay is especially interesting for the technologically important class of thin ferromagnetic films including multilayers and alloys of 3*d*-and the heavier 5*d* transition metals (TMs).

In our joint experimental and theoretical work we have performed time-dependent density functional theory calculations on the temporal evolution of CoPt, FePt, NiPt indicating that for early timescales optically induced intersite spin transfer (OISTR)[2] dominates the demagnetization process. We find that OISTR is driven by the large number of unoccupied 3d states in the 3d TMs, compared to that on the Pt site.

Experimentally, we have measured a CoPt-alloy with time-resolved XUV magnetic circular dichroism (MCD) in transmission geometry. Our results show partially decoupled spin dynamics for Pt and Co due to different spin-orbit coupling (SOC) strength on the individual atoms. Based on the experimental data and the theoretical calculations we demonstrate that the effective filling of the initially unoccupied minority states of the 3*d* TM substantially influences the demagnetization rate. Especially in the first tens of femtoseconds, this filling is done by transfer of minority electrons from Pt to Co. The large SOC strength of the 5*d* electrons in Pt ensures efficient spin flips which lead to the rapid reduction of spin polarization on the Pt site.

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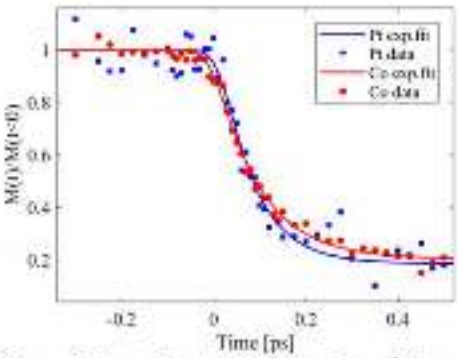

Figure 1. Transient spin dynamics of Co and Pt in a $Co_{50}Pt_{50}$-alloy.

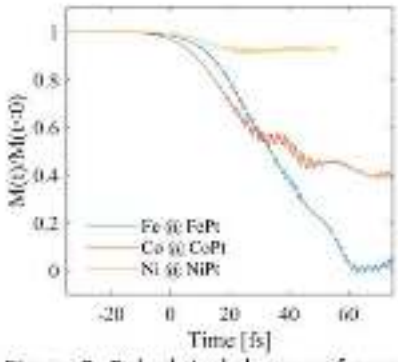

Figure 2. Calculated change of magnetization of Ni in NiPt, Co in CoPt and Fe in FePt.

O236 - Excitation and amplification of spin waves by spin-orbit torque

15. Spin waves, magnonics, ultrafast magnetization dynamics and optically driven spin excitations

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The emerging field of nano-magnonics utilizes high-frequency waves of magnetization – spin waves – for the transmission and processing of information on the nanoscale. The advent of spin-transfer torque has spurred significant advances in nanomagnonics, by enabling highly efficient local spin wave generation in magnonic nanodevices. Furthermore, the recent emergence of spin-orbitronics, which utilizes spin-orbit interaction as the source of spin torque, has provided a unique ability to exert spin torque over spatially extended areas of magnonic structures, enabling enhanced spin wave transmission.

Here, we experimentally demonstrate that these advances can be efficiently combined. We utilize the same spin–orbit torque mechanism for the generation of propagating spin waves, and for the long-range enhancement of their propagation, in a single integrated nano-magnonic device. The demonstrated system exhibits a controllable directional asymmetry of spin wave emission, which is highly beneficial for applications in non-reciprocal magnonic logic and neuromorphic computing.

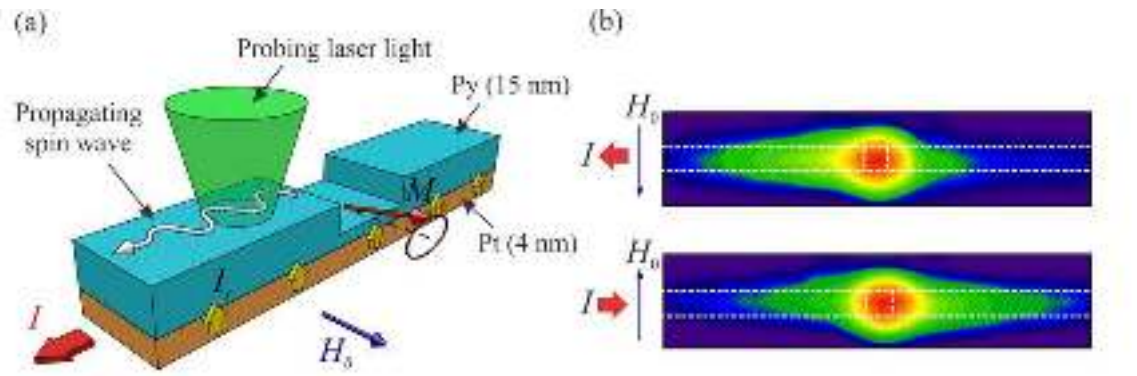

Figure: (a) Schematic of the experiment. (b) Unidirectional spin wave emission by the nano-notch oscillator. Dashed lines on the maps show the outlines of the waveguide and of the nano-notch.

O237 - Experimental evidence for inertial dynamics in ferromagnetic thin films

15. Spin waves, magnonics, ultrafast magnetization dynamics and optically driven spin excitations

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We report a direct experimental evidence of inertial spin dynamics in ferromagnetic thin films in sub terahertz (THz) frequency regime based on the recent reformulation of the inertial Landau-Lifshitz Gilbert equation. This equation predicts the appearance of spin nutations at frequencies orders of magnitude higher than the ferromagnetic resonance, characteristic of the spin precession described by the conventional LLG equation. Using the time-resolve magneto-optical Kerr effect, we observe that when a thin ferromagnetic film is excited by an intense narrowband THz pulse of variable frequency, its spins start to follow coherently with the THz magnetic field, and with an amplitude of the response which depends on the center frequency of the driving THz field. Our initial investigations suggests that there exists a broad resonance at around 0.5 THz (i.e. with precession period of ~ 2 ps) which is damped out on time scales of the order of 10 ps. This is orders of magnitude faster than conventional ferromagnetic resonances, and it points towards the existence of yet unobserved inertial dynamics in ferromagnetically ordered spin systems, similar to the motion of a classical spinning top. We will present detailed results on three different samples and show the consistency of our findings with simulations based on the inertial LLG equation.

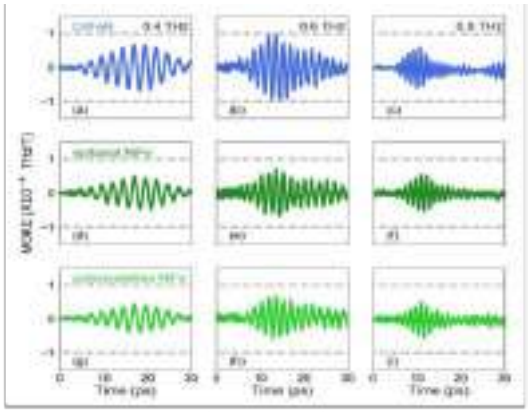

Figure 1: Time-resolved magneto-optical Kerr [MOKE] response of the magnetization to normalized terahertz fields centered around (a-c) 0.5 and (d-f) 1 THz for (a)-(c) an amorphous 10 nm CoFeB film on a glass, (d)-(f) an epitaxial $NiCoFe_2O$ (normal-cy) film grown on MgO substrate and (g)-(i) of a polycrystalline capacitor on silicon

O238 - Experimental realization of THz magnonic bandgaps in atomic-scale ferromagnetic multilayers

15. Spin waves, magnonics, ultrafast magnetization dynamics and optically driven spin excitations

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Band structure engineering of exchange spin waves is essential for nanoscale magnonics. Magnonic crystals – artificially designed periodic magnetic structures – could provide this functionality [1]. However, limited by current nanolithography technique, it is very challenging to fabricate a crystal with a feature size of few nanometers, which is on-demand for efficient control over exchange spin waves with THz frequencies.

Here we report on an entirely new approach of materials design for THz magnonics making use of quantum confinement of THz magnons in layered ferromagnets. Using spin-polarized high-resolution electron energy loss spectroscopy, we efficiently excited and detected different THz magnon modes associated with the quantum confinement in the thickness dimension of ferromagnetic multilayers. We show that the modes with quantization numbers $n = 0$ and $n = 1$ in Co/Fe layers grown on the Ir(001) and Rh(001) substrates disperse up to 65 THz in the first Brillouin zone. By changing the materials combination and the number of ferromagnetic layer, the magnon band structure in these systems can be largely tuned. For the first time, we observe the bandgaps opening up to several THz. We discuss the key mechanism for the formation of bandgaps, being the vertical variations of the interatomic exchange interaction. Our results pave a way to design atomic-scale magnonic crystals with capability of operation in THz frequency regime.

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O239 - Ferromagnetic resonance study of collective and localized modes in 3D magnonic crystals

15. Spin waves, magnonics, ultrafast magnetization dynamics and optically driven spin excitations

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Experimental and numerical results of spin-wave excitations in the meander-type YIG waveguide are presented. The meander-type YIG film was fabricated in the following manner. The periodic array of grooves was etched in the surface of GGG substrate. Then YIG film was sputtered on the top of the preprocessed substrate by means of ion-beam sputtering with fast annealing. Such structure we defined also in our previous works as 3D magnonic crystal. Advantage of the anisotropic ion-beam sputtering over, e.g., pulsed laser deposition is the uniform surface of hundreds of square centimeters and predefined YIG thickness in the wide range of 0.1–1 μm. In addition, deposition on the cold substrate and vacuum fast annealing provide the flatness and appropriate interface quality with the possibility of multilayer fabrication with the sequential repetitions of the fabrication stages. After fabrication, geometrical parameters of meander-like corrugated YIG film sample were measured by optical and electron microscopies, and profilometry. Scanning electron microscopy (SEM) reveals the film thickness $d \approx 150$ nm/ We note here, that part of the sample was coated with platinum to get rid of surface charge that led to the correct measurement of YIG film borders in SEM images. Period of the structure was around 20 μm, width of the microstripe antenna between etched grooves – $w_1 \approx 10$ μm, width of these grooves – $w_3 \approx 8$ μm, their depth – $s \approx 1.57$ μm, length of the grooves' walls w_2 varied from ≈1 to ≈2 μm. Besides, grooves' walls had the roughness ≈1 μm along the grooves direction. By the variation of the in-plane magnetization angle, we show that ferromagnetic resonance (FMR) spectrum essentially depends on the total height of the meander in the case of magnetic field orientation perpendicular to the microstrips. We demonstrate that the gradients of inhomogeneous static magnetic fields can lead to the effective generation of short-wavelength dipole-exchange waves having non-resonant spatial distribution. For the field applied perpendicularly to the microstrips, the FMR spectrum essentially depends on the total height of the meander and contains three frequency domains formed by forward volume magnetostatic waves, localized modes, and backward volume magnetostatic waves. In the experiment, we can observe only the region resulted from standing BVMSW modes. Absence of FVMSW region is most probably caused by non-verticality of etched grooves' walls while their "smoothed" edges reduced the internal field inhomogeneity and led to disappearance of localized modes. In the case of longitudinally magnetized structure, scattering of surface magnetostatic waves in the junctions of the vertical and horizontal segments caused the formation of the quasi-standing waves. At any direction of applied field, the gradients of inhomogeneous static magnetic fields can lead to the effective generation of short-wavelength dipole-exchange waves whose spatial distribution is non-resonant. Obtained results together with the possibility to integrate magnonics and semiconductor electronics on the base of YIG/GaAs structures can provide the basis for the development of 3D-elements for magnonics and spintronics devices with extended frequency characteristics controlled by the total height of the meander-type structure. Work is supported by RSF, Project 19-19-00607 and by Russian Federation (assignment 074-02-2018-286).

O240 - Field Dependence of Time-Resolved All-Optical Switching in Co/Gd Bilayers

15. Spin waves, magnonics, ultrafast magnetization dynamics and optically driven spin excitations

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In the search for new writing techniques in data storage devices, all-optical switching (AOS) provides unprecedented possibilities. Originally discovered in ferrimagnetic GdFeCo alloys [1], AOS gives rise to a toggle switch of the magnetization on the picosecond timescale after excitation with an ultrashort laser pulse. Recently, it was shown that single-pulse AOS can also be found in ferrimagnetic Co/Gd bilayers [2], opening up new possibilities for (interface) engineering of the stack, which makes it highly suitable for future applications. However, up until now only static measurements of AOS in Co/Gd have been reported, giving no information about the dynamic response of the system.

We report on the first time-resolved measurements of all-optical switching in Co/Gd, performed with a time-resolved MOKE setup. These measurements show that in Co/Gd bilayers the switching happens on the same picosecond timescale as in GdFeCo alloys. Because of the toggle switching of the magnetization, by measuring every other pulse we are able to measure the dynamics even at zero field, which allows us to measure the dynamics from zero field to ~500 mT. As visible in Figure 1, we see that on very short timescales the external field has a strong effect on the dynamic behaviour of the system, even for fields much smaller than the exchange field. This behaviour is similar to what is found in alloys. However, there are also some key differences in the behaviour on very short timescales. Most notably, in the alloys a plateau around zero magnetization is observed, which is not visible for the bilayers.

To better understand the exact switching mechanism in these bilayers we use a modified version of the M3TM model. This model can be used for both alloys and bilayers, where it explicitly takes into account the bilayer structure. From simulations with this model, the plateau around zero magnetization is expected to be present in both systems. Our currents efforts are focused on understanding why this plateau is not visible in the bilayers, and in general on explaining the dynamics in the bilayers. We expect that this research will provide an important next step in the understanding of AOS in ferrimagnets.

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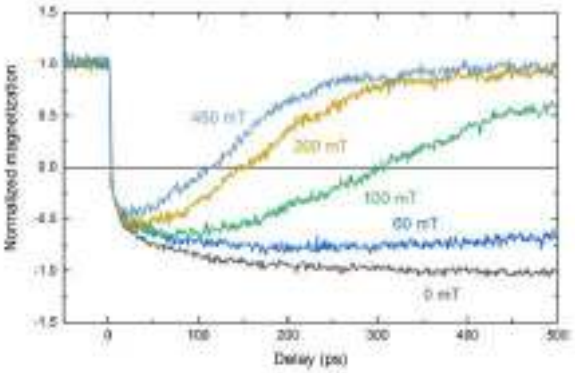

Figure 1. Time-dependent magnetization traces of Co/Gd for different applied fields. In these experiments the applied field is oriented in the positive direction, in the same direction as the initial state of the magnetization.

O241 - Low Gilbert damping in ordered Fe1-xRhx thin films

15. Spin waves, magnonics, ultrafast magnetization dynamics and optically driven spin excitations

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Magnetic relaxation, which is described by Gilbert damping, is an important issue, since it governs various magnetic properties such as magnetization reversal and attenuation of spin wave propagation. From the viewpoint of designing less-energy dissipative spintronic devices, ferromagnetic metals with a low damping constant α are essentially required. Recently, Schoen *et al.* reported that polycrystalline $Fe_{75}Co_{25}$ thin films showed a low damping constant [1], while Lee *et al.* subsequently demonstrated a very low damping constant as low as 7.1×10^{-4} in epitaxial $Fe_{75}Co_{25}$ thin films [2]. In this work, we study the compositional dependence of the damping constant of $Fe_{1-x}Rh_x$ films, where Rh is classified in the same group of elements as Co. Here, we demonstrate a very low damping constant of 9×10^{-4} in $Fe_{80}Rh_{20}$ thin films.

30-nm-thick $Fe_{1-x}Rh_x$ alloy films with compositions of $0<x<0.27$ were grown on single crystalline MgO(001) substrates at 600°C using molecular beam epitaxy technique by co-evaporation of Fe and Rh. X-ray diffraction ensures the epitaxial growth of all the films grown. Ferromagnetic resonance (FMR) measurements were done in in-plane magnetic fields up to 2780 Oe along FeRh[100] using a coplanar waveguide and a vector network analyzer at room temperature. The fitting of the frequency dependence of the FMR linewidth enables us to estimate the α values.

We find that α decreases with increasing Rh concentration up to around $x=0.2$ and increases for $0.2<x<0.27$. The minimum value of α is obtained to be 9×10^{-4} at round 20% of Rh concentration. The value is comparable to that of $Fe_{75}Co_{25}$ previously reported [2]. Such a low damping and the compositional dependence in $Fe_{1-x}Rh_x$ alloy are quite interesting. According to the band calculation by Jezierski, the density of states at the Fermi level $D(E_F)$ shows a minimum at round 20% of Rh concentration [3]. This behavior is analogous to that of FeCo, where the low damping occurs at the composition that has a minimum of the $D(E_F)$. From the results, we consider that the low magnetic damping in both FeCo and FeRh alloys has the same origin in the low $D(E_F)$ and its compositional dependence is likely associated with the variation of the $D(E_F)$.

This work was supported in part by JSPS KAKENHI Grant Numbers JP17H03377, JP18F18353, JST CREST Grant Number JPMJCR18J1, and the Asahi Glass Foundation.

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O242 - Magnetic damping in Co2MnGe Heusler compounds with A2, B2 and L21 ordering: ab initio results

15. Spin waves, magnonics, ultrafast magnetization dynamics and optically driven spin excitations

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Ultralow damping materials attract much attention recently due to their possible use in magnonic devices where the spin excitations may be used as sole carrier of information [1-3]. Experimentally it has been found that the magnetic damping parameters of Co_2MnGe drops drastically as the system evolves from *B2* chemical ordering via *A2* to $L2_1$ order. Intrinsic value as low as 0.0010 can be obtained for the fully ordered $L2_1$ Co_2MnGe [4].

We confirm this experimental trend via first principles calculations. The electronic structure, spin-orbit coupling parameter and the Gilbert damping parameter, α, was calculated for Co_2MnGe as chemical ordering improves from the completely disordered *B2* configuration via the semi-ordered *A2* to the fully ordered $L2_1$ configuration. We observe a drastic drop in the Gilbert damping parameter with ordering (see Figure 1, top). Similar behavior can be observed for the spin-orbit coupling parameter. We find that the drastic change in the damping parameter is related to the significant reduction of the density of states at the Fermi level, $n(E_F)$, as the *B2* order improves with only a minimal decrease of the damping value with further $L2_1$ order. Chemical ordering results in formation of band gap as it is shown in the bottom of Figure 1, leading to sudden decrease of $n(E_F)$. *Ab initio* value for the $L2_1$ Co_2MnGe is as low as 0.0005, in line with the experimental findings.

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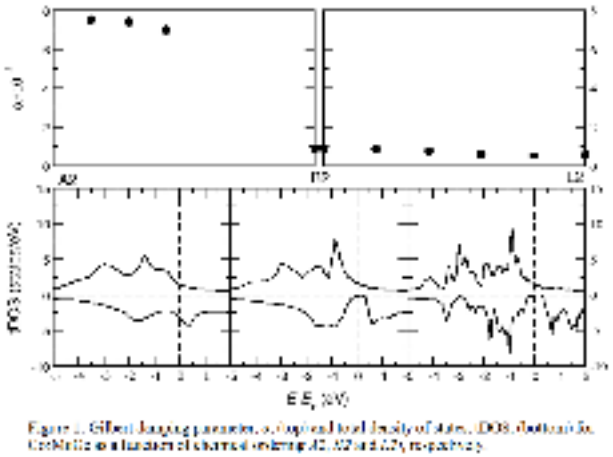

O243 - Nanoscale domain-wall dynamics in garnet films induced by a single laser pulse

15. Spin waves, magnonics, ultrafast magnetization dynamics and optically driven spin excitations

Mikhail Logunov[1, 2] , *Mikhail Gerasimov*[2, 3], *Sergey Ilin*[2, 3], *Sergey Safonov*[1, 2], *Alexandr Spirin*[2, 3], *Yannick Dusch*[2, 4], *Philippe Pernod*[2, 4], *Sergey Nikitov*[1, 2, 5]

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Laser-induced domain-wall (DW) motion is intensively studied because of the prospects for all-optical control of DW as a mobile nanoobject in spin-photonics devices [1-5]. Here, we report on DW motion induced by a single laser pulse. Using a magneto-optical pump-probe method together with a magnetooptical diffraction technique and with a spatial filtering technique, we registered a time evolution of nanoscale DW motion in an iron garnet film with 5 nm spatial accuracy and 1 ns temporal resolution. The amplitude of the DW displacement as a result of the single pump-pulse reaches hundreds of nanometers. The direction of DW motion is reversed when the helicity of the laser pump-pulse changes. We were able to experimentally measure the laser-induced local sample temperature increase. This made it possible to isolate the helicity-dependent DW motion, eliminating the thermal effect. The detected motion of DW is inertial in nature and continues after the end of the laser pulse for 100 ns, then reversal and relaxation to the initial state occurs. The observed DW velocity change in the process of their inertial motion is caused, as we believe, by the transformation of the spin structure of DWs. The dynamic increase in the sample temperature caused by the laser pump pulse and possible origin of the helicity-dependent DW motion are discussed.

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O244 - Optical pump power dependence of spintronic THz emitters

15. Spin waves, magnonics, ultrafast magnetization dynamics and optically driven spin excitations

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We have studied optically-driven spintronic THz emitters (STE) and observed a non-monotonic dependence of the THz emission on the optical excitation energy. Our results are important from two perspectives. First, we find that the right choice of laser pump energy is critical for the use of STE. Second, the results might help to better understand the intensively discussed competing mechanisms responsible for optically-induced demagnetization of ferromagnets (FM) and might even open a path for the control of them.

The quest for broadband THz emitters due to the growing importance of THz technology has led to novel mechanisms for electromagnetic wave emission. One of the most promising concepts for the next generation THz sources is the STE, which is based on spin-to-charge conversion [1]. It consists of a heterostructure of FM and non-FM metallic thin films. Upon excitation by ultrafast laser pulses a spin-polarized current is generated in the FM film and, when entering the non-FM layer, subsequently transformed into a transversal charge current by the Inverse Spin Hall Effect (see figure 1a). This charge current causes the STE to emit broadband electromagnetic radiation in the THz region [2]. Our work focuses on STE consisting of 2 nm CoFeB and 2 nm Pt. The STE is optically excited by femtosecond laser pulses obtained from an Yb-doped fiber amplifier (1040 nm center wavelength, more than 6 µJ pulse energy) and we detect the emitted THz pulse by means of electro-optical (EO) sampling (see figure 1b).

Figure 1c) shows the measured THz peak-to-peak signal versus optical pump beam energy, which is changed in a loop. Until an energy threshold of about 1 µJ the THz signal increases nearly linearly and subsequently drops for higher values. Upon decreasing the pump pulse energy, we observe a hysteresis-like behavior of the THz peak-to-peak signal.

We explain the non-monotonic dependence of the THz emission on the optical excitation energy by comparing the dominant hot electron relaxation mechanisms. The interaction of the laser pulse with the FM thin film leads to the creation of hot electrons in the exposed area of the STE, which are spin-polarized due to the exchange splitting between the majority and minority band in a FM. The spin accumulation created in this manner, is influenced by two hot electron processes, which in turn influence the THz generation in the STE. First, the spin superdiffusion creates a current transporting the excited electrons from the FM layer into the non-FM layer [3] leading to THz emission via the Inverse Spin Hall effect. With increasing optical excitation energy, however, the second process becomes dominant. Spin flips due to exchange interaction and Elliot-Yafett scattering lead to demagnetization [4] and reduce the spin polarization of the current. This process results in a decrease of the emitted THz signal.

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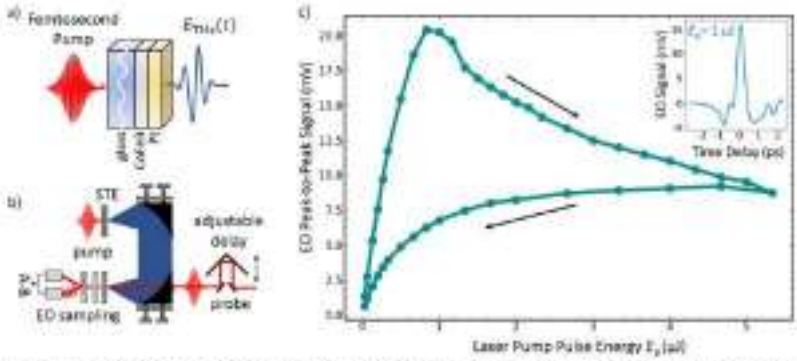

Figure 1: a) Working principle of the STE: A femtosecond laser pulse excites the CoFeB/Pt heterostructure on a glass substrate and leads to THz emission. b) Optoelectronic measurement scheme: The emitted THz radiation is detected by means of time-resolved electro-optical (EO) sampling. c) EO peak-to-peak signal, as a measure for the emitted THz radiation, versus laser pump pulse energy E_p. The inset shows the measured THz trace at $E_p = 1$ µJ.

O245 - Spin wave localization on phasonic defects in magnonic quasicrystal

15. Spin waves, magnonics, ultrafast magnetization dynamics and optically driven spin excitations

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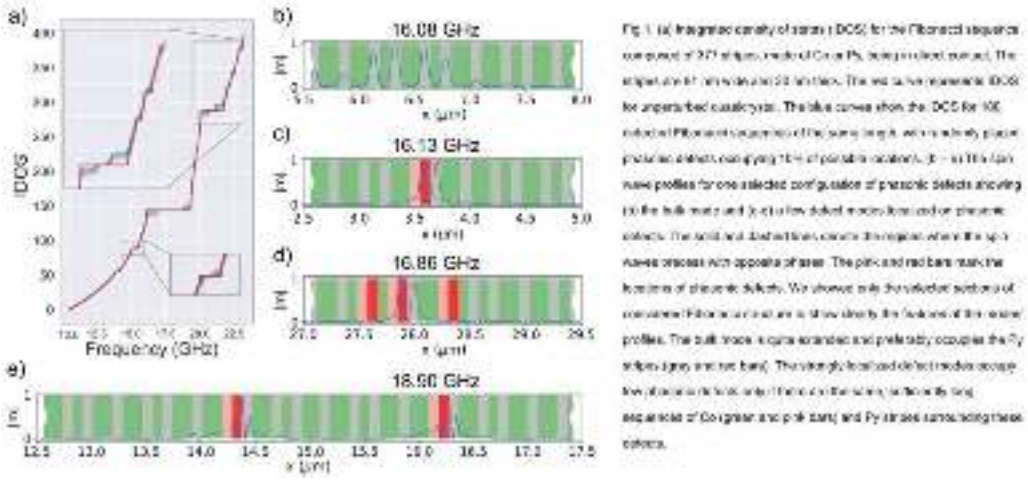
Phasons are the structural defects which are specific for quasicrystal. They are a local rearrangements of the constituent elements in the quasiperiodic structure. The phasons in atomic systems diffuse within the structure and coexist with phononic excitations. Here, we investigated the phasons in artificial magnonic quasicrystals – a Fibonacci sequence of Py and Co stripes. We considered phasonic defects in this system as a peculiar kind of static rearrangement of magnetic stripes. The phasonic defects are introduced by swapping the neighbouring Py and Co stripes in selected Py|Co pairs. The main goal of this study is to find the impact of the phasonic-like disorder on the spectrum and on the localization of spin wave eigenmodes in magnonic quasicrystals.

We investigated the perturbed Fibonacci sequences of stripes with lower concentrations of phasonic defects. The introduction of such defects does not change the average values of material parameters for considered composite structures. Therefore, in the regime of long-wavelengths, the spectrum of eigenmodes is the same as for the unperturbed Fibonacci sequence. In the frequency ranges corresponding to the band gaps we observed the gradual smoothing of IDOS which results in the bandgap closing for larger concentration of phasonic defects. We found out, that each spin wave defect mode occupies only few selected locations of phasonic defects. The selection of occupied defect(s) is different for different spin wave modes.

The calculations were done using the plane wave method with the supercell approach and were further compared to the outcomes of the finite element method performed with the aid of the COMSOL Multiphysics package.

The authors acknowledge the financial support of the National Science Centre Poland for Grant No. 2016/21/B/ST3/00452 and UMO-2017/24/T/ST3/00173.



O246 - Spin wave modes in Ni80Fe20 micro stripes imaged using time-resolved X-ray microscopy

15. Spin waves, magnonics, ultrafast magnetization dynamics and optically driven spin excitations

Santa Pile[1] , *Thomas Feggeler[2], Taddäus Schaffers[1], Ralf Meckenstock[2], Martin Buchner[1], Detlef Spoddig[2], Verena Ney[1], Michael Farle[2], Heiko Wende[2], Rysard Narkowicz[3], Kilian Lenz[3], Jürgen Lindner[3], Hendrik Ohldag[4], Katharina Ollefs[2], Andreas Ney[1]*

[1] Institute of Semiconductor and Solid State Physics, Johannes Kepler University Linz, Austria

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[3] Helmholtz-Zentrum Dresden-Rossendorf, Germany

[4] Stanford Synchrotron Radiation Laboratory, SLAC National Accelerator Laboratory, USA

For the development of novel spintronic devices it is important to understand the dynamic magnetic processes on the micro- and nanoscale [1]. By using lithographically fabricated (planar) micro resonators it is possible to measure ferromagnetic resonance (FMR) of small samples with a detection sensitivity of down to 10^6 spins [2]. Planar micro resonators can be further employed in combination with scanning transmission x-ray microscopy (STXM), X-ray magnetic circular dichroism (XMCD) and a time synchronization scheme between the X-ray pulses of the synchrotron and the microwave excitation (STXM-FMR). The STXM-FMR setup enables the visualization of high frequency magnetization dynamics in the GHz regime with a high lateral resolution of nominally 35 nm and a time resolution of 17.4 ps [3]. In this contribution we present the results for two perpendicular $Ni_{80}Fe_{20}$ micro stripes, 5*1*0.03 μm^3 each. The samples were fabricated using optical and e-beam lithography and pre characterized using conventional micro resonator FMR.

For STXM-FMR measurements a static magnetic field was applied in the plane of the stripes parallel to the long axis of one stripe (parallel stripe) and perpendicular to the long axis of the other (perpendicular stripe) [4]. The dynamic magnetic contrast measured by STXM-FMR in combination with micro magnetic simulations enable to directly observe uniform and spin-wave FMR modes of the $Ni_{80}Fe_{20}$ stripes (see Figure). The rough estimation (yellow solid and dashed lines in Figure) gives the velocity of the FMR nodes movement of about 30 km/s. Moreover we confirmed the possibility to influence the spin-wave modes by modifying the mutual positioning of the stripes. The nucleation center of the spin-waves can be shifted by moving the parallel stripe alongside the perpendicular stripe. Finally, owing to the elemental selectivity STXM-FMR measurements can be extended by further investigation of the spin pumping in a variety of samples, including multilayered structures.

On the Figure the STXM-FMR results for uniform and spin wave modes of the perpendicular $Ni_{80}Fe_{20}$ micro stripes are shown.

Financial support by the Austrian Science Fund (FWF), Project No. I-3050, ORD-49 and the German Research Foundation (DFG), Project No. 321560838 is gratefully acknowledged.

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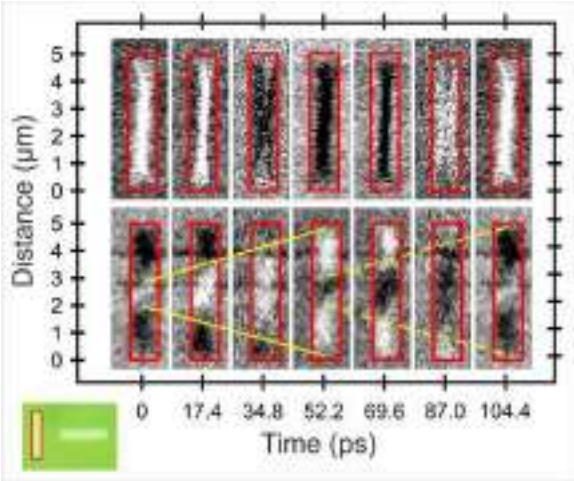
Distance (μm)
5
4
3
2
1
0
5
4
3
2
1
0
0
17.4
34.8
52.2
69.6
87.0
104.4
Time (ps)

O247 - Spin wave propagation in individual nano-sized Yttrium Iron Garnet magnonic conduits

15. Spin waves, magnonics, ultrafast magnetization dynamics and optically driven spin excitations

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Yttrium iron garnet (YIG) is a unique material with outstanding magnetic properties such as the lowest known spin wave damping. It is therefore well suited for the investigation of fundamental spin wave dynamics and a promising candidate for the application in spin wave based circuits and logic devices [1].
In this work, we study the impact of nanostructuring by means of electron beam lithography and successive ion milling on the spin wave propagation in individual spin wave waveguides. These structures are fabricated from a 44 nm thin high quality YIG film grown by liquid phase epitaxy (LPE) [2] and their width varies from a few microns down to 40 nm (Fig. 1.a). By exciting the magnetization dynamics with a coplanar waveguide antenna and performing spacial resolved Brillouin Light Scattering (BLS) microscopy measurements, the propagation of spin waves in such nanostructures is measured directly. Further, the spin wave decay length in these conduits in dependency on the conduit width is investigated. It is shown that the decay length decreases from 15.5 µm down to 1.8 µm (Fig. 1.b) for the smallest conduit width of 40 nm. However, this decrease is mainly assigned to a change of the dispersion which leads to a significant drop of the spin wave group velocity. This is verified by measuring the group velocity by exciting the spin waves in a pulsed manner and tracking the spin wave wave packet via time resolved BLS microscopy. Additionally, the spin wave mode spectra are extracted by means of thermal BLS spectroscopy measurements from which the effective exchange constant is derived. Here, no significant dependency on the conduit width is found which supports the conclusion that the impact of the nanostructuring process on the quality of the YIG is modest. These findings pave the way to a magnon based data processing in nano-sized magnonic circuits.
This research has been supported by ERC Starting Grant 678309 MagnonCircuits, DFG Grant DU 1427/2-1 and the Graduate School Material Science in Mainz (MAINZ).

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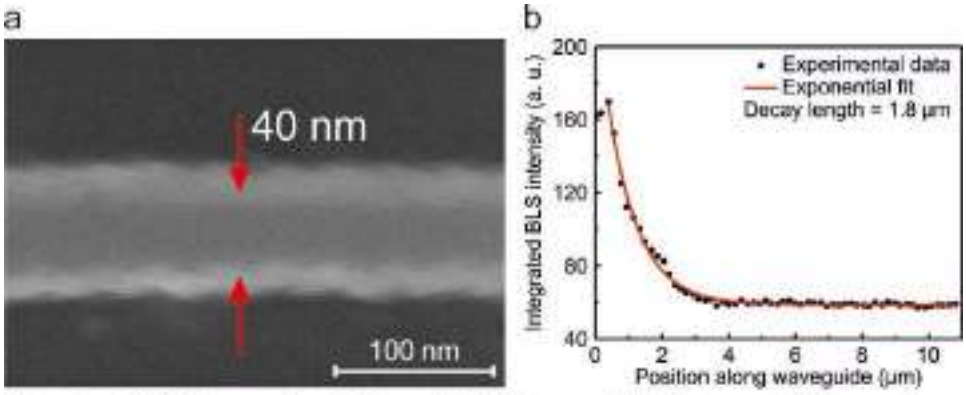

Figure 1: a) SEM micrograph of a 40 nm wide YIG waveguide. b) Exponential Decay of the spin wave intensity measured in Backward-Volume-Geometry in the structure shown in a) ,for an excitation frequency of 3.78 GHz and an external magnetic field of 55 mT.

O248 - Spin-wave propagation in magnonic waveguides prepared by FIB driven phase transition of Fe78Ni22

15. Spin waves, magnonics, ultrafast magnetization dynamics and optically driven spin excitations

Lukáš Flajšman[1] , *Kai Wagner*[2], *Jonáš Gloss*[3], *Marek Vaňatka*[1], *Viola Křižáková*[4], *Michael Schmid*[3], *Helmut Schultheiß*[2], *Michal Urbánek*[1, 4]

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In this work we present a novel system allowing for direct writing of magnonic waveguides by focused ion beam (FIB) irradiation of paramagnetic fcc $Fe_{78}Ni_{22}$ films grown on Cu(100) substrate. This system can be locally transformed by focused ion beam (FIB) to ferromagnetic bcc phase [1]. The transformed areas still retain ordered crystalline structure, where the properties can be controlled by the FIB irradiation procedure [2]. Using a directional scanning of the FIB it is possible to grow/transform different crystallographic orientations of the bcc structure with different directions of uniaxial anisotropy. This allows us to spatially control the uniaxial anisotropy direction. The combination of the control over the uniaxial magnetic anisotropy and saturation magnetization paves a way towards novel magnonic devices as it allows to change multiple magnetic properties within a single structure a thus stabilize exotic magnetization landscapes not seen in any conventional materials.
We present a very first results of spin-wave propagation in this system and we show, that due to the possibility of extended control over the uniaxial magnetic anisotropy we are able to fabricate magnonic waveguide where the magnetization easy axis points in the short direction of the waveguide. Consequently we show the spin-wave propagation in zero magnetic field in so called Damon-Eshbach geometry. The phase resolved Brillouin light scattering has allowed us to further extract the spin-wave dispersion in our system. The analytical model [3] together with dynamic magnetization profiles show, that the dynamic magnetization boundary conditions of magnonic waveguides made from ferromagnetic bcc structures embedded in fcc paramagnetic matrix differ from conventional systems as e.g. permalloy waveguides where the boundary is magnetic material-air.

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O249 - Spinwave Steering by Local FIB Irradiation of YIG Films

15. Spin waves, magnonics, ultrafast magnetization dynamics and optically driven spin excitations

Martina Kiechle[1] , *Adam Papp[1], Simon Mendisch[1], Valentin Ahrens[1], Markus Becherer[1]*
[1] Technical University of Munich

We experimentally demonstrate influencing spinwave (SW) propagation in yttrium iron garnet (YIG) thin films by local focused-ion-beam (FIB) irradiation. The FIB irradiated area can potentially act as the functional medium in magnonic devices, i.e. modifying the SW phase and/or the amplitude. The dispersion relation in such irradiated areas is changed without the need of using different materials and without structuring the propagation medium, e.g. by lithography and etching. This technology could open the door to the realization of spatial filters and spin waves gratings, which are required for spin-wave-based computing devices, e.g. spin-wave-based Fourier transform and filtering [1].

Changing the effective magnetization M_{eff} and the Gilbert damping α_{G} in YIG thin films can be achieved by means of FIB – this has also been shown recently in [2]. Implantation of high energy Ga+ ions causes a cascade of dislocations in the crystal, which changes the magnetic properties locally. We investigated the effect of ion irradiation on the magnetic properties of YIG thin films by means of broadband Ferromagnetic Resonance (FMR) on film level. Process parameters of FIB such as dwell time, beam current, spot size and acceleration voltage have been attuned, in order to find an appropriate ion dosage and implantation depth for the YIG film thickness. The hereby obtained magnetic parameters, i.e. saturation magnetization and damping, were included in micromagnetic simulations conducted in Mumax3. These simulations are used to predict the spinwave interference patterns created by the FIB patterns.

We present the measured interference pattern of spinwaves, while and after passing through regions with altered magnetic properties in YIG. The experimental characterization is accomplished via electrical input and optical readout. RF-driven coplanar waveguides (CPW) serve as excitation antennas and the magnetization patterns are examined with time-resolved magneto-optical Kerr effect (TRMOKE) microscopy. The characterization platform is visualized schematically in Figure 1. Hereby, the magnetic moments in the film are aligned with a magnetic bias field and the respective perpendicular microwave field components of the CPW excite the SWs. As a next step, the laser spot of the TRMOKE detects the changes in magnetization and images the SW-interference landscapes. Different irradiation patterns have been created and analyzed, including slits and SW gratings.

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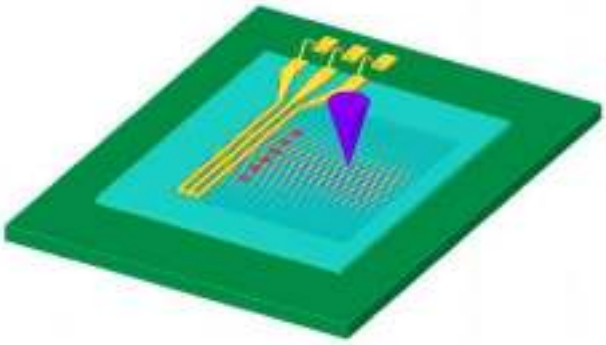

Figure 1: Schematic illustration of the modified spinwave propagation via locally FIB irradiated spots. SWs are laterally excited by the microwave magnetic field of the CPW. The laser spot of a time-resolved MOKE setup detects the respective magnetization pattern with picosecond resolution.

O250 - The emission of ultra-short spin waves in antiferromagnets by a domain wall driven by spin current

15. Spin waves, magnonics, ultrafast magnetization dynamics and optically driven spin excitations

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Antiferromagnets (AFMs) have great benefits for the future spintronic applications [1] such as involving high frequencies (up to THz range) and high speeds (up to dozens of km/s) of magnetic excitations. Also, the AFM spin-torque nano-oscillators (STNOs), in which the applied spin current rotates the Neel vector with high frequencies [2-4], do not require external magnetic field for their operation. The advanced spintronic devices will require high-speed propagating spin waves (SWs) as signal carriers between separate STNOs, i.e. SWs with the high wavevectors, the excitations of which remains challenging.

We demonstrate theoretically and by micromagnetic simulations (MuMax3) that the simple spin texture, such as an AFM domain wall (DW), driven by spin current, can act as an emitter of the propagating spin waves with high wavevectors in AFMs with the bi-axial anisotropy. We consider AFM with the strong anisotropy along the easy axis and the lower one in perpendicular direction. In the proposed generator (Fig. 1a), the spin current with the polarization directed along the easy axis, excites the precession of the Neel vector within the DW. The threshold current is defined by the value of the second anisotropy, and frequency ω is tuneable by the strength of spin current. We show that the above precession of the DW leads to the excitation of magnons with the frequency 3ω (blue color on Fig. 1b), i.e. triple of DW precession (red color on Fig. 1b). Such a process leads to a robust emission of the propagating SWs in the AFM strip in the case, when $3\omega > \omega_{AFMR}$. Consequently, the maximum achievable frequency of SWs is $3\omega_{AFMR}$, which corresponds to a very short wavelength of the SW, comparable with the exchange length of the AFM (Fig. 1c). Particularly, in the simulations we achieved the minimum wavelength around ~20 nanometers for the chosen parametres of a typical AFM. The SW emission occurs, when the applied current overcomes a threshold value $\sigma j_{th} > \alpha\, \omega_{AFMR}/3$, where σ defines charge to spin conversion efficiency [2] and $\alpha << 1$ – effective damping parameter. When the frequency ω approaching ω_{AFMR}, the emitted SWs experience abrupt drop of the frequency with current, however, the amplitude of SWs increases significantly in this case. The later effect can be explained as the effective change of the anisotropy type by a spin current.

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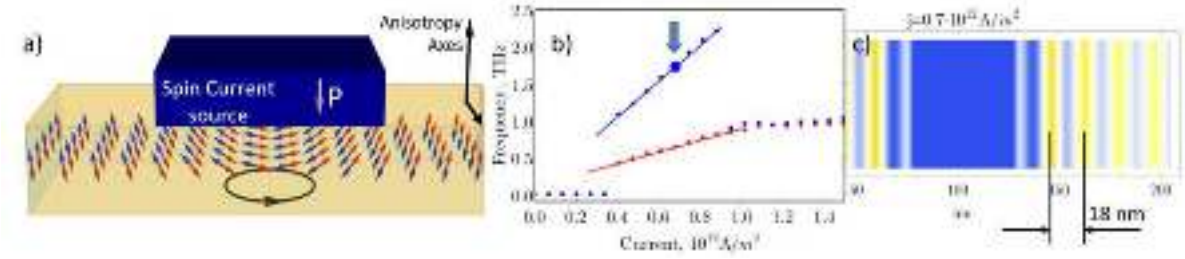

O251 - Thermally induced magnetic switching in GdFeCo using picosecond laser pulses - experiment vs theory

15. Spin waves, magnonics, ultrafast magnetization dynamics and optically driven spin excitations

Florian Jakobs[1] , *Thomas Ostler*[2, 3], *Charles-Henri Lambert*[4], *Yang Yang*[5], *Akshay Pattabi*[4], *Roy Chantrell*[6], *Sayeef Salahuddin*[4, 7], *R. B. Wilson*[8], *Jon Gorchon*[4, 7], *Jeffrey Bokor*[4, 7], *Unai Atxitia*[1]

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Femtosecond (fs) laser pulses have revealed novel ways to control spin degrees of freedom at unprecedented speeds, with the most prominent example being the so called thermally induced magnetic switching (TIMS) in GdFeCo alloys. The heat loaded into the system by a fs laser pulse is sufficient to toggle switch the magnetization polarity. Besides using fs laser pulses, it has been shown recently, that nanostructures of GdFeCo alloys can be switched by the heat provided by a picosecond electric current, making use of the TIMS [1]. These surprising observations did not only open the door to picosecond spintronics, but furthermore questions the previous understanding and the underlying principles of TIMS. Namely, that picosecond heating is too slow of a stimulus to activate the exchange interaction that supposedly drives the transfer of angular momentum between the sublattices and enabling the switching process. This is usually translated into the necessity of sub-ps heating above the Curie temperature and element-specific distinct demagnetization to achieve TIMS.

In this work, computer simulations are quantitatively compared to experimental measurements of the dynamics of TIMS in GdFeCo-alloys using laser pulses from fs to ps. We use atomistic spin dynamics methods (ASD), which have proven to be an ideal theoretical toolbox to model TIMS in those materials [2].
We find a set of parameters for the atomic model able to describe and reproduce all of our experimental observations over various Gd-concentrations and pulse durations, ranging from a couple of femtoseconds up to picoseconds while keeping an extremely high degree of accuracy. As an example, figure a) shows switching and non-switching dynamics of two GdFeCo alloys with different Gd-concentrations for both experiments and simulations.
Our experimental data using fs-laser pulses shows TIMS for a narrow range of Gd-concentrations and laser fluences, which are in agreement with previous measurements. By continuously increasing the pulse duration from fs timescale to ps, we observe a further shrinking of the range of Gd-concentration and fluences that allow for switching.
The high degree of accuracy of our ASD model simulations allow us to further explore the impact of various relevant parameters for TIMS that are typically unaccessible to experiments. Such as laser pulse duration and fluence, Gd-concentration and element-specific relaxation parameter.
By these means we observe switching up to a pulse duration of 4.5ps for a range of Gd-concentrations. See Figure b) for the full switching/no-switching phase diagram; fluence, Gd-concentration and maximum pulse duration.
For those laser durations, both Gd and Fe-sublattice magnetization dynamics become similar. This highlights the fact that the previous criterion of distinct element-specific demagnetization is insufficient in explaining picosecond pulse TIMS. Our theoretical findings suggest that this criterion should be substituted by distinct element-specific energy/entropy

dynamics. Moreover, in our theoretical model TIMS can be enabled without heating the sample above the critical temperature.

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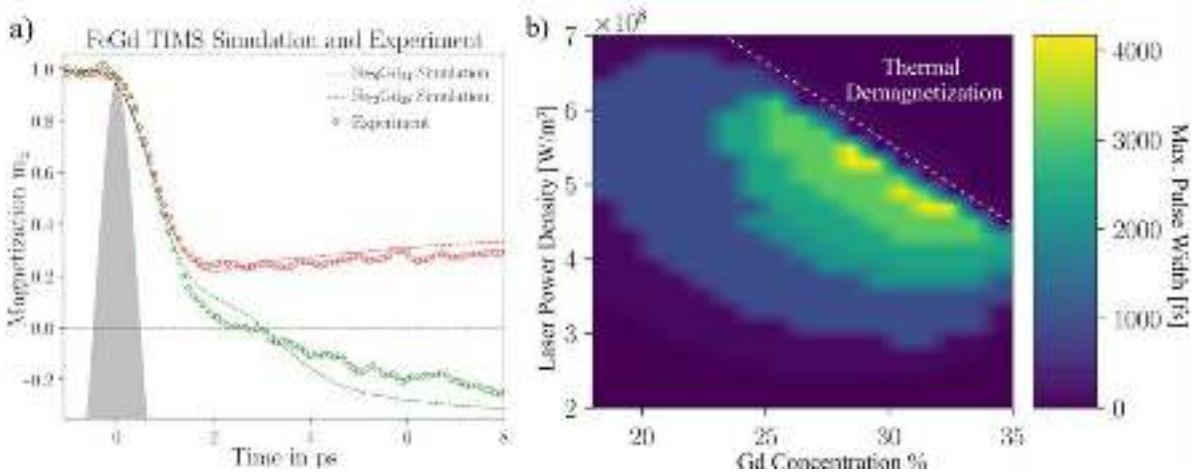

O252 - Time and space-resolved non-linear magnetoacoustic dynamics

15. Spin waves, magnonics, ultrafast magnetization dynamics and optically driven spin excitations

Laura Thevenard[1] , *Meriam Kraimia[1, 2], Piotr Kuszewski[1], Aristide Lemaître[3], Jean-Yves Duquesne[1], Kais Boudjaria[2], Catherine Gourdon[1]*

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The author has chosen not to publicise the abstract.

Field 5

Field 6

O255 - Twisted magnonic beams carrying orbital angular momentum

15. Spin waves, magnonics, ultrafast magnetization dynamics and optically driven spin excitations

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Low-energy eigenmode excitations of magnetically ordered systems are spin waves that can be quantified by quasiparticles termed magnons. Magnons can be thermally and non-thermally excited, confined, spectrally shaped, and guided by material design [1]. Magnonic currents are routinely generated at low energy cost and do not suffer from Ohmic losses, which make them an attractive medium for communication, and processing of information. Here we present propagating spin waves that carry a definite and electrically tunable orbital angular momentum (OAM) constituting a ”twisted magnon beam”. Starting from fundamental equations for spin dynamics we present how OAM beams emerge in magnonic waveguides and how to topologically quantify and steer them. A key finding is that the topological charge associated with OAM of a particular beam is tunable externally and protected against damping (cf. Fig.1). Coupling to an external electric field via the Aharanov-Casher effect allows for electrical tuning of the topological charge [2]. This renders possible OAM-based robust, low-energy consuming multiplex magnonic computing, analogously to using photonic OAM in optical communications [3], and high OAM-based entanglement studies [4], but here at shorter wavelength and lower energy consumption, and ready integration in magnonic circuits utilizing the versatile toolbox for material and spin waves engineering.

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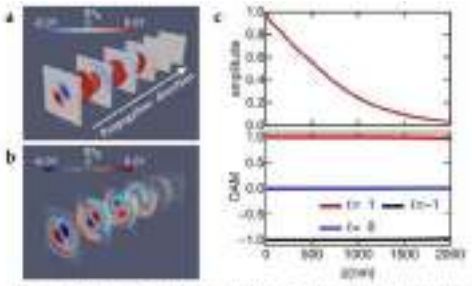

Fig.1: Spin wave propagating along a cylindrical microtube of the insulating magnet yttrium iron garnet. a) Snapshot of the magnon beams after 2 ns for the x component of the triggered magnetization. b) Vortex configuration of the excitation modes along the tube. c) The z resolved amplitude and the orbital angular momentum of spin waves. In a), b), and c) the spin waves are excited locally at z = 0 interface by a twisted rf magnetic field having the amplitude B_{rf0} = 10 mT and frequency B = 5 GHz.

O256 - Ultrabroadband THz radiation from Ta/NiFe/Pt nanolayers triggered by femtosecond laser pulses

15. Spin waves, magnonics, ultrafast magnetization dynamics and optically driven spin excitations

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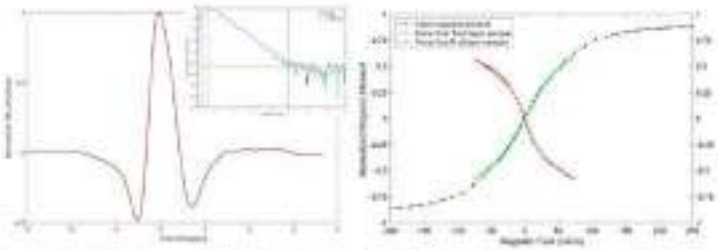
Terahertz (THz) radiation covers the electromagnetic spectrum range between optical far infrared and radio-frequency millimeter waves, approximately from 30 to 0.3 THz, and is used in a broad range of fields ranging from security, communication and bio- and medical imaging, to astronomy and materials testing in fundamental science. The latest research has been focused on THz emitters of ultrafast electromagnetic transients with broad THz-range spectra, in order to control and capture spin, charge or phase-transition related processes on pico- and sub-picosecond time scales. In this context, recent observation of THz emission from optically excited ferromagnet/normal metal (FM/NM) nanolayers establishes a very elegant link between laser optics, spintronics, and THz radiation, merging these three very active scientific fields and having a tremendous potential for future applications.

We have generated sub-picosecond electromagnetic transients from Ta (2nm)/NiFe (2nm)/Pt (2nm) nanolayers using a train of 100-fs wide laser pulses with the fluence of up to 7.25 mJ/cm^2 and a static, tunable magnetic field **H** (up to ±70 A/m) applied in the plane of a sample. Resulting power spectra of the generated electromagnetic transients extend up to 5 THz with a 3-dB cut-off at 0.85 THz (see Fig. 1 left) For the same laser power, excitation with blue light (400-nm wavelength) generates THz transients with amplitudes approximately three times larger than transients resulting from excitation by infrared light (800-nm wavelength). The THz amplitude is also tunable by the **H** intensity and follows very closely the hysteretic behavior of the sample magnetization vs. **H** field dependence of the NiFe layer (Fig. 1 right). Our experiments confirm that transient THz signals are generated exclusively within the NiFe/Pt bilayer.

The observed THz transients are directly proportional to the charge current density $\boldsymbol{J_C} = D_{\mathrm{ISHE}} (\boldsymbol{J_S} \times \sigma)$, due to inverse spin Hall effect (ISHE) mechanism, where D_{ISHE} is a coefficient representing the ISHE efficiency in a material, and $\boldsymbol{J_S}$ and σ are the optically-generated spin current density and spin polarization, respectively. While the THz generation mechanism is linearly related to the amplitude of $\boldsymbol{J_C}$, the THz amplitude can be tuned by controlling σ and $\boldsymbol{J_S}$, the quantities directly affecting $\boldsymbol{J_C}$. Since σ is linked to sample magnetization μ, the THz amplitude follows the μ(**H**) behavior. THz transients emitted by our spintronic emitters are linearly polarized and the direction of THz polarization is perpendicular to both the sample magnetization, as well as, to the optically-triggered spin current density $\boldsymbol{J_S}$; therefore, it can be controlled by rotating the **H** direction around the sample surface normal. Finally, our THz emitters can lead to wide-spread applications in compact hand-held THz diagnostic devices, in local device-to-device communication with a large data transfer capacities, and as sources for further material- and circuit testing at THz frequencies.



O257 - Ultrafast Nanoscale Quantum Magnetism: from Entangled Magnons to Machine Learning

15. Spin waves, magnonics, ultrafast magnetization dynamics and optically driven spin excitations

Giammarco Fabiani[1] , ***Johan Mentink***[1]
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The explosive growth of digital data and its related energy consumption is pushing the need to develop fundamentally new physical principles for faster, smaller and more energy-efficient control of materials. Ultimately, future technology should provide room temperature operation down to femtosecond timescales, nanoscale dimensions and at an energy dissipation as low as the Landauer limit (~zJ). We will argue (i) that femtosecond *quantum*dynamics directly gives access to an energy cost in the zJ range and (ii) that access to such nanoscale quantum dynamics is possible in antiferromagnets by ultrafast control of the exchange interaction [1]. Clearly, to exploit these dynamics for implementing computing principles, access to the non-linear regime is needed. This, however, poses a big challenge for theory and until now the non-linear dynamics could be simulated only for systems containing a few 10s of spins. To meet this challenge, we implemented the recently developed neural quantum states [2] and applied it to study the ultrafast spin dynamics in the 2D quantum Heisenberg model triggered by ultrafast control of the exchange interaction [3]. We find excellent agreement for small systems where the dynamics is still accessible with exact diagonalization. Moreover, for large systems and for small perturbations, close correspondence with interacting spin-wave theory is obtained. Rapid convergence with the number of neural network parameters is found in all cases. These results pave the way to study the ultrafast quantum dynamics of systems of order 1000 spins as relevant for magnetic materials, with great potential for finding new ultimately fast and energy-efficient scenarios for (brain-inspired) computing at the nanoscale. An open source version of our code termed “ULTRAFAST” is provided [4].

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[2] G. Carleo and M. Troyer, Science 355, 602 (2017)
[3] G. Fabiani and J.H. Mentink, Investigating Ultrafast Quantum Magnetism with Machine Learning. *arXiv:1903.08482 (2019)*
[4] https://github.com/ultrafast-code/ULTRAFAST

O258 - Wavelength-selective optical detection of spin waves beyond the diffraction limit

15. Spin waves, magnonics, ultrafast magnetization dynamics and optically driven spin excitations

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The introduction of spin waves in next-generation computing devices is expected to lead to several advantages, such as the ability for wave computing or chargeless information transport [1]. However, its introduction is hampered by the inability to efficiently excite and detect these spin waves. One of the more interesting routes to do this is optically, but here the usable spin wave wavelength is limited by the optical diffraction limit. In this work, we demonstrate optical detection of spin waves beyond the diffraction limit by nanostructuring several light absorbing elements (a grating) on top of a magnetic strip (see figure 1a). Within this strip the spin waves are excited electrically using a spin wave antenna and are detected by focusing a pulsed fs-laser onto the grating. The presence of this grating will modify the laser spot leading to a spatial modulation of the light transmitted to the strip. If the grating periodicity matches the spin wave wavelength, the result is a non-vanishing magneto-optical Kerr effect due to this spin wave. In figure 1b the magneto-optic response of such a measurement is shown, where a spin wave resonance is observed belonging to a spin wave with wavelength of 1 µm measured with a laser spot 12 µm in diameter. This proofs that the grating works as intended and can indeed be used to detect spin waves beyond the diffraction limit. Additionally, as a result of the spatial filtering of the grating the measurement is extremely wavelength selective.

Our current efforts are aimed at unravelling the measured spectra. This is done using a simple analytical model that describes the excited spin waves based on a Fourier analysis. After the spin waves have propagated the expected magneto-optical contrast is calculated using the spatial filtering of the laser spot as a result of the grating. The resulting behaviour is qualitatively similar to the measurements (such as the one in figure 1b) solidifying the interpretation. This technique is expected to provide a new non-invasive and artefact free way of measuring spin waves as a function of position and help integrate the field of optics with nanoscale magnetism. We have been able to detect spin waves with a wavelength of 700 nm using a laser spot of 10 µm but upon downscaling this technique even further the extensive knowledge of the near-field optics community can be used to further optimize the devices.

[1] A. V. Chumak, V. I. Vasyuchka, A. A. Serga and B. Hillebrands, Nat. Phys. 11, 453 (2015)

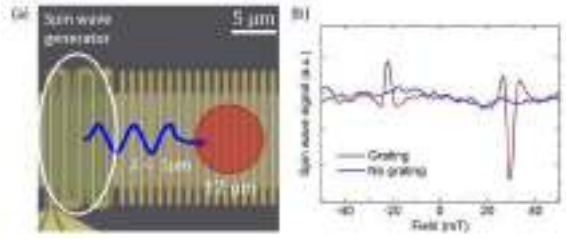

Figure 1. (a) Fabricated device. We use an electrical spin wave antenna (generator) to generate spin wave of wavelength 1 µm. This wave propagates out, and we can detect this spin wave using a grating and a laser spot with diameter of 12 µm. (b) Optical spin wave measurements with and without grating. The resonance at ±25 mT corresponds to a spin wave with a wavelength of 1 µm measured with a spot size of 12 µm. This resonance is no longer present if the grating is not used.

16. Magnetotransport, spintronics, spin orbitronics and spin caloritronics.

O259 - All-electric spin Hall transistor using a Rashba channel

16. Magnetotransport, spintronics, spin orbitronics and spin caloritronics.

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The various designs of spin transport devices have been suggested and developed. Among them a representative device, the spin field effect transistor (spin−FET) proposed by Datta and Das in 1990 has been experimentally verified quite recently. To implement this operation, electrical spin injection, detection, and precession should be simultaneously demonstrated. Modulation of the channel conductance by using an electric field to induce spin precession requires the channel with a strong Rashba spin splitting, which is required for spin modulation, has small spin diffusion length. Thus, the enhancement of the spin-FET performance is very limited with a conventional spin transistor design. Furthermore, spin injection efficiency from the highly conductive ferromagnet to the semiconductor channel is still very low and therefore many approaches for increasing spin injection current is being tried.

To overcome this obstacle, we develop an all-electric spin transistor by utilizing direct and inverse spin Hall effects for spin injection and detection, respectively, without a ferromagnetic component. To implement an all-electric spin Hall transistor, we fabricated H-bar devices using an InAs-based quantum well channel that has a strong Rashba effect. The operation mechanisms of this device are the spin Hall effect and the gate-controlled spin precession, all arising from the spin-orbit coupling. The device consists of three regions as shown in Fig. 1(a). The first part of the device is the injection region where the direct spin Hall effect converts this charge current to a spin current. Thus a pure spin current is injected to the middle part of the device where the gate electrode is deposited on top of it. As there is no interface between these two regions, the spin current is efficiently injected into the gate-controlled region without noticeable loss. In this middle region, the spin precession is modulated by gating. The gate voltage controls the Rashba spin-orbit interaction and subsequently modulates the spin precession angle. The gate-modulated spin current is then injected to the detection region, where the inverse spin Hall effect converts the spin current to a charge current, thereby generating a Hall voltage.

For a comparison of output signals among different types of spin-FETs, we fabricated three types of spin transistor designs as shown in Fig. 1(b). They are the conventional Datta-Das spin-FET using ferromagnets ($Ni_{81}Fe_{19}$ electrodes) for both spin injection and detection, the spin Hall transistor using a ferromagnet (inverse spin Hall effect) for spin injection (detection), and the ferromagnet-free all-electric spin Hall transistor (this work). We find that the signal of the all-electric spin Hall transistor (~900 mΩ) is much larger than those of two other transistors (< 40 mΩ). Moreover, the symmetry of spin Hall effect allows all-electric spin Hall transistors to be utilized for both *p*- and *n*-type-like operations, which are essential parts in the complementary logic devices. Thus, this all electric spin transistor can be utilized for the logic device with a high speed and a low power consumption.

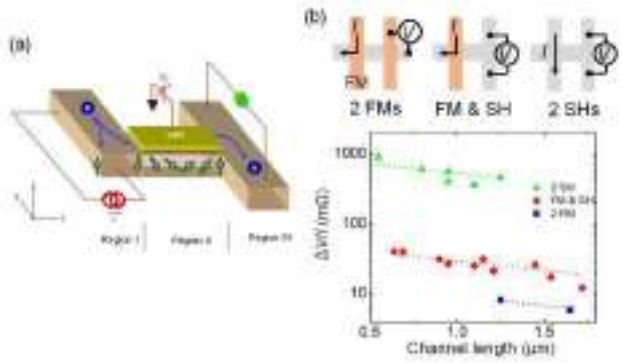

Fig. 1 Spin Hall transistor using a Rashba channel. (a) Operation mechanism of all-electric spin Hall transistor. (b) Magnitudes of spin transistor signals.

O260 - Anisotropic magneto thermal power imaging of spin-orbit torque switching in antiferromagnetic films

16. Magnetotransport, spintronics, spin orbitronics and spin caloritronics.

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Spin-orbit coupling effects such as the electrical anisotropic magnetoresistance (AMR) and the X-ray magnetic linear dichroism in combination with photoemission electron microscopy (XMLD-PEEM) have been used so far to reveal some of the most important properties of antiferromagnets, namely the ultrafast and the neuron-like switching of antiferromagnetic domains.

By exploiting the equivalent thermal effect, the anisotropic magneto thermal power (AMTP), in patterned antiferromagnetic CuMnAs films, we resolve magnetic domains in response to locally generated thermal gradients. We image the effects of reversible spin-orbit torque switching and find a direct correlation between spin-orbit torque induced changes in the locally generated AMTP signal and in the anisotropic magnetoresistance response. We confirm the magnetic domain structure by comparing our thermo-electric measurements with XMLD-PEEM.

O261 - Beating the walker limit with Bloch-point domain walls in cylindrical nanowires

16. Magnetotransport, spintronics, spin orbitronics and spin caloritronics.

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Since its proposal, the idea to vastly increase data storage density with a magnetic non-volatile 3D shift-register has sustained interest in domain wall (DW) motion. So far, experimental efforts have focused on flat nanostrips, which exhibit a wide range of noteworthy effects, yet suffer from intrinsic DW instabilities limiting their mobility. In contrast, ferromagnetic cylindrical nanowires (NWs) can host a novel type of magnetic DW, namely the Bloch-point wall (BPW), which due to its specific 3D topology should not experience the same fundamental issue. This could give rise to DW velocities over ≈1 km/s and fascinating new physics such as coupling to magnetic spin waves. However, experimental evidence of DW dynamics in NWs had lacking until now.

Here we report experimental results for both the field- [1] and current-driven [2] cases in FeNi and CoNi wires circa 100nm in diameter, bringing a mixture of confirmation of predicted effects, and new physics. Under magnetic field, above a threshold of circa 10 − 20 mT the topology of domain walls is not preserved, i.e. TVWs and BPWs may transform into one another, a fact overlooked so far in simulations, which considered diameters smaller than the relevant experimental cases. Under current, BPWs are robustly stabilised by the Œrsted field, which had been disregarded so far. As a consequence walls with a negative handedness are promoted under current, which is opposite to the predictions of a positive handedness promoted by the chirality of the LLG equation. We evidenced velocities in excess of 600 m/s, setting a five-fold record for spin-transfer-torque-driven DW motion in standard ferromagnets. These results are quantitatively reproduced by micromagnetic modelling and/or simulations. We are thereby approaching the conditions where fascinating new physics are expected, such as the strong coupling of DWs with spin waves (the spin Cherenkov effect).

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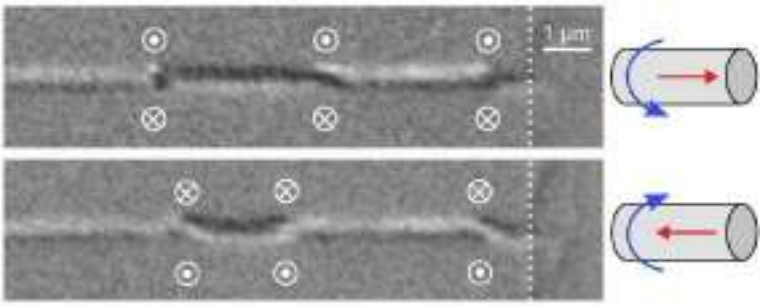

***FIG**. Observation of the switching of Bloch-point wall handedness with shadow XMCD-PEEM, following the application of current pulses of opposite polarity and density $1.4 \cdot 10^{12}$ A/m²*

O262 - Chaotic pattern generation and symbolic dynamics in a nanocontact vortex oscillator

16. Magnetotransport, spintronics, spin orbitronics and spin caloritronics.

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Nanocontact vortex oscillators (NCVO) are spin-torque devices where large current densities drive vortex gyration around a nanocontact in a magnetoresistive stack [1]. In contrast to nanopillars, NCVO exhibit unique dynamical states caused by the self-phase locking between the vortex core gyration and periodic switching of the core. When the ratio between these two frequencies is irrational, chaotic dynamics appears. Since a chaotic signal contains much complexity, much effort has been devoted to understanding how to exploit such phenomena for information technologies, such as random number generation, encryption, and encoding information via symbolic dynamics [2-4].
We investigated experimentally the chaotic time-series data of an NCVO at 77 K. From the measured output signals, we were able to identify a well-defined series of patterns [Fig. (a)]. The patterns comprise building blocks denoted by pn, where p is the vortex-core polarization, and n is an integer number of required core gyration for the switching. We analyzed the pattern sequence by reconstructing the attractor [Fig. (b)], then extracted symbolic dynamics from the Poincaré surface [Figs. (c) and (d)]. The generated bit arrays were found to be random in the chaotic regime, which is suggestive of a chaotic state subject to thermal noise. This was confirmed based on the block entropy and Lempel-Ziv complexity. We calculated the probability of each bit and their moving as a function of the input current amplitudes, which shows we can control the characteristics of the chaotic sequences electrically. These results illustrate the feasibility of chaos-based information processing using spintronic nanodevices.

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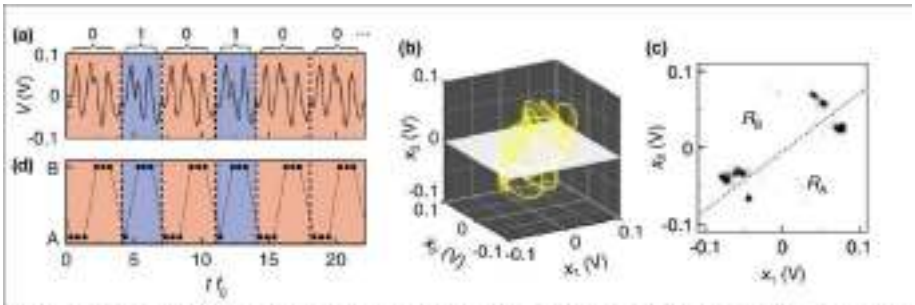

Figure (a) Time-resolved signal from a nanocontact vortex oscillator at the chaotic regime. f_0 is the gyration frequency. The bits, 0 and 1, are distinguished by colors. (b) Strange attractor reconstructed from the measured signal in (a). The white surface represents a Poincaré surface. (c) The Poincaré surface with intersection points by the attractor. The dashed line is a partition to divide the regions into R_A and R_B for the symbolic dynamics. (d) Symbolic dynamics calculated from the Poincaré surface.

O263 - Computing with a frequency encoded signal and different variables of a Spin Torque Nano-Oscillator

16. Magnetotransport, spintronics, spin orbitronics and spin caloritronics.

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The aim of bio-inspired computing is to design chips inspired by the architecture of the human brain to reduce the size, and the excessive energy consumption of conventional computers when it comes to performing cognitive tasks.

Neurons can be considered as non-linear oscillators which interactions are mediated by synapses. Spin Torque Nano-Oscillators are promising devices to emulate neurons at the nano-scale in bio-inspired chips. They are indeed non-linear oscillators with low noise level, they can be manufactured with a diameter of 10 nm, and be integrated with CMOS technology.

In previous work, we demonstrated bio-inspired computing with a single Spin Torque Nano-Oscillator [1]. The information to be processed by the neuron was encoded in the amplitude of an electrical current, and the output signal was the amplitude of the self-oscillations induced by the input current and measured by magnetoresistance effect.
In larger networks of nano-neurons, Spin Torque Nano-Oscillators could be coupled through the microwave signal they emit. If the frequency of an external signal is sufficiently close from the self-oscillation frequency of a Spin Torque Nano-Oscillator, its magnetization can be synchronized to this external signal.
This is why, in this work, we study how to encode the input signal in the frequency of a microwave signal transmitted to the oscillator [2]. In our experiment, this signal is transmitted through the microwave magnetic field generated by an alternating current in a strip line placed above the sample.

To encode the input signal, we choose a range of frequencies close to the self-oscillation frequency of our oscillator. Hence we benefit from the synchronization phenomena, which reduces the phase noise of oscillations by several orders of magnitude, and from the non-linear evolution of the frequency, the amplitude and the phase of the self-oscillation (figure 1).

Finally, we experimentally validate the performance of these three non-linear dependencies on a pattern recognition task. In order to do so, we use a single Spin Torque Nano-Oscillator to sequentially emulate 25 neurons using the technique of time-multiplexing. We demonstrate that it is possible to differentiate square wave signals from sine wave signals with an accuracy of more than 99% using either the frequency, the amplitude or the phase of the Spin Torque Nano-Oscillator as readout information. We also find a direct link between the recognition rate and noise and the non-linearity of these variables. These results represent a new step forward in the design of a deep artificial neural network leveraging the coupled dynamics of interconnected Spin Torque Nano-Oscillators.

[1] J.Torrejon et al, Nature 547, 7664 (2017).

[2] D.Marković, N.Leroux et al, App. Phys. Lett. 114, 012409 (2019).

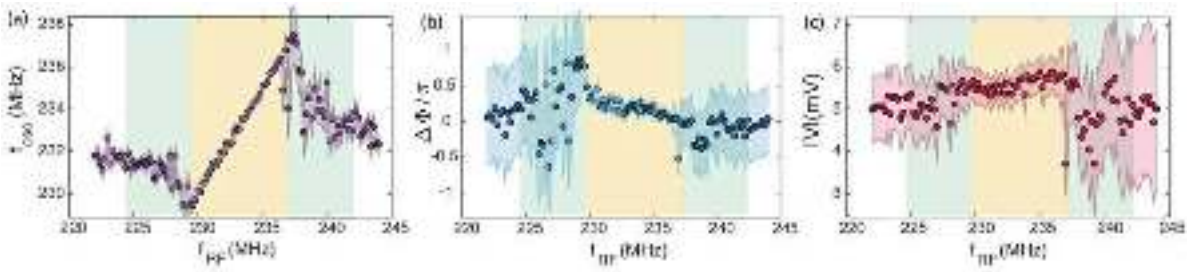

figure 1 : evolution of (a) the frequency, (b) the phase, (c) the amplitude of the self-oscillations of a Spin Torque Nano-Oscillator with the frequency of an external signal

O264 - Element-resolved current-induced magnetization dynamics in ferrimagnetic alloys

16. Magnetotransport, spintronics, spin orbitronics and spin caloritronics.

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Ferrimagnetic amorphous alloys comprising of a rare earth element (RE) and a transition metal (TM) allow for fine tuning of the saturation magnetization, bulk perpendicular anisotropy and coercivity by varying the temperature and the $RE_xTM_{(1-x)}$ stoichiometry. Among the available tools to manipulate the state of ferrimagnetic systems, current-induced spin orbit torques can be effectively employed to control their net magnetization, for example to deterministically switch it between two metastable orientations, in a qualitatively similar way to ferromagnets. However, differently from ferromagnets, the spin-orbit torque efficiency depends strongly on temperature and composition, being maximal at the magnetization compensation point, where the two sublattice magnetizations balance each other and the total magnetization vanishes. Additionally, it has been shown theoretically and experimentally that the velocity of domain walls in ferrimagnets, driven by magnetic fields or spin-orbit torques, peaks at the angular momentum compensation temperature, at which the angular momenta of the RE and TM compensate one another. In fact, unprecedented velocities as high as 1 km/s have been observed in the vicinity of this compensation point.
Despite these recent findings, the exact dynamics of ferrimagnets triggered by spin-orbit torques, which is expected to develop on the ns and sub-ns time scales, is unknown. In particular, the dynamics exhibited by the individual sublattices remains elusive, as standard optical and magneto-transport techniques are mostly sensitive to the magnetization of the TM. Here, we exploit the elemental sensitivity of the synchrotron radiation to study the temporal and spatial evolution of both the RE and TM magnetizations subjected to spin-orbit torques, allowing for sub-ns time resolution and about 30 nm space resolution. By employing a pump-probe scheme, we excite the magnetization dynamics of 500 nm and 1 um wide dots by injecting ns-long electrical current pulses (pump), while asynchronously sensing the magnetization state by scanning the x-rays (probe) across the sample. The temporal resolution allows us to image how the magnetization reversal takes place and to shed light on the interplay between spin-orbit torques and temperature effects in the RE and TM sublattices at sub-ns timescales.

O265 - Enhancement of spin mixing conductance in Ru/FeCo/Ru heterostructure: effect of Re doping

16. Magnetotransport, spintronics, spin orbitronics and spin caloritronics.

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We report a method to engineer the spin-mixing conductance (SMC) using ferromagnetic resonance (FMR) spectroscopy. To establish this, Re doped Ru/FeCo/Ru heterostructures were prepared using DC magnetron sputtering. Using out-of-plane FMR measurements, the observed SMC is enhanced by 100% up to for 6.6 at% Re doping, while the saturation magnetization decreases only by 32% with the increase of Re concentration. This study opens a new direction of tuning the spin-mixing conductance in magnetic heterostrucutures by doping of the ferromagnetic layer.

Introduction and sample preparation

The generalized form of the pure spin current (a 2×2 matrix in spin space) is governed by the spin-dependent conductance, which depends on the reflection (r) and transmission (t) matrices. The SMC is defined as $g^{\uparrow\downarrow} = (e^2/h)[M - \Sigma r^{\uparrow}(r^{\downarrow})^*]$, where M is the number of propagating quantum channels at the Fermi level and $r^{\uparrow(\downarrow)}$ is the reflection matrix for spin-up (spin-down) electrons. The first part of this equation $(e^2/h)M$ is called the Sharvin conductance, where M is proportional to the Fermi surface averaged density of states at the interface [**1**]. Using DC magnetron sputtering, rhenium (Re) doped polycrystalline $Fe_{65}Co_{35}$ alloy thin films with different thickness were deposited at room temperature on $Si(100)/SiO_2$ substrates with Ru as seed and capping layers. The Re concentration (x) in the $(Fe_{65}Co_{35})_{100-x}Re_x$ ($0 \leq x \leq 12.6$ at%) thin films was varied by changing the deposition rate of Re. The nominal thicknesses of the FeCo films were 5, 10, 15, 20 and 30 nm and the nominal thickness of the Ru layer was 3 nm.

Result and discussion

The dynamics properties of Re-doped (0−12.6 at%) polycrystalline $Fe_{65}Co_{35}$ thin films with Ru as capping and seed layers have been investigated using room temperature in-plane (IP) and out-of-plane (OP)-FMR measurements. Comparison of the effective damping parameters extracted from IP and OP measurements indicate that the IP damping parameter is affected by two-magnon-scattering (TMS). The thickness dependent OP results for the effective damping parameter, after subtracting the radiative and the eddy-current damping contributions, indicate that the enhancement of the damping is due to the spin-pumping contribution. By further analysis of the OP-FMR results, free from TMS, radiative and eddy current contributions, a non-monotonic dependence of the real part of the effective spin-mixing conductance on Re concentration is observed as shown in Fig. 1. The increase of $Re(g^{\uparrow\downarrow}_{eff})$ with increasing doping from 0 at% to 6.6 at% Re is tentatively explained by a corresponding increase of the interfacial SOC in the Ru layer. Apart from this, an enhancement of the bulk Gilbert damping is found with an increase in Re doping, while $\mu_0 M_s$ decreases by 32% with increasing Re concentration [2]. This study opens a new direction of tuning the spin-mixing conductance in magnetic heterostructures by doping the ferromagnetic layer, thus providing a method for optimizing the design of spintronic devices.

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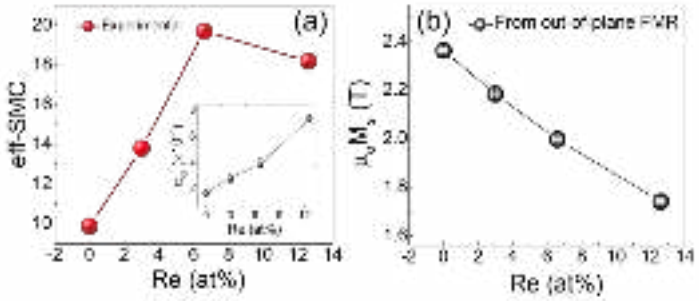

Fig. 1: (a) The real part of the SMC vs. Re concentration. Inset shows an enhancement of bulk Gilbert damping with an increase of Re concentration. (b) Experimentally observed $\mu_0 M_s$ vs. Re concentration from out-of-plane FMR measurements [2].

O266 - Enhancing Light Emission in Interface Engineered Spin-OLEDs through Spin-Injection at High Voltages

16. Magnetotransport, spintronics, spin orbitronics and spin caloritronics.

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Spin-based electronics is one of the emerging branches in today's nanotechnology and the most active area within nanomagnetism. So far spintronics has been based on conventional materials like inorganic metals and semiconductors. Still, an appealing possibility is that of using molecule-based materials, as components of new spintronic systems [1]. In particular, by taking advantage of a hybrid design one can integrate molecular materials showing multifunctional properties into spintronic devices. In this talk, we illustrate the use of this approach to fabricate multifunctional molecular devices combining light and spin-valve properties (i.e., Spin-OLEDs).
So far only one report has been published which is based on the fabrication of an organic light emitting diode (OLED) with ferromagnetic electrodes [2].

Our approach is based on the use of a HyLED (Hybrid Light Emitting Diode) structure in which LSMO and Co are employed as ferromagnetic electrode, the ferromagnetic (FM) electrodes are used to enhance the electroluminescence intensity of the OLED through a magnetic control of the spin polarization of the injected carriers. The major difficulty is that the driving voltage of an OLED device exceeds a few volts, while spin injection in organic materials is only efficient at low voltages. The fabrication of a spin-OLED that uses a conjugated polymer as bipolar spin collector layer and ferromagnetic electrodes is reported here. Through a careful engineering of the organic/inorganic interfaces[3], it is succeeded in obtaining a light-emitting device showing spin-valve effects at high voltages (up to 14 V). This allows the detection of a magneto-electroluminescence (MEL) enhancement on the order of a 2.4% at 9 V for the antiparallel (AP) configuration of the magnetic electrodes[4]. This observation provides evidence for the long-standing fundamental issue of injecting spins from magnetic electrodes into the frontier levels of a molecular semiconductor. The finding opens the way for the design of multifunctional devices coupling the light and the spin degrees of freedom.

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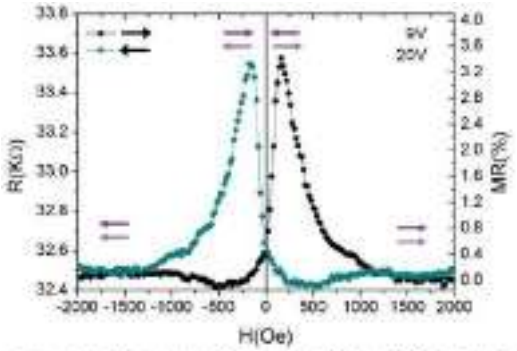

Figure 1. Magnetoresistance at 9 V and 20K of the PEIE SO. Black arrows depict the field sweep direction. Purple and grey arrows point the FM electrodes magnetization direction

O267 - High frequency voltage-induced ferromagnetic resonance in magnetic tunnel junctions

16. Magnetotransport, spintronics, spin orbitronics and spin caloritronics.

Marek Frankowski[1] , *Witold Skowroński[1], Stanisław Łazarski[1], Jakub Chęciński[1], Jakub Mojsiejuk[1], Takayuki Nozaki[2], Kay Yakushiji[2], Shinji Yuasa[2]*

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Recently, a few different mechanisms have been proposed to maximize the effect of an electric field on magnetic properties of materials [1], including diluted magnetic semiconductors, charge migration multilayer and voltage controlled magnetic anisotropy (VCMA). It has been already demonstrated that, by utilizing the VCMA effect, driving magnetization into a precession at several GHz is possible, which is promising for high-frequency devices.

In this work we present studies on CoFeB/MgO/CoFeB-based MTJs deposited on W buffer [2]. Using a relatively thin CoFeB bottom free layer and different annealing temperatures, a high perpendicular magnetic anisotropy (PMA) energy of up to 1.5 MJ/m3 was achieved, which in turn enabled a voltage-induced ferromagnetic resonance (V-FMR) excitation at frequencies up to 31 GHz. In addition, V-FMR measurements in combination with a vector network analyser (VNA)-FMR investigation was used to determine magnetization damping in the discussed multilayers. We repeated measurements after sample annealing in a high-vacuum furnace subsequently at T_A = 200, 250, 300 and 350 $^{\circ}$C. Independently, the same multilayers were fabricated into pillars of 2 × 4 μm ^{2} using an electron-beam lithography and an ion-beam milling for transport measurements.

We analyze the voltage-induced spin-diode lineshape [3,4] for different excitation frequencies and field bias angles for both free and reference layers. We observe the lineshape change with the applied field magnitude (which is propotional to the excitation frequency), ranging from fully antisymmetric to fully symmetric [5]. We attribute this change to different orientations of magnetization vectors in free and reference layer, which is confirmed with macrospin simulations.

Finally, we calculate the magnetization damping from the linewidth vs. frequency slope and, with support of macrospin simulations, discuss when this method is appropriate. In particular, we find that the magnetization has to be closely aligned with the applied field direction, which is not necessarily true for high PMA values that at the same time are required for high frequencies.

This work was supported by the National Science Centre, Poland, grant No. LIDER/467/L-6/14/NCBR/2015 by the Polish National Centre for Research and Development and National Science Centre, Poland, grant No. UMO-2015/17/D/ST3/00500. Calculations were supported by PL-GRID infrastructure.

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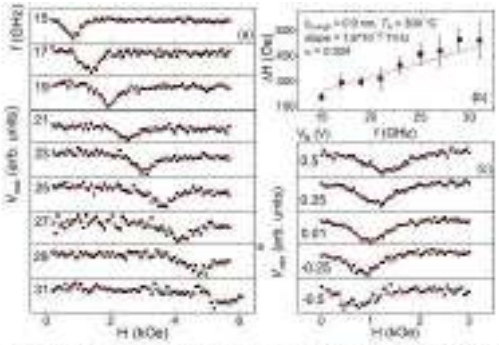

Fig 1. (a) spin-diode voltage output vs. magnetic field applied at 85° to the sample plane together with a fit to the sum of the symmetric and antisymmetric Lorentz curves. Note that the resonance frequency range reaches 31 GHz for relatively small magnetic fields. (b) damping coefficient calculated for an example anisotropy; (c) constant voltage bias influence on the spin-diode effect – note that, due to high overall anisotropy, no significant change occurs in the lineshape.

O268 - In-situ Measurement of the spin Seebeck Effect with Polarised Neutron Reflectivity

16. Magnetotransport, spintronics, spin orbitronics and spin caloritronics.

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The spin Seebeck effect (SSE) – generation of a spin polarised current in a magnetic material subjected to a temperature gradient [1] – is a magnetothermal effect that could be used for generation of pure spin currents for spintronic applications. It is most often detected indirectly by placing a heavy metal such as Pt in contact with a magnet and measuring the voltage generated by the inverse spin Hall effect. This is, however, plagued by artefacts such as the anomalous Nernst effect (ANE) [2], or proximity induced ANE [3] and there are outstanding questions with regards to the influence of the interface on the detected voltage. In addition, recent work has shown an increase of the measured 'spin Seebeck voltage' for multilayer films that could be a result of enhanced magnon propagation [4], or a change in the ANE contribution to the measured voltage.

Polarised neutron reflectometry (PNR) can be used to directly probe the magnetism of thin films as a function of depth [5,6], which makes it a possible route to directly observe the spin Seebeck effect. The challenges with this technique, however, lie in the development of a sample environment that can maintain a suitable temperature gradient, whilst not distorting the sample, or introducing temperature dependent or time varying artefacts. We will show development of a thermal cell for in-situ SSE-PNR measurements of potential spin Seebeck multilayers, where we observe evidence of a change in magnetisation profile - as measured by the spin asymmetry - when a temperature gradient is applied to a SSE device (Figure 1).

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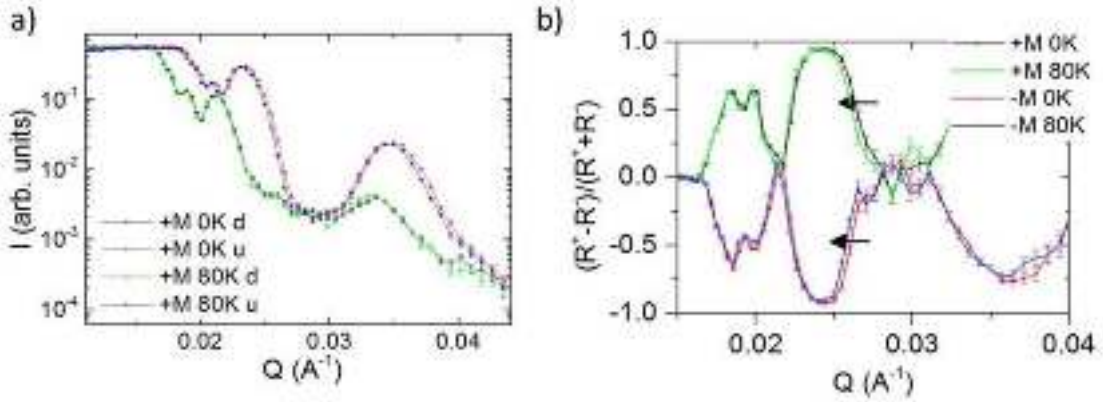

Figure 1 – In-situ SSE-PNR data obtained for a multilayer {Fe_3O_4:Au} film using the thermal cell. (a) Raw data for ΔT = 0K, and ΔT = 80K. (b) Corresponding spin asymmetry.

O269 - Limitations of collective spin transport in easy-plane magnets

16. Magnetotransport, spintronics, spin orbitronics and spin caloritronics.

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Some aspects of magnetism can be described by a continuous field-theory, i.e. by the micromagnetic framework. The magnetic equations are rather complex since these comprise all non-linearities of the Landau-Lifshitz-Gilbert equation; but for special systems, e.g. easy-plane magnets with small out-of-plane component, the equations reduce to a form that is similar to the Gross-Pitaevski equation, describing the time evolution of a Bose condensate—and, therefore, superfluidity. Moreover, the order parameter of an easy-plane magnet (magnetization for ferro- [2] or Néel vector for antiferromagnets [3]) exhibits a rotational invariance around the out-pf-plane axis. This SO(2) invariance is strictly equivalent to the U(1) gauge symmetry of the macroscopic wave function of a Bose condensate.
Because of this very resemblance, there is a specific type of transport in such magnets called “spin superfluidity” [1-3]. There is, however, a major difference: a dissipative term resulting from Gilbert damping, unavoidably leading to dissipation in the spin superfluid. Fortunately, this damping can be quite small, particularly in magnetic insulators.

The present work rests on atomistic spin simulations of easy-plane ferro- and antiferromagnets, carried out within the scope of the analytical theory of the field equations and beyond. The numerically investigated systems refer to the concept of non-local spin-transport measurements, where a spin current is excited at one position and measured at another via the (inverse) spin-Hall effect respectively, see graphic depiction. We study one of the striking features of this transport: the unusual transport range that deviates from the normal diffusive exponential decay. Furthermore, our approach allows to test limitations of this kind of transport—e.g. with respect to a finite temperature, disorder, or high driving strengths—presented in this contribution. Especially the former two are relevant for possible experimental realizations.

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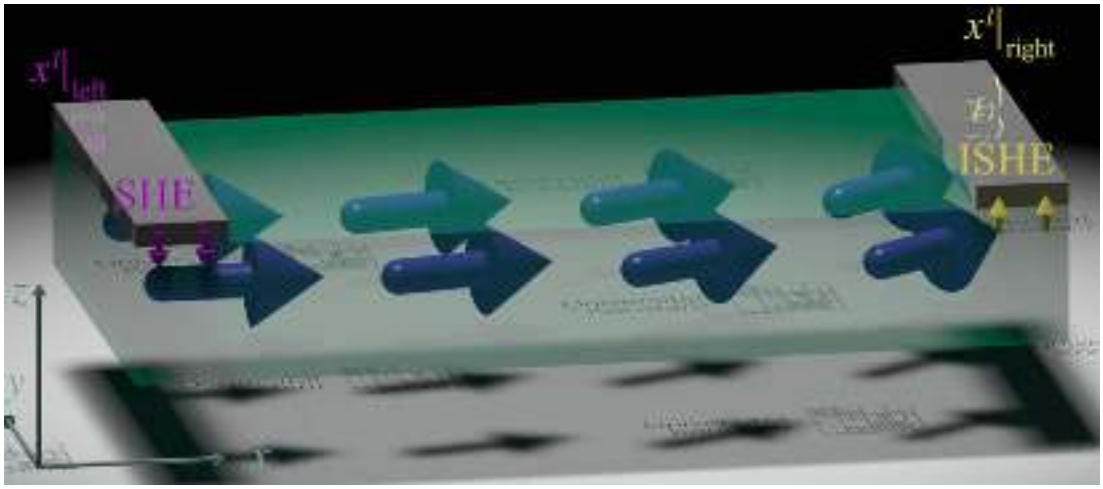

O270 - Nearly 1km/s domain wall velocity using pure spin transfer torques in Mn4N thin films

16. Magnetotransport, spintronics, spin orbitronics and spin caloritronics.

Toshiki Gushi[1, 2] , ***Sambit Ghosh***[2], *Matic Jovičević Klug*[3], *Jose Peña Garcia*[3], *Jan Vogel*[3], *Hanako Okuno*[4], *Jean-Philippe Attané*[2], *Takashi Suemasu*[1], *Stefania Pizzini*[3], *Laurent Vila*[2]

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In this work, we will describe the magnetic properties of a new material, made of abundant and cheap elements, and show that it is a promising candidate for the development of a sustainable spintronics: epitaxial Mn_4N films.

Spintronics, which is the basis of a low-power, beyond-CMOS technology for computational and memory devices, remains up to now entirely based on critical materials such as Co, heavy metals and rare-earths. Here, we show that Mn_4N, a rare-earth free ferrimagnet made of abundant elements [1], is an exciting candidate for the development of sustainable spintronics devices.

Mn_4N thin films grown epitaxially on $SrTiO_3$ substrates possess remarkable properties, such as a perpendicular magnetisation, a very high extraordinary Hall angle (2%) and smooth domain walls, at the millimeter scale [2]. Moreover, domain walls can be moved at record speeds by spin polarised currents, in absence of spin-orbit torques, with average speed reaching 900 m/s at $1.4*10^{12}$ A/m². This can be explained by the large efficiency of the adiabatic spin transfer torque, due to the conjunction of a reduced magnetisation and a large spin polarization [3]. Whereas in the past years the whole spintronics community shifted its focus from spin-transfer torques to spin-orbit torques, these results shows that classical spin-transfer torques remains highly competitive for current-induced DW motion. We will show that in such an epitaxial ferrimagnet, the magnetic compensation point can be reached by substitution of Ni in Mn_4N thin films and that domain wall propagation direction is reversed.

Finally, we show that the coercivity of Mn_4N films can be easily tuned by a gate voltage, this ability constituting a tool for DWs or nanomagnets manipulation. We show that the application of gate voltages through the SrTiO3 substrates allows modulating the Mn_4N(4 nm) coercive field with a large efficiency, reaching -15pJ/m², a value hardly obtained in best reports with sub-nm thick layers.

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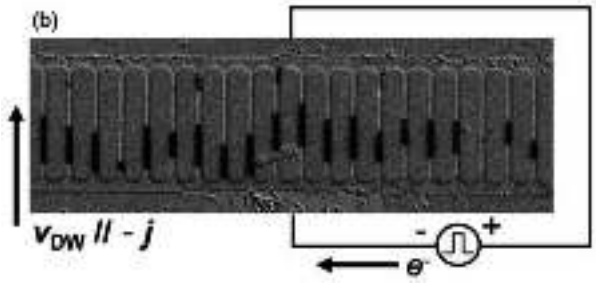

Differential MOKE image after eight current pulse injection of 1.2 A/m2 and 1 ns. The area through which the DW propagated appears in black. The DW motion direction is opposite to the current, and thus follows the electrons flow.

O271 - New developments for flexible spin current circuits

16. Magnetotransport, spintronics, spin orbitronics and spin caloritronics.

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The spin angular momentum of an electron is a quantum mechanical property having two states (up↑ or down↓). Over the past two decades, utilizing spin currents, that are streams of spin-polarized up or down electrons, has led to a colossal expansion of memory storage capacity in computers through the giant and tunnel magnetoresistance effects, enabling the information technology age. Beyond this great development, where spin-polarized currents travel through distances~nm, in pursuit to create spin current circuits, spin transport through materials has been extensively explored. With the advent of the two-dimensional material graphene, today it is possible to transmit spin currents over tens of microns at room temperature, up to hundred times longer than normal metals[1]–[3]. In this presentation, I will discuss how the exceptional resilience of graphene can be harnessed to realize flexible graphene spin circuits, demonstrating the possibility of highly efficient spin transport in graphene over flexible substrates for the first time. Furthermore, I will discuss how to enhance the stability of such circuits by engineering highly resilient nanomagnets for spin injection into graphene.

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O272 - Noise of charge current generated by a driven magnet

16. Magnetotransport, spintronics, spin orbitronics and spin caloritronics.

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We determine the noise of charge current that is generated by a precessing magnetization of a small itinerant ferromagnet, which is driven by ferromagnetic resonance (FMR) and tunnel-coupled to two normal metal leads. Even when the leads are in equilibrium with each other, i.e. neither voltage nor thermal bias is applied, the electron system is driven out of equilibrium by the precessing magnetization. In turn, a non-equilibrium electron distribution develops in the small ferromagnet. This distribution is governed by the dynamics of the magnetization and determines the (zero-frequency) noise of charge current. We show that this noise can be used to gain information about the magnetization dynamics.

O273 - Nonequilibrium Theory of the Induced Effective Spin-Orbit Torque in Magnetic Tunnel Junctions

16. Magnetotransport, spintronics, spin orbitronics and spin caloritronics.

Juan David Vasquez Jaramillo [1] , *Fabian Pauly*[1]

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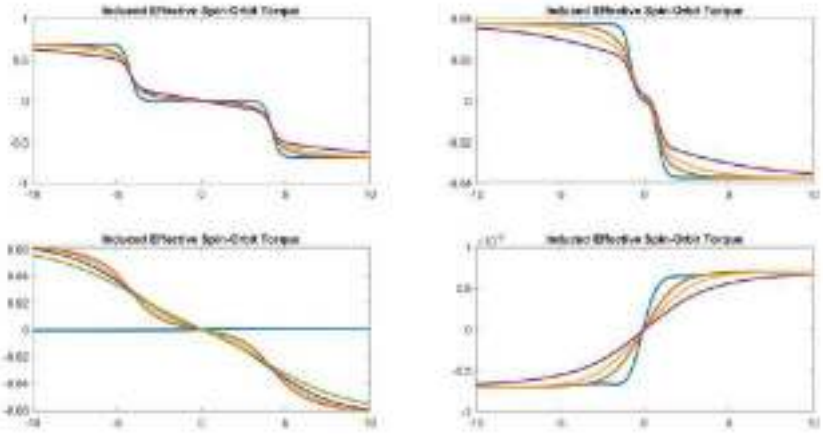
The chiral induced spin selectvity effect has emerge as an important effect both from the fundamental and aplied scenario across a range of application of thin layer magnetism, including spintronics. In conventional spintronics devices, for instance a magnetic tunnel junction, the spin filtering effect plays a crucial role and the comprehension of its generating mechanism and how it can be control has become a fascinating challenge both from the experimental and theoretical arena. Moreover, recent experimental progress has shown that in thin ferromagnetic layers, the efficiency of spin filtering increases notoriously as a consequence of an applied potential difference, making this manifestation purely a nonequilibrium effect. The essential consequence of such nonequilibrium effect is the perception of unusually large spin-orbit potentials, therefore, enhancing the spin-orbuit torques. In the present work, we propose a theory that predicts the emergence of an induced Torque in the presence of an applied bias voltage in a magnetic tunnel junction, possesing identical symmetry laws as the ones contained in the Dzyaloshiinski-Moriya tensor (anty-symmetric exchange interaction). The theory derives from the coherent state path integral in the Keldysh contour, which allows the evaluation of an induced effective spin orbit torque in terms of nonequilibrium Green's functions, and complying with the basic arguments of anti-symmetrization propose by Igor Dzyaloshinskii. We furthermore show that the above mentioned effective spin-orbit torque adds or subtracts from the present Dzyaloshinskii Moriya interaction in the system of study depending on the orientation of the tunnel junction bias voltage polarization, and we exemplify this concept by evaluating the effective torque for a two spin system driven out of electrochemical equilibrium as well as from thermal equilibrium. This new theoretical development promises to shine some ligh on the nonequilibrium origins of the chiral induced spin selectivity effect and opens up new control possibilities for spintronic devices, mainly targeting spin valves and tunnel magnetoresistive devices.



O274 - Observation of Large Unidirectional Rashba Magnetoresistance in Ge(111)

16. Magnetotransport, spintronics, spin orbitronics and spin caloritronics.

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[4] Unité Mixte de Physique, CNRS, Thales, Université Paris Sud, Université Paris-Saclay, 91767, Palaiseau, France

Tuning spin-orbit coupling (SOC) in semiconductors is of high interest as it could open a door towards spin manipulation with electric fields in an all-semiconductor technology platform. The existence of Rashba states at the subsurface of Ge(111) has been demonstrated by photoemission measurements and ab initio calculations [1].
Here we are interested in studying the influence of the specific spin texture in Ge(111) subsurface states on magneto-transport properties. For this purpose, we investigated the variation of the electrical resistance of Ge(111) grown epitaxially on semi-insulating Si(111) under the application of an external magnetic field. We report the observation of a unidirectional magnetoresistance (UMR) that scales linearly with both the applied current density j and the magnetic field B. At low temperature, the UMR dominates all other MR contributions and can reach several percent for a magnetic field of 1 T and a low current density of 20A.cm^{-2}.
A similar MR behavior was reported in the literature in the topological insulator Bi_2Se_3 and two-dimensional electron gases, though orders of magnitude smaller than in Ge(111). Within a simple model based on spin –dependent scattering, we provide a new interpretation of UMR. Indeed, we ascribe the origin of this magnetoresistance to the interplay between the externally applied magnetic field and the Rashba-Edelstein effect in the spin-split subsurface states of Ge(111). When increasing the temperature, the unidirectional magnetoresistance progressively vanishes due to carrier activation into the bulk. The highly developed technologies on semiconductor platforms point toward a ready optimization of the phenomenon.

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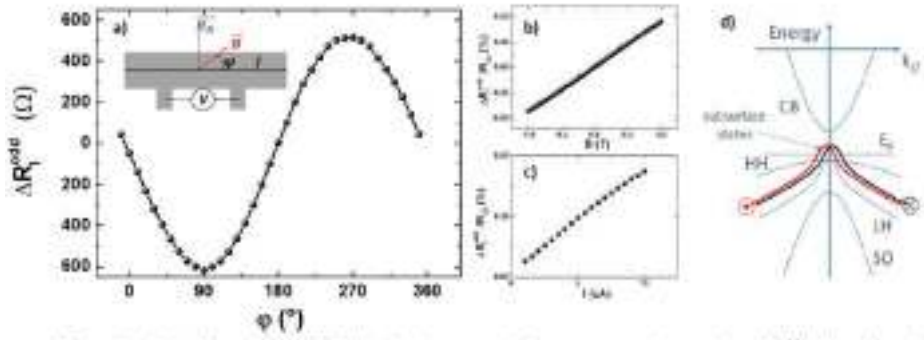

a) Experimental evidence of the UMR, the inset represents the measurement geometry, ΔR_l^{odd} is the odd part of the longitudinal resistance defined as $[R_x(+I) - R_x(-I)]/2$. Magnetic field b) and current c) dependence of the UMR signal, taken at φ=270° where the signal intensity is maximum, normalized by the zero field resistance. d) Scheme of the electronic band structure of Ge. The subsurface states split by Rashba spin-orbit coupling are highlighted and lie in the bandgap above the valence band.

O275 - Quantum magnetization fluctuations via spin shot noise

16. Magnetotransport, spintronics, spin orbitronics and spin caloritronics.

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Recent measurements in current-driven spin valves demonstrate magnetization fluctuations that deviate from semiclassical predictions. We posit that the origin of this deviation is spin shot noise. On this basis, our theory predicts that magnetization fluctuations asymmetrically increase in biased junctions irrespective of the current direction. At low temperatures, the fluctuations are proportional to the bias, but at different rates for opposite current directions. Quantum effects control fluctuations even at higher temperatures. Our results are in semiquantitative agreement with recent experiments and are in contradiction to semiclassical theories of spin-transfer torque.

O276 - Role of spin and charge currents on the Dzyaloshinskii-Moriya interaction

16. Magnetotransport, spintronics, spin orbitronics and spin caloritronics.

Ramon Cardias[1, 2] , *Anders Bergman*[2], *Attila Szilva*[2], *Manoel Bezerra-Neto*[3], *Marcelo Ribeiro*[4], *Yaroslav Kvashnin*[2], *Jonas Fransson*[2], *Angela Klautau*[1], *Olle Eriksson*[2, 5], *Lars Nordström*[2]

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Spin Hamiltonians are highly used to make a connection between first principles calculations on atomistic- and macroscopic magnetism. Interactions between magnetic moments, e.g. Heisenberg exchange, Dzyaloshinskii-Moriya interaction, single site anisotropy etc; may be calculated from first principles methods and mapped onto spin Hamiltonians in order to obtain properties such as the magnetic ground state, phase transitions, Curie temperature, magnetization dynamics etc, for macroscopic systems. These interactions are usually calculated from a ferromagnetic configuration, but for highly studied systems nowadays, such as magnetic skyrmions, it is important to know the influence of different magnetic configurations to these interactions. We have derived an expression for the Dzyaloshinskii-Moryia vector interaction (DMI) where all the three components of the vector can be calculated independently of the magnetic configuration. Here, we have chosen the Cr triangular trimer on Au(111) and Mn triangular trimers on Ag(111) and Au(111) surfaces to illustrate the implementation of the derived DMI into the RS-LMTO-ASA method. Our results show that the DMI value (module and direction) is drastically different for collinear and non-collinear states. Based on the relation between the spin and charge currents flowing in the system and the non-collinear magnetic configuration of the triangular trimer, we argue that the drastic change between the DMI calculated considering a collinear and a non-collinear magnetic configuration can be explained by the mechanism behind the spin and charge currents flowing through the atoms when the spins are aligned in a non-collinear (NC) fashion. Lastly, we present a simple example of a Mn dimer on a W(001) surface to illustrate didactically how spin currents behave and could influence on the DMI under non-collinearity.

O277 - Spin galvanomagnetic phenomena in ferromagnetic-metal/heavy-metal heterostructures

16. Magnetotransport, spintronics, spin orbitronics and spin caloritronics.

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Spin Hall Magnetoresistance (SMR) effect has been recently examined both theoretically and experimentally in heavy metal (H)/ferromagnet (F) heterostructures [1-3]. It is well known, that SMR originates from difference in resistance between the states of spin accumulation parallel to and perpendicular to the magnetization of ferromagnetic layer. In the case of ferromagnetic insulators one can assume that such defined magnetoresistance consists only of SMR contribution.

However, in the case of metallic H/F heterostructures, proper estimation of SMR can be obscured by other possible magnetoresistance effects that occur simultaneously such as, for instance, anisotropic magnetoresistance (AMR) which plays significant role in in-plane magnetized ferromagnetic metals.

Here, we revisit the theory of spin Hall magnetoresistance for the case of heavy-metals coupled to ferromagnetic metals and determine the contributions to multilayer magnetoresistance from SMR as well as AMR. For this aim we specifically consider AMR effect in diffusive transport in ferromagnet [4] and compare the theory to experimental results for H/F heterostructures where H:W, Pt and F:Co, CoFeB. This analysis allows us to consider total magnetoresistance effects in H/F bilayers coupled to antiferromagnetic insulator (AF) NiO and properly determine the influence of spin currents at F/AF interface on SMR effect.

Acknowledgments

This work is supported by the National Science Centre grant Spinorbitronics UMO-2016/23/B/ST3/01430. WS acknowledges National Science Centre Grant No. 2015/17/D/ST3/00500. We would like to thank W. Powroźnik, M. Schmidt and J. Aleksiejew for technical support.

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O278 - Spin transport in a charge current induced magnon Bose-Einstein condensate at room temperature

16. Magnetotransport, spintronics, spin orbitronics and spin caloritronics.

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In the field of spintronics, the quasiparticle excitations of a magnetic material (magnons) represent one of the most promising surrogates for the electron in conventional charge-based electronics. Still, however, spintronic information processing is performed mainly on a pure classical, charge-based level.
Bose-Einstein condensation (BEC) constitutes the perequisite of dissipationless transport phenomena in superconductivity and superfluidity and is therefore likewise required for modern quantum technologies. While a BEC in atomic superfluids is typically only achieved at low temperatures, a driven quasiparticle system can condensate into the ground state even at room temperature. Although a collective quantum state of magnons was already realized in 2006, clear evidence for superfluid transport of Bose-Einstein condensed magnons is still missing.
In this study, we demonstrate the transport of spin (angular) momentum in a charge current induced magnon Bose-Einstein condensate at room temperature and study its transport properties in a 13.4 nm thin yttrium iron garnet (YIG) film. We create the magnon condensate in the YIG by sourcing a DC current through an adjacent Pt strip injecting a spin current into the YIG. Above a critical DC current, the magnon conductivity increases by almost two orders of magnitude, indicating zero resistance magnon transport, i.e. the realization of spin superfluidity. Within the magnon condensate, we identify two distinct regimes: the continuous condensation of magnons into the ground state and the full compensation of the effective magnon damping.

We gratefully acknowledge financial support by the Deutsche Forschungsgemeinschaft (DFG) via projects AL2110/2-1, WE5386/4-1 and HU1896/2-1.

O279 - SPIN-PELTIER EFFECT DUE TO ULTRAFAST DOMAIN WALLS MOTION IN ANTIFERROMAGNETS

16. Magnetotransport, spintronics, spin orbitronics and spin caloritronics.

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Recent research into many applications involve the magnetization dynamics in a thermodynamic environment. Novel thermal spin physics phenomena include for example, the spin-Seebeck effect, where the magnetization dynamics occurs due to a temperature gradient. The inverse phenomenon is the Spin-Peltier effect -- heat generation by magnonic spin currents [1]. Recently a micromagnetic approach [2] for self-consistent treatment of magnetization dynamics and temperature was developed. Since the temperature rise exists for any irreversible processes, an irreversible movement of a magnetic object such as a domain wall is accompanied by some temperature change. Along this line, any moving domain wall produces a temperature raise which is also a signature of the spin-Peltier effect. In most of the situations, the dissipated magnetic energy into heat is minimal, and therefore neglected. Additionally, the temperature raise is typically rapidly taken away by thermal diffusion of electrons and phonons. For example, the overall temperature increase in permalloy stripes by DW motion is below 1 mK and is characterized by rapid by temperature diffusion. We show that a high speed and extreme magnetic excitation localization are paramount for efficient transfer of energy from the spin-degrees of freedom to the electronic system and subsequently to the lattice. We find that domain walls in antiferomagnets present a giant spin-Peltier effect, due to their ultrahigh mobility and ultra-small widths originating from the domain wall contraction at high velocities. To illustrate our findings, we show that electric current driven domain wall motion in the antiferromagnetic metal MnAu can carry a localised heat wave with the maximum amplitude up to 1K . This effect has the potential for nanoscale heating sensing and functionalities.

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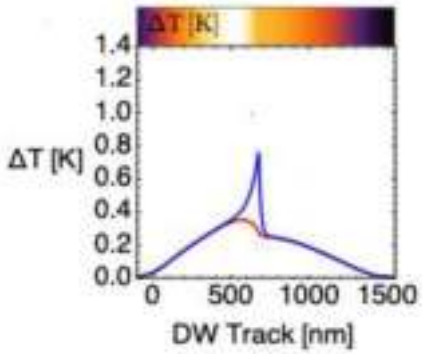

Figure 1. Electron (blue) and phonon (red) temperature accompanying the domain wall motion in antiferromagnetic Mn_2Au metal

O280 - Spin-to-charge conversion in Bi2Se3/Ge (111) probed by optical spin orientation

16. Magnetotransport, spintronics, spin orbitronics and spin caloritronics.

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Topological insulators (TIs) are predicted to host exotic properties like topologically protected surface states (TSS) showing Dirac-like band dispersion and strong spin-momentum locking. Such characteristics make this class of materials ideal for the generation and the detection of spin currents. The spin-charge interconversion efficiency is given by the spin Hall angle, which can be experimentally estimated using different techniques such as spin pumping-ferromagnetic resonance (FMR) or spin-torque-FMR measurements. In both techniques, the material is in contact with a ferromagnetic film. Although those methods showed success in the past decade to characterize heavy metals like Pt or W, they fail in providing reliable results with topological insulators since ferromagnetic materials are known to chemically react with TIs. The presence of TSS at the interface between the ferromagnet and the TI is even questionable.

In this work, we grow single crystalline Bi_2Se_3 thin films on low n-doped (10^{16} cm^{-3}) Ge (111) by molecular beam epitaxy. Germanium is an optically active material with a long spin diffusion length ($l_{sf} \approx 10$ µm at room temperature) and it is compatible with the current Si technology platform.

We propose an original method to probe the spin-to-charge conversion in TIs by taking advantage of the Ge optical properties. We designed microdevices (Fig. 1a) where pure spin currents with in-plane spin polarization are generated by optical spin orientation in Ge when the laser beam hits the edge of Pt bars [1,2]. Spin currents are then detected in a non-local geometry by the inverse Rashba-Edelstein effect in a Bi_2Se_3 bar at room temperature.

Our technique allows us to probe the bottom surface of the TI layer in epitaxy on Ge(111), which is of higher quality than the top one and do not require the use of an extra ferromagnetic layer. We repeated this experiment with a light (resp. heavy) metal Ti (resp. Pt) detection bar in order to compare the spin detection efficiency. Our results highlight a much stronger efficiency using Bi_2Se_3 as a spin detector and pave the way toward spintronic devices without using ferromagnetic compounds.

[1] C. Zucchetti and al, Phys. Rev. B 96, 014403 (2017)
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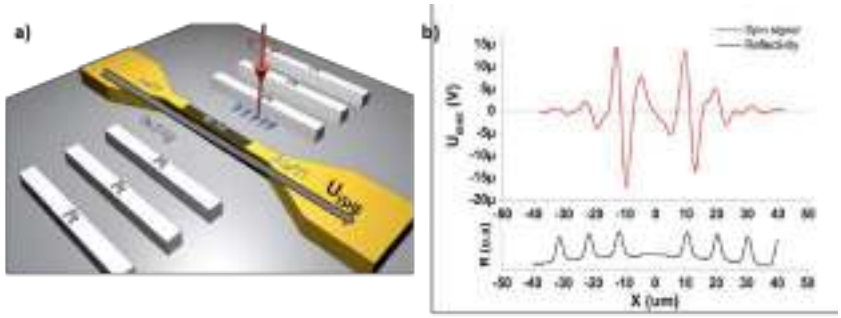

a) Illustration of the microdevice used for optical spin orientation. b) Integrated profiles of the sample reflectivity (bottom) and the inverse Rashba-Edelstein effect signal (top). The scattering of circularly polarized light on the right (left) edge of a Pt stripe will create a pure spin current in germanium with in-plane orientation pointing to the right (left) respectively. The spin current is then absorbed and converted into a charge current in the Bi_2Se_3 bar by inverse Rashba-Edelstein effect.

O281 - Spin-transfer torque in ferrimagnetic tunnel junctions from first principles

16. Magnetotransport, spintronics, spin orbitronics and spin caloritronics.

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Antiferromagnetic and low-moment ferrimagnetic materials hold a great promise for novel spintronic devices, because of their relative immunity to stray fields and their high (THz) frequency spin dynamics modes. The tetragonal ferrimagnet Mn_3Ga (a $D0_{22}$-structure Heusler alloy) has been proposed as a good candidate for spintronic applications because of its high Curie temperature and unusual magnetic order at the verge of non-collinearity, driven by two orthogonal anisotropies – a large c-axis uniaxial and a much smaller easy plane anisotropy [1]. Another technological advantage of Mn_3Ga is its epitaxial compatibility with MgO substrates for thin film growth and high Fermi level spin polarisation.

Here we report on the coherent spin-transport properties of a theoretically-conceivable junction of Fe|MgO|Mn3Ga (see Figure) from first principles. Using the non-equilibrium Green's function (NEGF) approach to quantum transport, as implemented in the Smeagol code [2] for the spin-density functional theory (SDFT) Hamiltonian of the Siesta method [3], we evaluate the linear response spin-transfer torkance (STTk) as well as finite bias spin-transfer torque (STT) up to a few tens of a Volt applied (for our STT methodology see Refs. [4] and [5]). We find a tunnelling magnetoresistance (TMR) effect of about 50% at low biases and sizable staggered STTk and STT with long wave-length spatial beating deep inside the Mn_3Ga (we report of large-scale calculations with self-consistent scattering region extending up to about 78Å or 95 atomic monolayers of Mn_3Ga). Analysis of the Fermi level transmission shows a dominating single-channel majority-spin transport at the Gamma point (in the P-state, see Figure) and a rather suppressed minority-spin channel. This is practically reversed in the AP state. The spatial beating of the STT is consistent with the two-channel transmission model of Stiles and Zangwill [6]. Such phenomenology in our ferrimagnetic tunnelling junction is dictated by the strong spin-filtering of the Fe|MgO part of the stack. Our observations suggest that, because of this long-range modulation, the efficiency of the staggered STT as a switching mechanism for the ferrimagnet might be greatly affected by the thickness of the Mn_3Ga layer.

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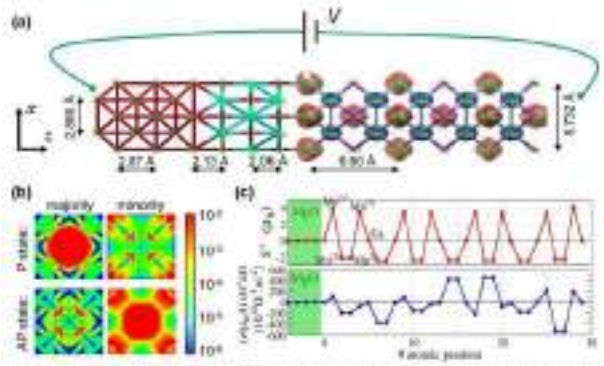

Figure: (a) Schematic of the Fe/MgO/Mn$_2$Ga junction studied, with the iso-surfaces representing the calculated equilibrium spin density along the *z*-axis. The lion load is polarized along *x* for the STT calculations. (b) Fermi-level (μ_F, $k_\parallel$)-resolved transmission for majority and minority spin in the two possible collinear spin alignments of Fe and Mn$_2$Ga ('P state' is with the interfacial Mn aligned with Fe and 'AP state' is when they are anti-aligned). (c) Atomic position resolved (indexed along *z*-axis) spin and spin-transfer torkance in Mn$_2$Ga for the 90° spin-alignment described in (a).

O282 - Strong suppression in inverse spin Hall effect at first order magnetic phase transition temperature

16. Magnetotransport, spintronics, spin orbitronics and spin caloritronics.

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Ferromagnetic or antiferromagnetic materials exhibiting large spin fluctuations at around the second-order transition temperatures, Curie temperature (T_C)[1, 2] or Néel temperature (T_N)[3], have drawn a great deal of attention because of the enhancement of spin pumping and spin torque efficiency. However, the detailed mechanism of the enhancement has not been clarified yet. Here we investigate the spin transport properties at the first order phase transition temperature around which the contribution of spin fluctuation might be different than that at the second order phase transition temperature. For this purpose, we chose Pd-doped FeRh which undergoes the first order transition from antiferromagnetic (AFM) to ferromagnetic (FM) phases with increasing temperature. Then we performed spin pumping induced inverse spin Hall effect measurements using a tri-layer $Fe_{47}Rh_{50}Pd_3$ (Fe(Rh, Pd), 60 nm) / Cu (10 nm) / $Ni_{81}Fe_{19}$ (NiFe, 10 nm) sample. In this tri-layer films, the inserted Cu layer eliminates interlayer exchange coupling between Fe(Rh, Pd) and NiFe layers. Spin currents were then injected into Fe(Rh, Pd) from NiFe by spin pumping technique. The thermomagnetic curve of the Fe(Rh, Pd) film in Fig. 1 (a) shows the AFM-FM phase transition at 345 K on heating. Interestingly the effective spin mixing conductance determined from the linewidth analysis of ferromagnetic resonance in the NiFe layer on heating process exhibits a sharp enhancement around the transition temperature as in Fig. 1 (b), meaning that the spin current injection efficiency was dramatically increased. This may be the characteristic behavior of spin susceptibility at the first and second order phase transitions. We also performed inverse spin Hall voltage measurements at the same device. The inverse spin Hall current (I_{ISH}) plotted in Fig. 1 (b) revealed that the sign of spin Hall angle for Fe(Rh, Pd) is negative in both AFM and FM phases. Despite the dramatic increase in the spin current injection efficiency, I_{ISH} was strongly suppressed around the AFM-FM phase transition temperature. This may be attributed to the enhanced relaxation of the spin current due to the presence of the dispersed particulate FM domains in AFM matrix in which non-collinear spin structures[4] and lattice distortions[5] co-exist, thereby the injected spin current may attenuate. These findings indicate that the inhomogeneous magnetic structure can affect strongly the spin transport properties.

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[4] J. Massey *et al.*, arXiv, arXiv:1807.01615 (2018).

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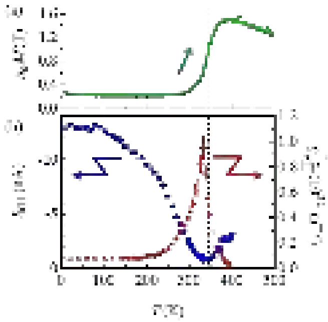

Fig. 1. (a) Magnetization of Fe[illegible]Rh[illegible]/Pt ([illegible] nm). The applied temperature on heating process under in-plane external magnetic field of 0.1 T. Black dashed line indicates the AFM – FM phase transition temperature at 345 K which is determined from the inflection point of $M - T$ curve. (b) Temperature dependence of effective spin mixing conductance $g_{eff}^{\uparrow\downarrow}$ (red, open circle) and the inverse spin Hall current j_s (blue, open circle) on heating process.

O283 - Thermally assisted magnetisation reversal in a Giant Magnetoresistive Junctions

16. Magnetotransport, spintronics, spin orbitronics and spin caloritronics.

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The spin-caloric effects, such as the Seebeck [1], Peltier [2] and Nernst [3] effects, are gaining significant attention due to the potential to harvest previously wasted energy in the form of heat [4]. In ferromagnetic insulators like yttrium iron garnet (YIG) or Fe3O4, spin waves can be generated via the spin-Seebeck effect in the presence of a thermal gradient. For ideal efficiency this thermal gradient can be provided by the operation of the device itself via Joule heating. While the usual length scale for these gradients is micrometers, in this work a current-perpendicular-to-plane (CPP)-giant magnetoresistance (GMR) device has been insulated with Fe3O4 on a nanometric scale to evaluate the assistance of magnetisation reversal by a Seebeck spin-wave.
A Heusler-alloy GMR multilayer, consisting of Co2Fe0.4Mn0.6Si (CFMS) (5)/Ag0.78Mg0.22 (5)/ CFMS (5) (thickness in nm), was grown via ultra-high-vacuum sputtering on a MgO(001) substrate with a Cr (20)/Ag (40) seed layer and was capped by Ag(2)/Au (5) layers. The seed and Heusler alloy layers were annealed at 650oC and 500oC respectively to aid crystallisation. Photo- and electron-beam lithography followed by Ar-ion milling were used to fabricate a series of elongated pillars with major axis lengths between 100 and 1000 nm. As shown in fig. 1, the milling was stopped ~1 nm into the bottom CFMS layer. For adhesion a Cr (1)/AlO (2) insulating layer was deposited underneath a 5 nm Fe3O4 channel around the GMR pillar.
Figure 2 shows a typical GMR behaviour for the pillars. When the field is swept from a positive to negative direction a 2% GMR ratio is observed, characterised by a broad rotation-controlled reversal followed by a sharper nucleation reversal. This is typical of a low-coercivity Heusler alloy such as CFMS. However, when the magnetic field is swept from negative to positive an 8% GMR signal is observed, four times greater than that in the opposite direction.
The current application generates a thermal gradient in the Fe3O4 channel via Joule heating, which in turn creates a spin-wave via the Seebeck effect. This aids the magnetisation reversal of the free layer via the stray field from the Fe3O4. This thermal assistance is asymmetric due to the significant coercivity (~1 kOe) of the Fe3O4 layer compared to the soft Heusler alloy with coercivity <50 Oe.
This behaviour can also be observed in current-induced magnetisation reversal, and this will be further discussed at the conference. This study was partially supported by JSPS-EPSRC Core-to-Core programme (EP/M02458X/1) and ICC-IMR.

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[2] J. Flipse et al, Phys. Rev. Lett., 113, 027601 (2014)
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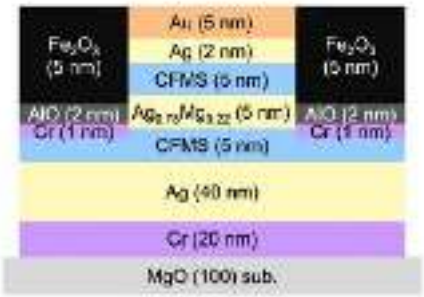

Fig. 1 – Schematic of thermally assisted GMR device

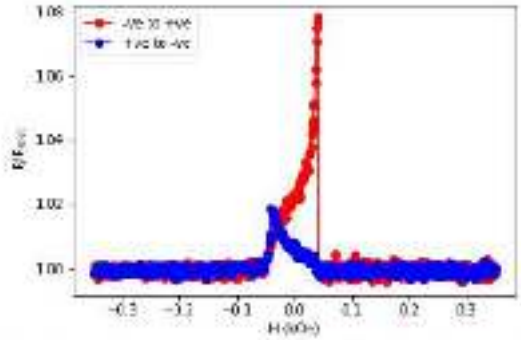

Fig. 2 – Typical asymmetric GMR behaviour of spin-Seebeck enhanced GMR via Fe_3O_4

O284 - Ultra-low switching current density in all-amorphous W-Hf / CoFeB / TaOx film stacks with PMA

16. Magnetotransport, spintronics, spin orbitronics and spin caloritronics.

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In our previous work [1], we investigated the spin Hall effect of W-Hf thin films, which exhibit a phase transition from a segregated phase mixture to an amorphous alloy below 70% W. Accompanied by a jump in resistivity, the spin Hall angle shows a pronounced maximum at the composition of the phase transition. A maximum spin Hall angle of θ_SH=-0.20 was obtained for amorphous W0.7Hf0.3.

Using polar Kerr microscopy, we study the domain wall structure and magnetization switching of amorphous W-Hf / CoFeB / TaOx stacks with perpendicular magnetic anisotropy and large spin Hall angle. We observe current-induced domain wall motion without an in-plane assist field, indicating Néel-type domain walls with an effective Dzyaloshinskii-Moriya field strength of B_DMI = 10mT. Investigations of magnetization switching as a function of in-plane assist-field and current pulse-widths reveal switching current densities as low as 3 x 10^9 A/m² for milliseconds-long pulses. We trace this ultra-low switching current density back to the very low depinning current density, or, equivalently, to the very small depinning field. We compare our results with typical nanocrystalline Ta / CoFeB / MgO / TaOx films, which we adjust to have the same perpendicular anisotropy field. This system typically shows switching current densities about two orders of magnitude larger. The ratio of switching current density and depinning current density is approximately the same in both systems. Our work demonstrates that careful control of domain wall pinning in spin-orbit torque based devices is mandatory to unleash their full potential.

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O285 - Voltage controlled mutual synchronization of spin Hall nano-oscillators

16. Magnetotransport, spintronics, spin orbitronics and spin caloritronics.

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The author has chosen not to publicise the abstract.

Field 5

Field 6

P444 - Spin pumping in non-magnetic/epitaxial-ferromagnetic heterostructures for spintronic applications

16. Magnetotransport, spintronics, spin orbitronics and spin caloritronics.

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Spintronic devices comprising ferromagnetic(FM)/non-magnetic(NM) layers, where the NM layer possesses strong relativistic spin orbit coupling(SOC), can potentially replace conventional microelectronic devices, yielding better functionality owing to energy harvesting, fast switching and high-speed data processing. These devices, by exploiting the spin Hall(SHE) and inverse spin Hall(ISHE) effects, as well as the Rashba Edelstein(REE) and inverse REE (IREE) effects, can efficiently generate pure spin currents in the bilayers. The SOC in the NM layer can be of bulk as well as of interfacial origin and may yield both damping like(DL) and field like(FL) torques. The DL torque can act against the restoring Gilbert damping to generate spin auto-oscillations, while the FL torque helps in switching the magnetic state of the FM layer. In case of ISHE and IREE based devices, the dissipation less pure spin current is generated by spin pumping, which is converted into a charge current in the NM layer[1, 2]. In presence of interfacial SOC, a non-equilibrium spin accumulation develops at the FM/NM interface with inversion asymmetry. The accumulated spins exert both DL and FL like torques on the magnetization of the FM layer. Furthermore, the Berry curvature induced SHE also produces a sizable DL torque, which e.g. has been seen in the ferromagnetic semiconductor (Ga,Mn)As[3]. However, some basic properties for devices need to controlled, like spin backflow, spin memory loss and magnetic proximity effects that may arise at/near the interface in FM/NM bilayers, properties that can reduce the overall spin angular momentum transfer across the FM/NM interface[4, 5]. Based on the above discussion, epitaxially grown $Co_{60}Fe_{40}$(CoFe) and $Ni_{81}Fe_{19}$(Py) films have been chosen as FM layers in our studies with β-W and β-Ta as suitable NM layers because of their high SOC and large spin Hall angles(SHAs). By using out of plane ferromagnetic resonance(FMR) measurements, the spin pumping mechanism has been investigated by probing the changes of the effective Gilbert damping constant() while varying the thickness of the individual layers in *β*-W,Ta/CoFe and *β*-W/ Py heterostructures. From the observed thickness dependence of , the interface spin memory loss with (without) corrected interfacial spin mixing conductance and the spin diffusion length are found to be $1.13\pm0.02\acute{}10^{19}m^{-2}$ ($1.24\pm0.07\acute{}10^{19}m^{-2}$) and 6.50±0.75nm (4.00±0.71nm), respectively, for *β*-Ta/CoFe. The corresponding results for *β*-W/CoFe are $3.60\pm02\acute{}10^{19}m^{-2}$ ($2.57\pm0.15\acute{}10^{19}m^{2}$) and 3.20±0.90nm (2.16±0.89nm), respectively. The spin memory loss parameter is found to be ~9% and ~2% for *β*-W and *β*-Ta, respectively, based CoFe heterostructures. The observed interfacial spin mixing conductance for the *β*-W/Py system, without spin memory loss correction, is $1.38\pm0.05\acute{}10^{19}\ m^{-2}$, and the spin diffusion length 2.25±0.37 nm, values that are comparable with the corresponding values obtained for the *β*-W/CoFe system.

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Poster

1. Biomagnetism and medical applications

P1 - Changes in Ca2+ Release in Human Red Blood Cells under Pulsed Magnetic field

1. Biomagnetism and medical applications

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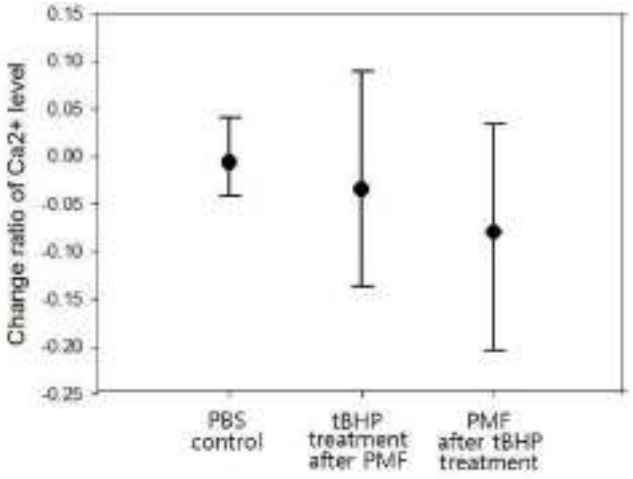
Since red blood cells (RBC), unlike other eukaryotic cells, do not have nuclei, mitochondria, and internal organelles, and Ca2+ is related to a highly versatile intracellular signal to regulate many different cellular processes, it is known that the role of calcium ions in RBC is very important. Also it is reported that the concentration of Ca2+ in the RBC is highly related to RBC deformability (RBCD). The higher Ca2+ level in RBC, the worse RBCD deteriorates. In addition, it is known that due to tBHP(tert-Butyl hydroperoxide) inhibiting Ca-pump ATPase activity in intact RBC, the concentration of intracellular Ca2+ increases in RBCs that have been oxidatively stressed by tBHP. The decreases in RBCD may exert a significant effect on blood flow resistance through the microcirculation and aggravate the flow disturbance.

Also our previous study suggest that the pulse magnetic field (PMF) plays a role in preventing RBC hemolysis from oxidative stress and improving RBCD. Therefore, in this study, we have elucidated the relationship between PMF and intracellular Ca2+ level to understand how PMF affects oxidative stressed RBCs using tBHP.

Our PMF device consisted of magnetic field generator and single layered coil of 10 turns with an elliptical shape of 12 cm × 4.5 cm using a plat square-shaped single stranded wire of 1 mm in thickness and 3 mm in width. The maximum magnetic field intensity is 0.27 T, 5 mm away from coil, and it is rapidly decreasing and pulsating pulse. The pulse duration was 306 us including 3 micro-pulses, and pulse repetition rate was 1 Hz.

To investigate the influence of PMF on oxidized RBC, hematocrit was adjusted to 5% by using human RBC and plasma, and tBHP(100 μM) was treated on RBC for 30 minutes to give oxidative stress. Blood was directly exposed to PMF for 3 min.

The first group was exposed to PMF and then treated by tBHP. The second group was treated by tBHP and then exposed to PMF. The former accounts for the effect of PMF to prevent oxidative stress, and the latter does the effect of PMF to help RBC recovery from the oxidative stress. The results were confirmed by Ca2+ level in the RBC. After PMF exposure, there was the decrease of Ca2+ concentration in both groups, inducing the increase of RBCD. However, in the latter case, the Ca2+ level is lower than that of the former case, so that the magnetic field is more effective for the recovery of oxidized RBC. (Fig.1) In conclusion, this study suggests a possibility to use PMF as a new modality in improving circulatory regulation in health and hemodynamic derangements in disease.


0.15
0.10
0.05
0.00
-0.05
-0.10
-0.15
-0.20
-0.25
Change ratio of Ca2+ level
PBS control
tBHP treatment after PMF
PMF after tBHP treatment

P2 - Co/Pd-based synthetic antiferromagnetic multi-stacks for biomedical applications

1. Biomagnetism and medical applications

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Mesoscale magnetic particles (from few nanometers to microns) are a major class of materials with the potential to revolutionize current clinical diagnostic and therapeutic techniques. They are commonly fabricated by bottom-up chemical methods; however, recent studies have demonstrated that top-down approaches based on techniques developed for micro/nano electronics can be used to fabricate monodisperse magnetic micro/nanoparticles with a complex structure and shape that are hard to obtain by means of chemical routes [1,2]. In this work, thin film stacks consisting of multiple repeats of single $[Co/Pd]_N/Ru/[Co/Pd]_N$ units with antiferromagnetic coupling and perpendicular magnetic anisotropy were investigated and exploited as a potential starting material to fabricate free-standing synthetic antiferromagnetic microdisks. For this purpose, films were directly grown on a sacrificial optical resist layer (AZ5214) spinned on a thermally oxidized Si substrate, which would serve to obtain free-standing particles after its dissolution. Furthermore, the film stack is sandwiched between two Au layers to allow further bio-functionalization. The samples fulfill all the key criteria required for biomedical applications, i.e., zero remanence, zero field susceptibility at small fields and sharp switching to saturation, together with the ability to vary the total magnetic moment (by changing the number of repetitions of the multi-stack) without significantly affecting any other magnetic features (Figure 1 left). Moreover, the samples show a strong perpendicular magnetic anisotropy, which is required for applications relying on the transduction of a mechanical force through the particles under an external magnetic field, such as the mechanical cell disruption, which is nowadays considered as promising alternative to the more investigated magnetic hyperthermia approach for cancer treatment [3]. Preliminary results on microdisks (M = 5, diameter: 2 mm, pitch: 4 mm) obtained from the continuous multistacks by combing electron beam lithography and Ar ion milling are also discussed (Figure 1 right).

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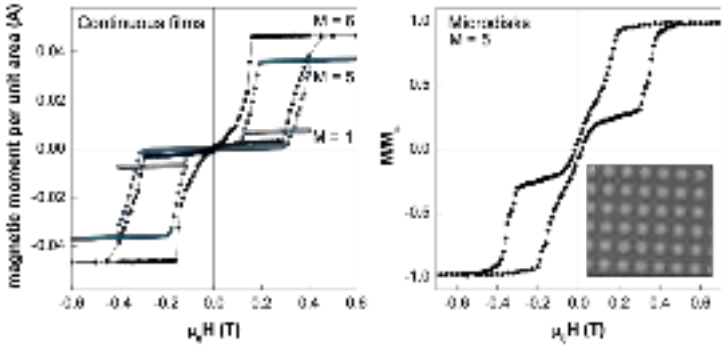

Figure 1. Room temperature out-of-plane hysteresis loops of $([Co/Pd]_5/Ru(0.4\ nm)/[Co/Pd]_4)_M$ multistacks. (Left) Continuous films (M = 1, 5, and 6), the magnetization is normalized to the sample surface area. (Right) Microdisk array (M = 5, diameter: 2 mm, pitch: 4 mm).

P4 - Heat dissipation characteristics and functionalization of magnetic nanoparticles

1. Biomagnetism and medical applications

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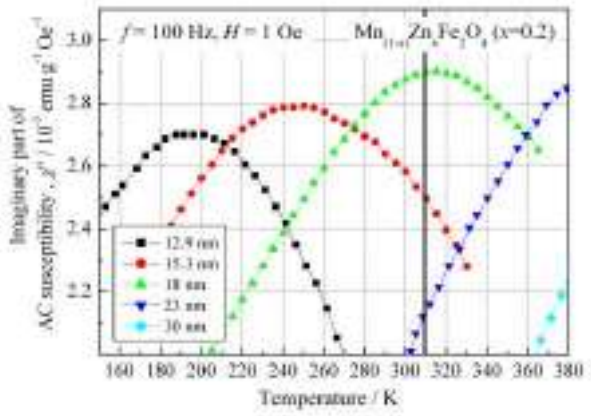
Mn-Zn nanoparticles and Co-Zn nanoparticles surrounded by amorphous SiO_2 with particle sizes between 7 and 30 nm were prepared by an original wet chemical method. Furthermore, in order to improve dispersion, these particles were produced by one-pot solvothermal synthesis by mixing the reagent of metal chlorides and NaOH in polyethylene glycol (PEG) solution. Particle sizes were controlled between 5 and 10 nm.

The heat dissipation characteristics of the particles were investigated by measuring AC magnetic susceptibility and the relationship between the imaginary part of AC magnetic susceptibility χ'' and the increase in temperature in the AC field was estimated. Effective heat dissipation for magnetic hyperthermia treatment in AC field depends on the magnetic relaxation parameters. The particle size and composition of the samples were varied and examined. Fig.1 shows the temperature dependence of the imaginary part of the AC magnetic susceptibility χ'' for the various particle size of $Mn_{0.8}$ $Zn_{0.2}Fe_2O_4$ nanoparticles in a 1 Oe, 100 Hz field. The peak shifted higher temperature as the particle size increased. As expected, most effective heat dissipation was observed for 18-nm samples.

We have carried out in vitro experiments using cultured human breast cancer cells. Magnetic nanoparticles were distributed on a cultured dish, and cell viability was evaluated. and a significant hyperthermia effect was observed. It was found that toxicity of magnetic nanoparticles was decreased by covering with PEG.

Spin echo MRI measurements for Mn-Zn ferrite nanoparticles were performed using a 0.3-T MRI system. The same particles showed effective relaxivity, R_2 values and significant contrast was observed in the phantom image.



P5 - Immuno-magnetic sorting of circulating tumor cells using microstructured NdFeB-PDMS composites

1. Biomagnetism and medical applications

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Circulating tumor cells (CTCs) are found to be valuable indicators of cancer stage. First the count of CTCs from blood has been clearly associated with bad prognosis in many cancer types. Besides, Epithelial-Mesenchymal Transition (EMT) phenotype of CTCs was found to favor invasiveness, immune escape and metastasis [1]. Last, the formation of CTC-clusters facilitates metastasis, as compared to isolated CTCs, so their presence is strongly correlated with a dramatically shorter overall survival time. In this context, monitoring CTCs can serve to analyze treatment response and carry out personalized therapy [2]. However, recovering CTCs from blood samples is challenging due to their scarcity: in 1 mL of blood, the number of CTCs varies from 1 to 3000, while the number of red blood cells (RBCs) and white blood cells (WBCs) is of 109 and 107, respectively. Microfluidic devices are interesting tools for cellular handling as they offer precise spatial and temporal control in a miniaturized environment compatible with cell or cell cluster size. Moreover, these devices can be easily made in low cost polymers such as polydimethylsiloxane (PDMS) using microfabrication tools. Among the different approaches to isolate CTCs, immuno-magnetic based micro-devices, combining antigen-antibody recognition and contactless magnetophoretic force, offer high selectivity and the possibility to recover living cells for subsequent analysis (drug testing, cell culture…)[3]. An external bulk magnet is often used to create a magnetic flux pattern, but larger gradients, so reachable forces, are obtained when integrating micrometer-sized magnetic flux sources in the close region of the fluidic channel.
Microstructure engineering of composites, made of magnetic particles and a polymer, can be an efficient way to integrate magnetic flux micro-sources in microfluidic devices, and breaks with standard microfabrication approaches [4]. Here we investigate mixtures of NdFeB particles with PDMS. During the reticulation of PDMS, a magnetic field pattern is used to create arrays of NdFeB particle agglomerates. Those structures of NdFeB can serve as magnetic traps. Depending on the NdFeB particle concentration, one can vary the traps size and density. In this work, the typical trap size is of 8 µm and the density is around 1000 mm-2. Figure 1(a-b) shows reconstructed 3D views from X-ray tomography, and a schematic of the microfluidic device. We first used model superparamagnetic microbeads (12 µm) to assess trapping performances of the composites under varying fluidic conditions. We then performed preliminary experiments to specifically immuno-capture WBCs. To do so, magnetic nanoparticles (300 nm) were functionalized with DL650 labeled anti-CD45 antibody, and incubated with WBCs. We observed efficient WBC trapping using NdFeB-PDMS composites in microfluidic devices (Figure 1 (c-d)). These results demonstrate the potential of this approach for the immuno-magnetic sorting of CTCs, either by positive selection, or by any negative selection through the capture of WBCs in pre-filtered blood sample.

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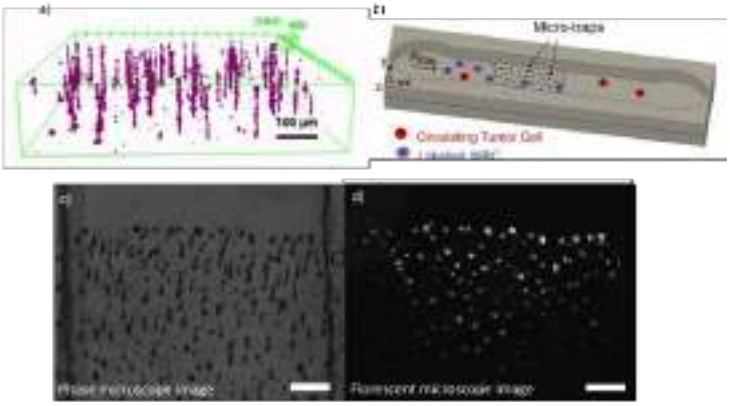

Figure 1. (a) Reconstructed 3D views from X-ray tomography performed on a volume of 648 x 648 x 15 μm³ of a NdFeB-PDMS composite membrane. (b) Schematic of the sorting device. (c-d) Phase and fluorescent microscope images of immuno-magnetically labeled MDCs (DL558 labeled anti-CD45 grafted on 300 nm magnetic particles) captured on micro-traps. The scale bar in (c-d) corresponds to 100 μm.

P6 - Influence of magnetic bead concentration on ferromagnetic resonance based detection

1. Biomagnetism and medical applications

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Recently, it was shown that magnetic patterned films based on antidot arrays can be employed as high-sensitivity magnetic field detectors, exploiting their dynamic behavior in the Gigahertz range. The sensing mechanism was demonstrated for the case of magnetic nanoparticles or beads adsorbed on the surface of permalloy nanostructured films [1-3]. In particular, the magnetic stray field generated by the particles interact with the magnetization state of the antidot array, producing a measurable shift in its ferromagnetic resonance (FMR) frequencies. The geometrical properties of the patterned film microstructure can be tuned to maximize the generated signal.
In this framework, we aim at investigating, from a modeling point of view, the dynamic response of permalloy antidot arrays with hexagonal lattice, in presence of different types of magnetic beads with variable size and saturation magnetic moment. Particular attention is given to the influence of bead concentration on the FMR signal, in order to determine a relationship useful for bead quantification. The calculation of the sensing element response is performed by means of an advanced micromagnetic solver, which was engineered to run on Graphics Processing Units to efficiently solve the Landau-Lifshitz-Gilbert equation [4]. The final spatial distribution of magnetic beads on the antidot array surface is predicted by means of a Newtonian dynamics model. This enables us to describe bead transport considering the effects of viscous drag force, the inter-bead magnetostatic interactions and the action of the magnetic force due to the antidot array.
The final objective is a parametric analysis, aimed at determining the effects of bead concentration on the sensing element FMR spectra, in order to define a quantification relationship associated with the shifts in the FMR frequencies of edge, extended and localized modes. As an example, the figure below shows the FMR response of a permalloy antidot array with circular holes (diameter of 330 nm and centre-to-centre distance of 500 nm), comparing the cases with different types of beads on the film surface. The bead presence produces a clear shift in the FMR frequencies (in the order of 0.5 GHz for complete hole-bead filling).

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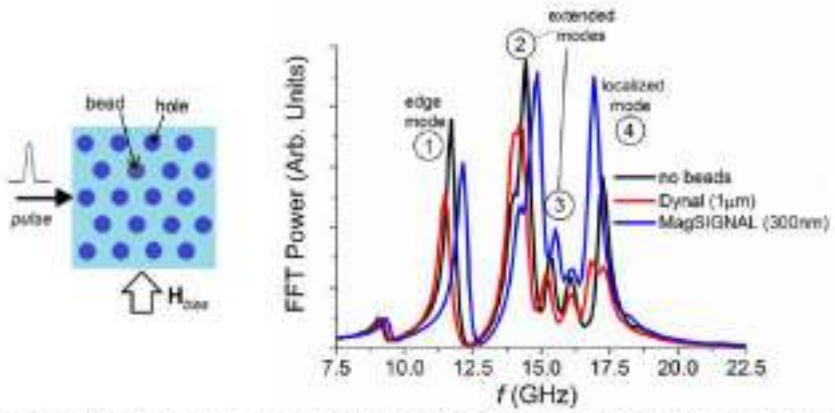

Comparison of ferromagnetic resonance spectra of a permalloy antidot array in presence and absence of magnetic beads with different size and magnetic moment.

P7 - Magnetic properties of Fe2O3 nanoparticles and naproxen in mesoporous silica for drug delivery

1. Biomagnetism and medical applications

Adriana Zeleňáková[1] , ***Jaroslava Szűcsová***[1], *Romana Palková*[1], *Ondrej Kapusta*[1], *Ľuboš Nagy*[1], *Dáša Halamová*[2], *Veronika Huntošová*[3], *Vladimír Zeleňák*[2]

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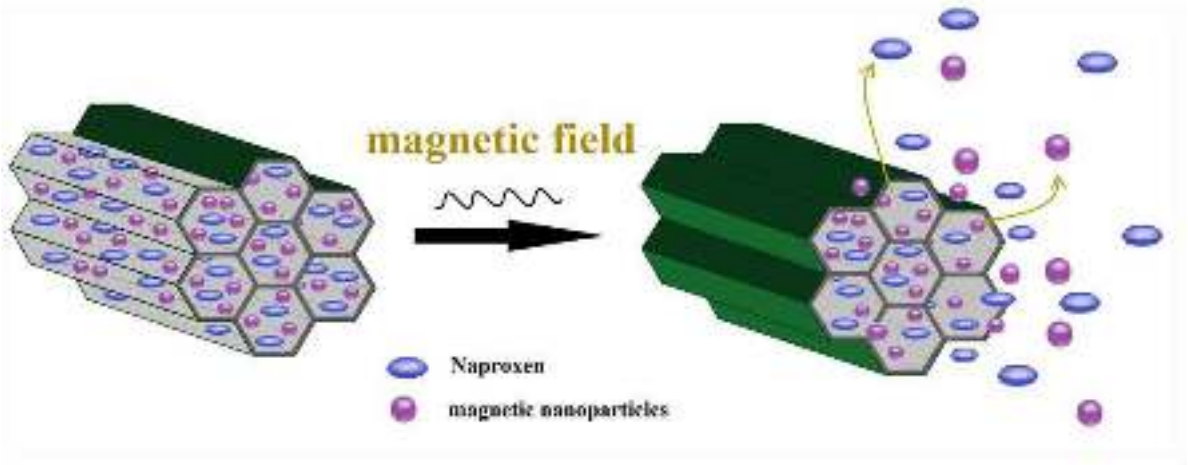
Over the past few years have been studied nanodevices based on nanoparticles, which are important in the delivery of drug into a biological system. The reason for the further study of nanoparticles is that delivery of the drug is not appropriate due to the impaired absorption of the drug or the tissue non-specific delivery. This is a disadvantage in the treatment of cancer. Therefore, development of new functional materials for the delivery, targeting and release of drug, and review of conditions of this process is necessary. The principle of drug delivery is based on a multi-component system comprising a drug and magnetic nanoparticles, which enable the control of drug delivery with the assistance of a magnetic field.

In this article we have focused on studying drug delivery system consisting of mesoporous silica MCM-41 anchored with magnetic nanoparticles Fe_2O_3 (sample MCM-41@Fe_2O_3) and naproxen (sample MCM-41@naproxen). The structural characteristics evaluated by TEM and dynamic light scattering method confirm that silica matrix control the growth of Fe_2O_3 MNPs and serve as nanoreactor for preparation of superparamagnetic iron oxide nanoparticles (SPIONs) with very low particle size distribution. The magnetic properties were studied by SQUID magnetometer in temperature range from 2-300 K in DC and AC external magnetic field up to 5T. The magnetic properties of composite MCM-41@Fe_2O_3@naproxen are determined by the properties of Fe_2O_3 nanoparticles loaded within nanopores. After encapsulation of the magnetic nanoparticles into the mesoporous silica the particles keep their superparamagnetic behaviour and could be used for vectored drug delivery using magnetic field and preparation of smart drug delivery systems. Magnetic properties of liquid sample (sample MCM-41@Fe_2O_3@naproxen in physiology solution with pH=7) are very similar to powdered sample showing that relaxation process is caused by Neel relaxation with very small contribution of Brown relaxation. The sample with magnetic nanoparticles exhibits high magnetic moment under the effect of magnetic field, but no remanent magnetic moment is present when the external magnetic field is removed. This property has advantage in *in vivo* applications. After therapy using external magnetic field, when the external magnetic field is switched off, the magnetic dipoles of the SPION nanoparticles randomize and zero net magnetic moment is spontaneously recovered.


magnetic field
Naproxen
magnetic nanoparticles

P8 - Magnetic studies on Mn-Zn ferrite nanoparticles internalized into cells

1. Biomagnetism and medical applications

Andrea Gálisová[1] , *Lenka Kubíčková[2, 3], Ondřej Kaman[2, 4], Jarmila Kuličková[2], Magda Vosmanská[5], Ivan Leontovyč[1], Vít Herynek[6],* ***Zdeněk Jirák***[2]

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Internalization of magnetic nanoparticles into living cells is a crucial prerequisite for certain biomedical applications, namely for cell tracking and monitoring of labelled structures by MRI and MPI and for remote manipulation of cells by external fields in cell therapy and regenerative medicine. Although tremendous effort has been devoted to develop efficient procedures for preparation of nanoparticles with controlled shape and size and diverse biocompatible coatings, rather little attention has been paid to analyse magnetic properties of the internalized particles and to investigate their intracellular breakdown, with rare exceptions such as [1]. The present study is focused on the quantitative analysis of cell-internalized Mn-Zn ferrite nanoparticles.

Magnetic nanoparticles of the composition $Mn_{0.62}Zn_{0.41}Fe_{1.97}O_4$ (MZF) and the mean size of crystallites 11 nm were synthesized under hydrothermal conditions [2]. The MZF particles were coated by silica (MZF@sil), mesoporous silica (MZF@m-sil), mesoporous titania (MZF@m-tit) or were stabilized by citrate (MZF@cit), see [3,4] and references therein. An additional sample was prepared by combining the citrate-stabilized particles with mannose (MZF@cit-Man) to facilitate the uptake by cells [5]. Then, human pancreatic cancer cells PANC-1 were incubated with the differently coated samples at the concentration of 0.2 mmol($Mn_{0.62}Zn_{0.41}Fe_{1.97}O_4$)/L for 48 h, after which only the adhered cells were harvested, washed three times with a buffer to remove uninternalized particles and counted. The experiments were accompanied by a negative control and evaluation of cell viability and growth for all experiments. The cell samples were subjected to SQUID magnetometry after drying and to chemical analysis by ICP-MS after mineral digestion.

The independent determinations of Mn, Zn and Fe by ICP-MS led to the sums of 1.8, 8.1, 11.3, 11.4 and 14.1 pg(Mn+Zn+Fe)/cell, as corrected on negative control, for the MZF@sil, MZF@m-sil, MZF@m-tit, MZF@cit and MZF@cit-Man, respectively. In contrast, the saturated magnetic moment of the samples, carefully corrected on mounting material and dry cells, provided the estimates of 2.3, 9.5, 11.4, 8.04 and 8.21 pg(Mn+Zn+Fe)/cell under an assumption that magnetic cores remained intact and retained the magnetization of bare sample. The considerably lower estimates for the MZF@cit and MZF@cit-Man are obviously related to partial dissolution of magnetic cores covered only by an organic monolayer. At the same time, the ZFC-FC susceptibilities provided insight into the magnetic state and size of particles internalized in the cells, for illustration see Fig. 1. For citrate-stabilized particles, the bifurcation of ZFC-FC curves demonstrated a considerable shift of blocking temperatures to lower temperatures compared to initial coated samples.

In conclusion, mesoporous silica, mesoporous titania or citrate monolayer ensured high cellular uptake of nanoparticles. While silica and titania ensured core stability intracellularly, the citrate-stabilized particles were probably partially dissolved and may not represent a safe cellular label.

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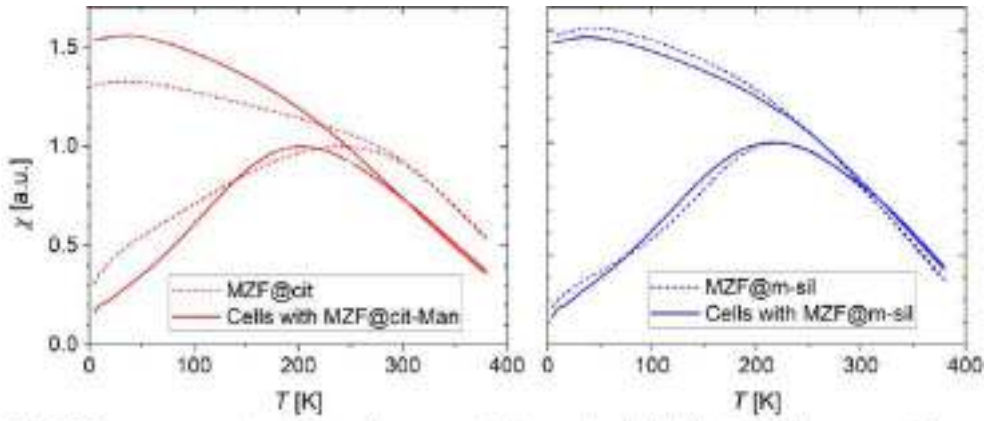

ZFC-FC measurements of magnetic nanoparticles and cells labelled with the nanoparticles at H = 20 Oe. The susceptibilites are normalized to χ = 1 at the maximum of the ZFC curve.

P9 - Modelling of magnetic bead transport in a microvascular network

1. Biomagnetism and medical applications

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Magnetic nanoparticles can be advantageously used as MRI contrast agents or mediators for hyperthermia treatment, as well as to label, deliver and separate biomaterials, mainly thanks to the capability to be magnetically manipulated, independently of microfluidic and biological processes [1]. In *in vivo* applications one crucial aspect is the control of their transport in the tissue microvasculature and their release to target areas, mechanisms that can be driven by external magnetic field gradients [2]. Experimental results can be interpreted with the aid of *in silico* simulations that can also be employed in the design of novel nanosystems and set-ups for drug delivery. In this framework, we have developed a numerical model that enables us to calculate the trajectory of an ensemble of magnetic nano/microbeads injected in a blood vessel and manipulated by an applied magnetic field. The model is based on the coupling of the Navier-Stokes equations for the fluid dynamics problem with classical Newtonian formulation for bead motion [3]. The physical phenomena included in the model are: the magnetic force generated by the external field; the viscous drag force due to the interaction with blood flow; the magnetostatic dipolar interactions between nearby beads; the steric repulsive force due to the stabilizing effect of the surface coating layers [4]; the surface interactions with the vessel epithelium (collision and adhesion processes) [5]. The blood velocity profile in the vessel is obtained by solving the Navier-Stokes equations with finite element method, under the hypothesis of laminar flow and negligible velocity perturbation due to beads. Collision and adhesion dynamics for nano/microbeads close to vessel walls are simulated with a probabilistic approach, by calculating an adhesion probability function that takes into account the size of the beads, their instantaneous orientation with respect to the vessel surface, the densities of ligands on bead surface and of receptors on the endothelial substrate.
The developed numerical model is applied to study the influence of bead properties (size and magnetic moment) on transport, aggregation and adhesion processes, focusing on specific spherical nano/microbeads with magnetization curve approximated with Langevin function. Particular attention is given to the study of different arrangements for the external field sources in order to optimize the bead accumulation at vessel walls, process driven by magnetic force. The analysis of bead motion is done in realistic 3D vessel geometries reconstructed by means of the Vascular Modelling Toolkit (VMTK) Software.
As an example, the figure shows the results obtained for a set of 100 nanobeads with 300 nm size and 0.002 pAm^2 saturation magnetic moment, injected in a vessel with an average cross section radius of 50 µm. The magnetic field is produced by an external cylindrical magnet, in close proximity to the vessel.

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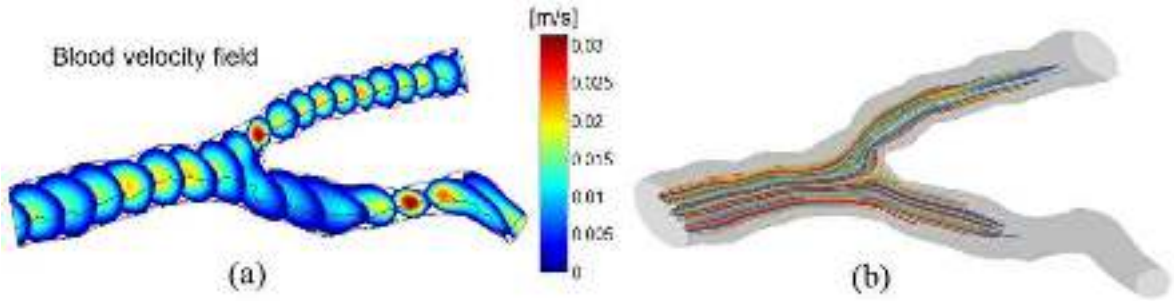

(a) Blood velocity field in a vessel segment extracted from a CT image of the abdomen. (b) Bead trajectories in the vessel segment after 30 ms from the injection.

P10 - Spatial distribution imaging of magnetic nanoparticles using pickup coil array

1. Biomagnetism and medical applications

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Magnetic particle imaging (MPI) is a new in-vivo biomedical imaging technique that uses the characteristics of nonlinear magnetic response of magnetic nanoparticles (MNPs), and many types of MPI systems have been proposed. The previously reported MPI system employ an additional DC gradient field to achieve high spatial resolution. In this case, the system requires a gradient coil that can generate a strong field gradient (typically 1–2 T/m), and coils should be arranged surround the target, or patients. Thus, the previous MPI system can apply only small animals, e.g., mouse and rat. Moreover, the fast changing gradient fields by moving the gradient field would cause peripheral nerve stimulation and implant heating.

In this study, we propose the spatial distribution imaging system that do not require gradient field coils. To achieve this, we employ a lot of pickup coils, i.e., pickup coil array. In this study, we used 16 pickup coils. Furthermore, we propose the method to increase the position information of the MNP samples by changing the amplitude of the ac magnetic field. Because the magnetization curve of the MNPs is nonlinear, the harmonic signal changes by the amplitude of the ac magnetic field. The increase of the information will improve the stability of the inverse problem.

Figure 1(a) shows the arrangement of the excitation coil and pickup coils. The number of turns of excitation and pickup coils were 50 and 5400, respectively. The excitation coil has a height of 20 mm, and inner and outer diameters of 200 mm and 280 mm, respectively. The pickup coil has a height of 6 mm, and inner and outer diameters of 2 mm and 8 mm, respectively. The detection direction of the pickup coils were x or y direction so that the magnetic flax generated by excitation coil does not across the pickup coils directly. The Resovist MNP samples containing 100 μg of Fe were arranged at (25 mm, -15 mm, -30 mm) and (25 mm, 0 mm, -30 mm), and the third harmonic signals obtained from pickup coils were measured by changing the current to 1, 2, …, 20 A for every 1 s. Then, the inverse problem is solved.

Figure 1(b) shows the estimated distribution of the MNP concentration. The open circles represent the positions and the sizes of the two MNP samples. As shown, two maxima were obtained in the MNP concentration. These maxima approximately correspond to the two MNP samples, and their positions are shown to be clearly separated. Thus, this result demonstrates that the positions of the two MNP samples with a spacing of approximately 10 mm were estimated with good accuracy without the gradient field coil and the measurement time is short.

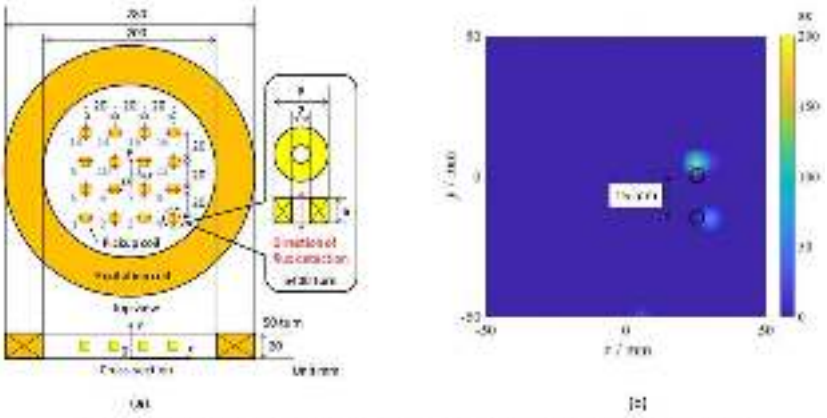

Fig. 3. (a) The arrangement of the coils and (b) the estimated distribution of the MNP concentration when the MNP samples were arranged at (25 mm, -15 mm, -10 mm) and (25 mm, 0 mm, -10 mm).

P11 - TMek: magnetophoretic capture of malaria infected red blood cells and hemozoin crystals

1. Biomagnetism and medical applications

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The most relevant methodologies for malaria diagnosis concern the direct parasite investigation by a microscopic examination (Gold Standard) and the indirect antigen detection implemented by rapid diagnostic tests (RDTs). Nevertheless, GS requires a lot of time for the process diagnosis with trained personnel and RDTs register a high number of false positives. TMek aims at developing a compact, low cost and easy to use diagnostic system, which allows a pan-plasmodic and rapid malaria detection, as sensitive and accurate as the GS.

The physical concept is that of exploiting the paramagnetic property of malaria infected erythrocytes and hemozoin crystals [1], which allows them to undergo a selective magnetophoretic separation driven by a magnetic field gradient. Upon separation, they concentrate at the surface of micrometric gold interdigitated electrodes placed in close proximity to magnetic concentrators whereas, healthy ones sediment under the action of gravity. Then, a change in resistivity, proportional to the amount of attracted particles, can be detected as an impedance variation by an electronic circuit, following a lab-on-chip approach.

The capability of the TMekdevice of performing the magnetophoretic separation has been tested by means of several capture experiments with treated bovine red blood cells. The blood treatment, which consists on turning the hemoglobin (diamagnetic) into methemoglobin (paramagnetic) [2], is achieved by a chemical preparation that involves the treatment of healthy erythrocytes with NaNO2 solution.

The experimental setup is composed by an inverted and fluorescence images (Fig 1) are taken in order to evaluate the capture efficiency defined as the ratio between the number of t-RBCs captured by nickel the number onto the chip surface with respect to the total number of RBCs.

One of the goals of these experiments was the determination of the best layout for the Ni array among the “20_80”, “20_160”, “40_80” and “40_160” geometries (Fig 2). The best geometry, which allows level of capture efficiency, within 10 minutes, of around 80-90%, is composed by an hexagonal layout of Ni cilinders of 20 µm height, with a diameter of 40 µm and a relative spacing between their centers of 160 µm. The fabrication processes involved in the realization of the nickel (Ni) concentrators array have been performed in Polifab cleanroom facilities.

Once designed through optical lithography, the cylindrical pillars are etched in a doped silicon (Si) substrate using Reactive Ion Etching and filled with Nickel electrodeposition technique.

In order to remove the overfilled nickel a polishing step, with a roughness lower the 50nm, is required.

An insulating layer (SiO_2) of 3µm thickness is deposited in order to electrically isolate the magnetic and electric layers.

Interdigitated electrodes are then fabricated using optical lithography and metal deposition techniques and designed in order to maximize the electrical signal.

The experimental setup consists on a motorized setup, for a repeatable standard movement of the permanent magnets, with low noise analog lock-in amplifier embedded. Different configuration angles of the setup with respect to the horizontal have been studied trough COMSOL simulations and tested in order to achieve the best capture efficiency.

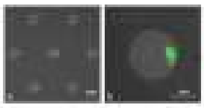

Fig. 2. Images of infected i-RBCs attracted by nickel concentrators in a "50_100" layout with a (10x) (a) and a (40x) (b) magnification.

Fig. 3. Capture efficiency dynamics for different layouts.

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P12 - Tuning the Curie temperature in amorphous alloys by current annealing for biomedical applications

1. Biomagnetism and medical applications

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Soft magnetic amorphous microwires are recently proposed as miniature temperature-sensitive elements for embedded sensor applications operating in the industrial temperature range of -20 – 100 [1]. In particular, such sensors are in high demand for controlling the inflammatory processes in various implants. The sensor operation is based on the dependence of magnetic properties on the proximity to the Curie temperature, . In particular, a sharp change in high-frequency impedance near can be used for developing MI-temperature sensors [2]. Other biomedical applications include hyperthermia methods with the use of ferromagnetic particles, for which controlling the Curie temperature in the range of 40 – 60 would be of considerable interest. To set the value of in the required temperature range, the alloys with additions of Cr, Ni, Mo can be used [3]. In the present paper, fine tuning of in low-Curie temperature microwires of composition FeCoBSiNi was realized by current annealing.

Physical properties of amorphous alloys produced by rapid quenching are significantly changed by annealing at temperatures lower than the crystallization temperature owing to structural relaxation. Modifications in chemical and topological short range orderings during annealing is responsible for the Curie temperature change. Kinetics of structural relaxation along with a randomizing effect dominating at higher annealing temperatures may result in a non-monotonic behavior of with respect to the annealing time and temperatures. This gives an opportunity to determine the annealing conditions to set a desirable value of and obtain an abrupt change in the magnetic behavior just below the Curie temperature. Current annealing was proposed to control the Curie point of amorphous $Fe_5Co_{27.4}B_{12.26}Si_{12.26}Ni_{43.08}$ microwires having a Curie temperature of 47 ^{o}C in as-prepared state and the crystallization temperature of 472 ^{o}C. The samples under investigation had a total diameter of 36 μm and a metal core diameter of 31 μm.

The current annealing was done in air atmosphere for different times (10-60 minutes), the current magnitude was in the rage of 50 to 110 mA, which produced the heating effect of 150-450^{o}C. The Curie temperature was deduced from measuring the initial permeability vs. temperature by RLC meter combined with a heating chamber. The value of almost linearly increases with increasing the current magnitude from 50 to 95 mA reaching a value of 80.5 ^{o}C. Further increase in the current magnitude produces a little change since the onset of crystallization is reached.

It is concluded that the step-current annealing is proposed as a simple and efficient technique to modify the Curie temperature of amorphous microwires.

Fig. 1. Dependence of the Curie point (T_C) of amorphous $Fe_5Co_{27.4}B_{12.26}Si_{12.26}Ni_{43.08}$ microwires on annealing current magnitude (annealing time was 60 minutes).

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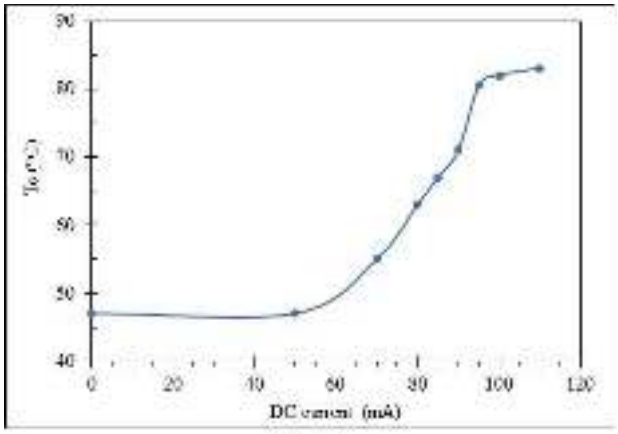

Figure 1

P13 - Viscosity-independent method for thermometry based on harmonic signals of Magnetic Nano Particles

1. Biomagnetism and medical applications

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Magnetic nanoparticles (MNP) thermometry has been extensively studied for remote and *in vivo* biomedical applications, such as thermally controlled drug release and hyperthermia cancer therapy. The MNP thermometry relies on temperature dependence of the MNP magnetic properties, e.g. harmonic signals generated by an AC excitation field. Temperature measurement is performed by calibration curves obtained in advance by measuring the temperature dependence of harmonic ratios, e.g. ratio of third and fundamental harmonics M_3/M_1 or fifth and third harmonics M_5/M_3. Here, the calibration curves have been modeled for MNP in water solution. Since viscosity, η, for practical *in vivo* applications is actually higher than the viscosity of water, it is important to investigate the effect of η on MNP harmonic signals in order to realize a viscosity-independent thermometry method.

In this work, we proposed a method to accurately estimate η of MNP samples from the measured harmonic signals even when viscosity of the sample is not known beforehand. The estimation of η can be used with calibration curves to realize a viscosity-independent thermometry method. We used four samples containing 800 μg (Fe) of MS1, which was obtained by magnetic fractionation of Resovist MNP sample (FUJIFILM RI Pharma) so as to have large moment values. The first sample consisted of MNP with pure water with η = 0.89 mPa**.**s. The other three samples contained an added amount of glycerol content 15%, 30%, and 45% of the total sample volume, which corresponds to η = 1.44, 2.57, and 5.2 mPa**.**s, respectively.

First, we investigated effect of η variation on harmonic ratios, i.e. M_3/M_1 and M_5/M_3. For this purpose, we define $R_{13}(\eta)=M_3(\eta)/M_1(\eta)= R_{13w}.g_{13}(\eta)$, with $R_{13w}=M_{3w}/M_{1w}$, where R_{13w} is the ratio for water solution sample, and $g_{13}(\eta)$ represents the effect of η. Similarly, for M_3 and M_5, we define $R_{35}(\eta)=M_5(\eta)/M_3(\eta)= R_{35w}.g_{35}(\eta)$, with $R_{35w}=M_{5w}/M_{3w}$. The dependences of g_{13} and g_{35} on η are shown in Fig. 1(a) when an AC excitation field of $\mu_0 H$=2.5 mT and f=11 kHz is used. As shown, 12.5% increase of g_{13} was measured over η range from 0.89 to 5.2 mPa**.**s. On the other hand, 1.8% decrease of g_{35} was measured. This demonstrates the dependence of harmonic ratios on η.

Next, we developed an iterative procedure to estimate η value using g_{13} and g_{35} curves shown in Fig. 1(a). Figure 1(b) shows the result of the iterative procedure when we estimate the viscosity of the samples with 15% and 30% glycerol content. Horizontal axis represents the iteration number i, while the vertical axis shows estimated η_i value for each iteration. In this procedure, initial η value is assumed to be that of water (η_w), i.e., $\eta_1=\eta_w$= 0.89 mPa**.**s. As shown in Fig. 1(b), η_i converged to certain values. The converged values were η = 1.44 and 2.58 mPa**.**s for 15% and 30% glycerol content samples, respectively, which agreed very well with the actual values. From the present method we can accurately estimate η value, and it enables us to estimate the temperature of the MNP sample of unknown viscosity.

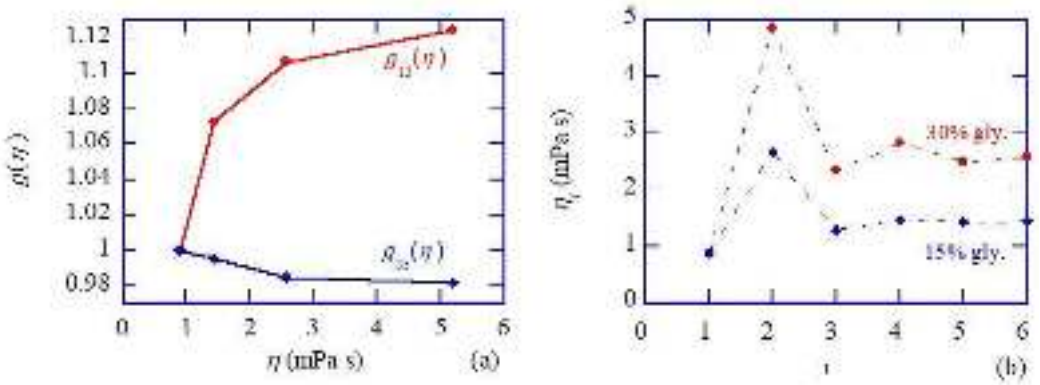

Fig. 1. (a) Dependences of g_{12} and g_{35} on η when AC excitation field with $\mu_0 H = 2.5$ mT and $f = 11$ kHz is applied. (b) Estimated viscosity vs iteration number.

P14 - Wash-Free Detection of Biological Target Utilizing Agglomerate Formation of Magnetic Markers

1. Biomagnetism and medical applications

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Immunoassay has been widely used for medical diagnosis to detect biological targets, such as disease related proteins and cells. We have been developing a wash-free detection of biological targets using bio-functionalized magnetic nanoparticles (or magnetic markers). In this method, markers that are bound to the targets (bound markers) are magnetically differentiated from unbound (free) markers by using Brownian relaxation of the markers. Hence, time consuming washing process for Bound/Free (B/F) separation can be eliminated.

Figure 1(a) shows the principle of wash-free detection of targets. For the wash-free detection, it is necessary for the Brownian relaxation time of the bound markers to be much longer than that of the free markers. In order to prolong the relaxation time of the bound marker, we utilize an agglomerate of bound markers, which is formed via the binding reaction between the detection antibody and the target. In the present study, C-reactive protein (CRP) was used as targets. The magnetic markers were made from magnetic nanoparticles (FG beads, Tamagawa Seiki) that were conjugated with CRP antibodies. As shown in Fig. 1(a), two types of markers conjugated with C2 and C6cc CRP antibodies were used. These markers were put into sample solution, and incubated for 60 min. After the binding reaction between targets and antibodies is finished, agglomerate of the bound markers is formed, as shown in Fig. 1(a). The Brownian relaxation time of the free markers, whose diameters are approximately 160 nm, is as short as 1.6 ms. On the other hand, the relaxation time of the agglomerate of the bound markers becomes much longer than 1 s.

After sample preparation, we detected magnetic signal from the sample. In the experiment, an excitation field with strength of 1 mT was applied to the sample in order to magnetize the markers. Then, the excitation field is turned off. The signal from the sample was measured 1.5 s after the excitation field was turned off. At this time, signal from the free markers decayed to zero due to Brownian relaxation, and only the signal from the bound markers can be detected. The signal was measured with a magnetoresistive (MR) sensor (HMC1001, Honeywell). Figure 1(b) shows detection result when the concentration of CRP was changed between 0.01-100 ng/mL. The vertical axis represents the signal detected with the MR sensor. As shown in Fig. 1(b), we obtained good correlation between the detected signal and the concentration of CRP. The detection limit was as low as 0.01 ng/mL. This result indicates the validity of the present method for wash-free detection of targets.

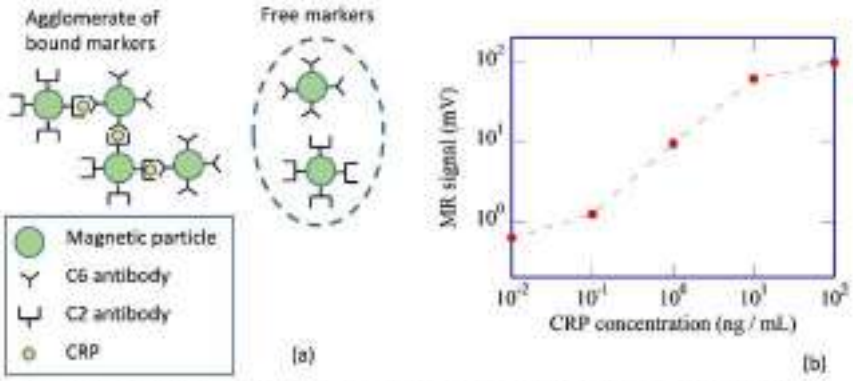

Fig. 1. (a) Principle of wash-free detection using agglomerate formation of magnetic markers. (b) Detection result of CRP.

2. Electronic structure and strongly correlated electron systems including superconductivity

P15 - S=1/2 coupled tetramer system Ba(TiO)Cu4(PO4)4 probed by magnetization, specific heat, and 31P-NMR

2. Electronic structure and strongly correlated electron systems including superconductivity

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The author has chosen not to publicise the abstract.

Field 5

Field 6

P16 - Structural, magnetic and transport properties of polycrystalline La0.60-xPrxCa0.40MnO3 manganites

2. Electronic structure and strongly correlated electron systems including superconductivity

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Among the doped rare earth manganites $La_{1-x-y}Pr_xCa_yMnO_3$ (LPCMO) has been recognised as the prototypical of the phase separated doped rare-earth manganites. As the band width (BW) is reduced, the tendency towards phase separation has been observed due to the occurrence of multiple magnetic phases coexisting, like charge-order antiferromagnetic (CO/AFM), charge-disordered paramagnetic (PM) and ferromagnetic phase (FM) phase. LPCMO has emerged as the most widely investigated phase separated manganite system. So, we have investigated the structural, magnetic and transport properties in low bandwidth manganites like $La_{0.60-x}Pr_xCa_{0.40}MnO_3$ system. Pr doped $La_{0.60-x}Pr_xCa_{0.40}MnO_3$ (LPCMO) (x = 0.30, 0.35, 0.40, 0.45) materials have been synthesized by using solid state method. Phase pureness is confirmed by Retiveld refinement of the powder X- ray diffraction (XRD) data, which authenticates orthorhombic structure with ***Pnma*** space group. All three lattice constants and bond lengths decrease with Pr doping. The magnetization measured (H@100 Oe) as a function of temperature exhibits paramagnetic (PM) to ferromagnetic (FM) transition and the divergence between the zero field cooled (ZFC) and FCC magnetization curve. The isothermal magnetization loops reveal the saturated magnetization at low temperature (5K). The temperature dependent resistivity of all samples have been measured without magnetic field and resistivity measurements show the insulating behaviour up to 60 K under zero magnetic field. The data of resistivity have been fitted by using variable range hopping model (VRH). Characteristic temperature (T_o), localization length (1/α) and average hopping distance (R) have been calculated by using this model. X-ray photoemission spectra of Mn2p and Mn2s core-level confirm dual valence state of Mn (Mn^{3+} and Mn^{4+}), which is responsible for the magnetic behaviour of LPCMO system. The correlation between the transport and observed magnetic properties of LPCMO samples will be described and discussed in paper.

P17 - Electronic structure and phase transitions induced by magnetic field and spin fluctuations in MnSi

2. Electronic structure and strongly correlated electron systems including superconductivity

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MnSi is one of the most well experimentally studied chiral ferromagnets without an inversion center. The Dzyaloshinsky – Moriya interaction leads to the appearance of a spin helix and to the skyrmion phase in a certain range of fields and temperatures. In weak external magnetic fields, the skyrmion phase does not appear. The strongly correlated ground state of MnSi is characterized by large zero fluctuations, which lead to the appearance of a crossover of quantum and thermodynamic phase transitions from the ordered phase of spin spirals to a paramagnetic state with helical short-range order.

We consider the strongly correlated system of degenerate d-electrons of MnSi in an external magnetic field, in which the skyrmion phase is formed. It is shown that the inclusion of an external magnetic field under these conditions leads to the suppression of zero fluctuations and an abrupt increase in entropy. In this case, the chemical potential of the system under consideration turns out to be in the region of the local minimum at the broad energy maximum of the density of electronic states (DOS). Mode-mode coupling parameter change sign. Phase transition occurs induced by the suppression of zero fluctuations and skyrmion A-phase arises. The solutions of the equations of the magnetic state, taking into account the features of the DOS near the Fermi level, were obtained. It describes the occurrence of inhomogeneous magnetization in the direction of the field and the observed rotation of the wave vector. We obtain that the vortex spin microstructure appears in the region bounded by the radius of spin correlations. It is shown that an with increasing temperature the thermal spin fluctuations leads to a first-order thermodynamic transition, accompanied by the sudden disappearance of the modulus of inhomogeneous magnetization. The transition to the paramagnetic state is accompanied by the appearance of a maximum of the uniform magnetic susceptibility and an entropy jump. Such a change in the electronic structure near the energy position of the chemical potential leads to the formation of a dip in the temperature dependence of the uniform magnetic susceptibility inside the A phase and was observed experimentally. We find that a shift of the Fermi level due to a change in the concentration of d-electrons can lead to the disappearance of the region of existence of the A-phase. It was observed for MnSi doped with iridium.

P18 - Energy structure of the spin-polaron quasiparticles in the systems with strong spin-fermion coupling

2. Electronic structure and strongly correlated electron systems including superconductivity

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Nowadays, it is established that the strong interaction between the oxygen holes and the localized copper spins causes the complicated behavior of the spectral and transport properties of cuprate superconductors. These strong spin-fermion correlations underlie the formation of the spin-polaron quasiparticles. In the work, taking into account the realistic crystalline structure of the copper-oxygen plane within the spin-fermion model and using the equation of motion technique, the spin polaron concept of the fermionic excitations in cuprate superconductors is implemented. On the base of the exact solution of the integral equation, it is shown that the self-energy part can be represented as a sum of two terms. The first term is connected with the one-cite correlations. The second term is induced by the contributions connecting with the quantum spin liquid state of the localized copper spins. The calculated energy structure consists of three branches. The lower branch is characterized by a minimum near point (π/2, π/2) of the Brillouin zone in accordance with the experimental data on cuprates. This energy branch is separated considerably from the two upper branches. The appearance of the lower branch is caused by the strong spin-fermion coupling which induces the exchange interaction between holes and localized spins at the nearest copper ions, as well as spin-correlated hopping.

P19 - Exotic specific heat anomaly in GdY: true 5/2–order transition, arises from the Lifshitz transition

2. Electronic structure and strongly correlated electron systems including superconductivity

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The order–order magnetic phase transition "helical antiferromagnet – ferromagnet" in Gd_XY_{1-X} system is believed to arise from the underlying Lifshitz electronic topological transition. This magnetic transition have been examined by means of the specific heat vs. temperature. The observed anomaly in the specific heat, unexpectedly, follows not the ordinary second–order transition behavior but the exotic second–and–a–half–order behavior, characteristic for the Lifshitz transition in temperature.

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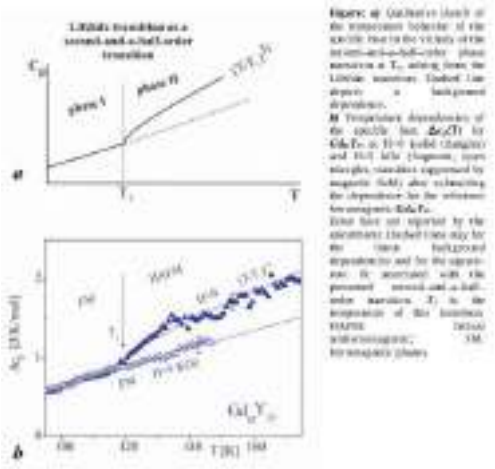

P20 - Harmonic voltage response to AC current in the nonlinear conductivity of iridium oxide Ca5Ir3O12

2. Electronic structure and strongly correlated electron systems including superconductivity

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$Ca_5Ir_3O_{12}$ has a hexagonal structure with noncentrosymmetric space group of (No. 189). In the structure, 1D chains of the edge-sharing IrO_6 octahedra form triangular lattices in the *c*-plane, as shown in Fig. 1. The average valence of Ir ions in $Ca_5Ir_3O_{12}$ is +4.67, so Ir^{4+} and Ir^{5+} exist in a ratio of 1:2. This situation can lead to the geometrical frustration of charge on both the triangular lattice in *c*-plane and 1D chains along the *c*-axis [1]. It is reported that $Ca_5Ir_3O_{12}$ exhibits an antiferromagnetic below 7.8 K and a second-order phase transition at 105 K [1]. The origin of this phase transition at 105 K is not clear at present; this is "hidden order" [1]. Recently, nonlinear electrical conductivity along the *c*-axis in a single crystal of $Ca_5Ir_3O_{12}$ is discovered even above 105 K [2].

To investigate the nonlinear electrical conductivity along the *c*-axis in detail, we performed harmonic voltage response experiments by application of sine-wave current. By using AC current, we can accurately measure the electrical conductivity when a small current is applied. Odd harmonics were observed below 200 K. The presence of harmonics means distortion of waveform, which is a proof of nonlinear conductivity. We will report this experiment results in this presentation.

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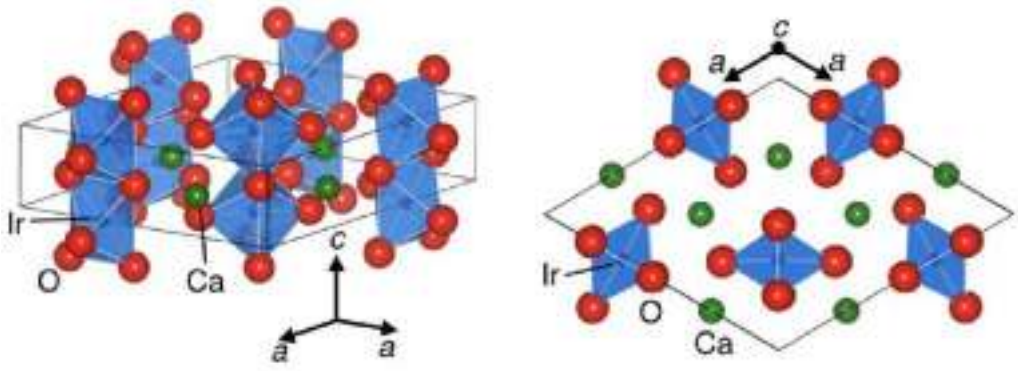

Fig. 1 Crystal structure of $Ca_5Ir_3O_{12}$.

P21 - Heavy quasiparticle bands in the underscreened quasiquartet Kondo lattice

2. Electronic structure and strongly correlated electron systems including superconductivity

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We study the quasiparticle spectrum in an underscreened Kondo-lattice (KL) model that involves a single spin degenerate conduction band and two crystalline-electric-field (CEF) split Kramers doublets coupled by both orbital-diagonal and non-diagonal exchange interactions. We find the three quasiparticle bands of the model using a constrained fermionic mean field approach. While two bands are similar to the one-orbital model a new genuinely heavy band inside the main hybridization gap appears in the quasiquartet model. Its dispersion is due to effective hybridization with conduction states but the bandwidth is controled by the size of the CEF splitting. Furthermore several new indirect and direct hybridztion gaps may be identified. By solving the selfconsistency equation we calculate the CEF-splitting and exchange dependence of effective Kondo low energy scale, hybridization gaps and band widths. We also derive the quasiparticle spectral densities and their partial orbital contributions. We suggest that the two-orbital KL model can exhibit mixed CEF/Kondo excitonic magnetism [1].

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P23 - LE-μ+SR Study of Superconductivity in the Thin Film Battery Material LiTi2O4

2. Electronic structure and strongly correlated electron systems including superconductivity

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The spinel oxides display a wide range of interesting physical properties, e.g. exotic magnetism; charge ordering, and superconductivity. Among them, spinel lithium titanates have attracted a lot of attention, indeed as a superconductor ($LiTi_2O_4$), but recently also as an electrode material for Li-ion batteries ($Li_4Ti_5O_{12}$). For $LiTi_2O_4$ the spinel crystal structure is face-centered cubic, the Li and Ti atoms are located at the positions of tetrahedral and octahedral sites, respectively. As a superconductor $LiTi_2O_4$ displays a transition temperature T_C~12 K. Band calculations reveal that conduction band states are mainly coming from Ti-3d bands which lie about 2–3 eV above the O-2p bands. This is a very peculiar feature since in other transition-metal spinels d and p orbitals usually hybridize and cross the Fermi level.

The published literature on $LiTi_2O_4$ is rather controversial with quite some discrepancies, which constitute a crucial impediment for understanding superconductivity in this system. The main reason is that the superconducting properties in $LiTi_2O_4$ were shown to be very sensitive to the exact composition, especially the Li/Ti stoichiometry. Consequently, a reproducible synthesis of $LiTi_2O_4$ samples (especially powder and single crystals) is very delicate. For the current study, high-quality stoichiometric $LiTi_2O_4$ epitaxial films were deposited by a pulsed laser deposition (PLD) technique using $MgAl_2O_4$ (111) substrates **[1]**. This substrate was chosen because spinel $MgAl_2O_4$ has a 4% smaller in-plane lattice constant than $LiTi_2O_4$. This is interesting since for other similar systems a compressive strain has been shown to increase the transition temperature. The high quality of the samples is highlighted by our resistivity measurements, which display a very sharp superconducting transition at T_C ~ 11.5 K. We have further performed the very first low-energy muon spin rotation study of such films **[2]**. By employing both vortex and Meissner state protocols we directly extracted the superconducting properties including the London penetration depth as a function of both temperature and muon implantation depth from surface to bulk. For temperatures T < Tc = 11.5 K the superconducting order parameter does not fit to a standard BCS model, which indicate a more exotic type of superconductivity in $LiTi_2O_4$ thin films **[3]**.

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P24 - Magnetic orderings and ability to investigate correlated electrons phase diagram in Mott insulators

2. Electronic structure and strongly correlated electron systems including superconductivity

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Non-collinear antiferromagnetic orderings in Mott insulators Nd_2CuO_4 of tetragonal symmetry are of interest in investigations of temperature-concentration phase diagrams of antiferromagnetic, spin, charge density waves and superconducting states of correlated electrons in $Nd_{2-x}Ce_xCuO_{4\pm\delta}$, when additional electrons are introduced, that is concerned with discussions of resonating valence bond, stripe states and High Temperature Superconductivity in Mott insulators. Non-collinear antiferromagnetism of ordered and polarized-ordered magnetic moments of four Cu ions and four Nd ions in magnetic unit cells of Nd_2CuO_4, with T_N(Cu) ~254K and T_N(Nd) ~3K is investigating with discussions of magnetic field dependencies of M_x(H,T) and M_y(H,T) separate components of samples magnetic moments, along and perpendicular to magnetic field, which were obtained using vector v.s.magnetometer. Magnetic phase transitions of non-collinear antiferromagnetic orderings of polarized-ordered and ordered magnetic moments of interacting Nd, Cu–Nd and Cu ions in Nd_2CuO_4**,** in magnetic fields H_{c1} ~42kOe at T ~1.8K, which are difficult to indicate in magnetic field M_x(H,T) dependencies, when magnetic fields are oriented along [110] axis, Fig.1a, are indicating by appearance of magnetic field M_y(H,T) dependencies, when magnetic fields are oriented at small "±" angles with respect to [110] axis, Fig.1b. Appearances of magnetic field M_y(H,T) dependencies of Nd_2CuO_4 in magnetic fields H_{c1} with maximums in fields H ~46kOe and next diminishing of magnetic field M_y(H,T) dependencies to zero values in high magnetic fields, at saturations of magnetic field M_x(H,T) dependencies to ~$2M_0$(Nd) values, with M_0(Nd) ~1.42μ_B, conditional by lower Kramers doublets of Nd ions in crystal fields, are determined by destruction of polarized non-collinear antiferromagnetic ordering of Nd ions at distraction of non-collinear antiferromagnetic orderings of Cu ions with orientations of ordered Cu magnetic moments perpendicular to magnetic fields in high magnetic fields. Magnetic field M_x(H,T) and M_y(H,T) dependencies, which are determined by polarization of Nd magnetic moments by ordered Cu ones with non-orthogonal orientations of ordered Cu magnetic moments with respect to magnetic fields, and magnetic fields H ~42-46kOe, are determined by effective fields of magnetic anisotropic interactions of Cu ions and effective fields of exchange and magnetic anisotropic interactions of Nd and Cu–Nd ions, indicated in discussions of splitting of lower doublets of Nd ions energy levels, Δε ~0.36meV, determined by Nd and Cu–Nd interactions, observed in inelastic neutron diffraction investigations of Nd_2CuO_4. For Cu and Nd magnetic systems non-collinear antiferromagnetic orderings can be determined by interactions, such as ¼ $D(\boldsymbol{\gamma}_1\boldsymbol{\gamma}_2)^2$, where $\boldsymbol{\gamma}_1$ and $\boldsymbol{\gamma}_2$ are antiferromagnetic vectors of two interacting magnetic ions of neighboring planes. Appearance of magnetic field M_y(H,T) dependencies of Nd_2CuO_4, Fig.1b, provides the ability to investigate temperature-concentration phase diagrams of antiferromagnetic and superconducting states of correlated electrons in $Nd_{2-x}Ce_xCuO_{4\pm\delta}$ Mott insulators. In cases, when in used in High Temperature Superconductivity, Mott insulators, appearance of stripe states are accompanied by changes of symmetry of magnetic anisotropy, that is difficult to detect in magnetic field M_x(H,T) dependencies, such changes can be detected in magnetic field M_y(H,T) dependencies, which are more sensitive to any changes of magnetic symmetry of magnetic ordeings in magnetic materials.

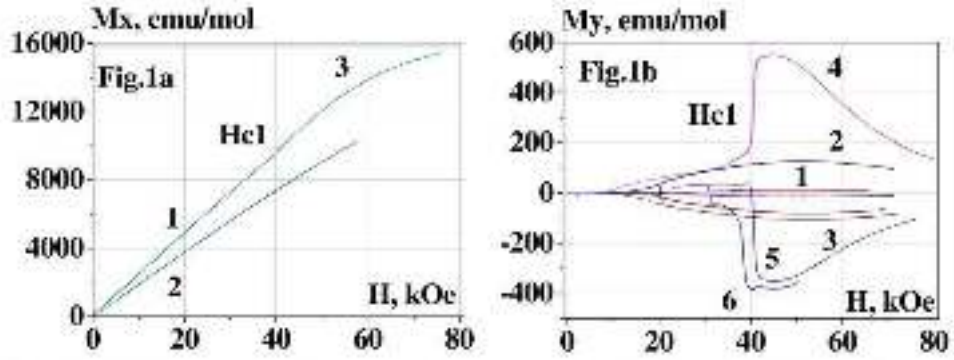

Fig.1a,b Mx(H,T) and My(H,T) magnetic moments of Nd_2CuO_4, when H are oriented along [110] axis, Fig.1a, and at small "±" angles with respect to [110] axis. Fig.1b, curves 2, Fig.1a and 1-3, Fig.1b. T~4.2K, curves 1, Fig.1a and 4-6, Fig.1b, T~1.8K, curve 3, Fig.1a, Mx =2Mo.

P25 - Magnetic structure dependent phonon dispersion in fcc Fe

2. Electronic structure and strongly correlated electron systems including superconductivity

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Fcc Fe is a weak magnet exhibiting magnetovolume instability and non-collinear magnetic structures under compression in contrast to bcc Fe. In this study, we performed ab initio calculations for studying the volume dependence of spin-spiral dispersion in fcc Fe by plane wave projector augmented wave method. It is shown that at low volumes, the magnetic configuration corresponding to the ground state is a spin-spiral of q2 = 2π/α(0.2, 0, 1), whereas for higher volumes, the ground state occurs for q1 = 2π/α(0, 0,0.6). Our results are very much consistent with the data from full-potential linearized augmented-plane-wave method (FP-APW+lo) study (Physical Review B, 2002, 66(1): 014447). Moreover, our calculations of phonon dispersion spectra for different collinear and non-collinear magnetic structures show a strong dependence of phonon frequencies on the magnetic structures indicating strong magnon-phonon interactions.

P26 - Manipulation of charge density waves by adsorption of metals in single layer niobium diselenide

2. Electronic structure and strongly correlated electron systems including superconductivity

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The author has chosen not to publicise the abstract.

Field 5

Field 6

P27 - Non-destructive determination of superconducting critical temperature by polarized neutron imaging

2. Electronic structure and strongly correlated electron systems including superconductivity

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One of the most important aspects in condensed matter research is the use of high quality and purity single crystals. Such samples are essential for fundamental studies where the analysed physical properties can be drastically affected by defects, impurities or inhomogeneities. When it comes to type II superconductivity, the fact that the fundamental pairing mechanism is not understood has driven a great amount of research into the characterization of intrinsic properties of these materials. The synthesis method of choice in the field of cuprate superconductors is the Traveling Solvent Floating Zone technique (TSFZ) [1], the advantages being the fact that no crucibles are used in the crystallization process, keeping contamination to a minimum and the possibility to grow centimetric size single crystals essential for neutron scattering investigations.

In $La_{2-x}Sr_xCuO_4$ (LSCO) compounds, which are of interest in this project, the distribution of Sr atoms is fixed after crystallization. However, the dopant concentration is difficult to monitor or control during the growth. Because of this, it is important to test the doping homogeneity throughout the crystals.

Here we demonstrate the use of polarization neutron imaging [2] as a non-destructive method for determining the superconducting critical temperature distribution along the sample length. In the presented experiment, we have trapped the applied magnetic field inside the single crystal by cooling the system below the critical temperature. We then measured the change in beam polarization caused by the local field within the sample. This way we were able to distinguish between the superconducting areas, where the magnetic field was present, and non-superconducting areas of the sample as a function of increasing temperature (see Figure 1). The data show an inhomogeneous distribution of critical temperatures along the crystal length, which is also the growth direction. We attribute this to a heterogeneous Sr doping throughout the sample.

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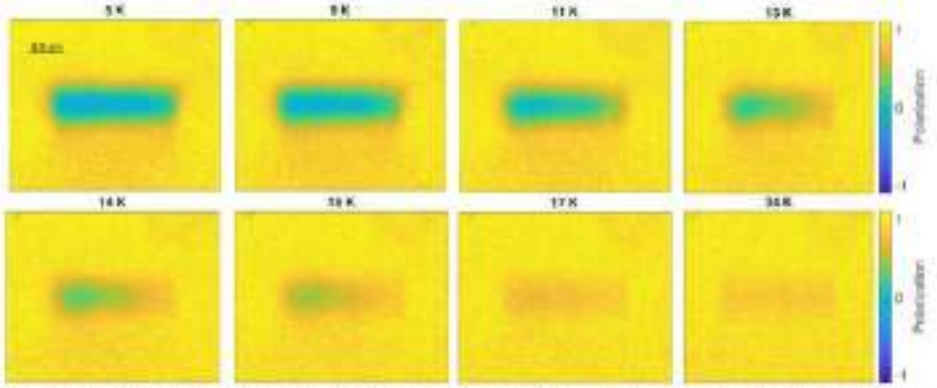

Figure 1: Temperature evolution of the recorded polarization. At the sample position, the trapped magnetic field induces a spin precession of the incoming neutron beam creating the visible contrast after passing through the spin analyser.

P28 - Non-linear least squares fit of specific heat data within Schotte-Schotte model using web page.

2. Electronic structure and strongly correlated electron systems including superconductivity

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Specific heat of rare-earth based materials at low temperatures can often be described by Schotte-Schotte model for Kondo impurity. Since several decades thousands of papers were published which were devoted to physics of rare-earth based compounds and often presented specific heat measurements for Kondo systems. Schotte-Schotte model for Kondo impurity in a magnetic field requires evaluation of trigamma function for complex argument values. Typical graphing software for general use does not provide such capability. Therefore, very few papers related to Kondo effect in rare-earth based compounds provided analysis within that model. In this report we present a web page which fits specific heat data with a sum of electronic, lattice and Schotte-Schotte terms. The interface is written in Javascript, whereas back-
is written in C and compiled to Javascript asm.js code using Emscripten compiler. The page is accessible at *http://www.jerzy.goraus.us.edu.pl/schfit.html* and was published in *Computer Physics Communications* (article in Press https://doi.org/10.1016/j.cpc.2019.02.010)

P29 - Observation of phonon anomaly in the hidden order at 105 K of iridium oxide Ca5Ir3O12

2. Electronic structure and strongly correlated electron systems including superconductivity

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Studies on the physical properties of Ir oxides for the last ten years have revealed the importance of spin–orbit interaction (SOI). In particular, in the case of Ir^{4+} ($5d^5$), the strong SOI leads to the narrow bands formed by the Jeff =1/2 states. Consequently, the system can easily become a Mott-insulating state with even a moderate amount of correlations on the 5d electrons. On the other hand, SOI can also have important effects on phonon properties. We will present the experimental and theoretical results on the phonon properties of iridium oxide $Ca_5Ir_3O_{12}$.

The crystal structure of iridium oxide $Ca_5Ir_3O_{12}$ is a hexagonal with noncentrosymmetric space group of *P-62m* (No. 189). In the structure, 1D chains of the edge-sharing IrO_6 octahedra form triangular lattices in the *c*-plane. $Ca_5Ir_3O_{12}$ has a mixed valance state of Ir $^{4+}$ and Ir^{5+} and the average valence of Ir ions is +4.67. This situation can lead to the geometrical frustration of charge on both the triangular lattice in *c*-plane and 1D chains along the *c*-axis [1]. $Ca_5Ir_3O_{12}$ shows a variable range hopping (VRH) conductivity [1-3]. Recently, we discovered that $Ca_5Ir_3O_{12}$ along *c*-axis shows nonlinear conductivity below room temperature by using the pulse sweep method [3]. In addition, $Ca_5Ir_3O_{12}$ indicates AFM ordering below T_N =7.8 K [1-4]. Furthermore, $Ca_5Ir_3O_{12}$ indicates a second order phase transition at 105 K, where the specific heat shows a sharp anomaly and the electrical resistivity shows a sharp bending [1,3]. The origin of phase transition at 105 K is not clear at present as the structural and magnetic transitions have not been confirmed in XRD, neutron scattering and mSR measurements for the polycrystalline samples [1,4].The origin of this phase transition at 105 K is not clear at present; this is "hidden order".

We performed the phonon measurements for single crystal $Ca_5Ir_3O_{12}$ by Raman scattering and inelastic X-ray scattering to reveal the origin of hidden order at 105 K. We found that the phonon dispersion observed at room temperature is in good agreement with the result by GGA calculations with SOI. These results on phonon dispersion in strongly correlated iridium oxide is a first report. Futhermore, we observed the phonon anomaly related to the hidden order at 105 K.

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P30 - Pressure induced magnetic order in the FM metal-insulator 1D magnet K2Cr8O16

2. Electronic structure and strongly correlated electron systems including superconductivity

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Materials with 1D-channels have interesting magnetic properties where the ground state is determined by the complex correlation of both intra and inter chain interactions. The title compound, K2Cr8O16, belongs to a series of quasi-1D compounds synthesised using a high- pressure/-temperature technique. The channels are formed by zig-zag Cr2O4 chains parallel to the c-axis and K cations occupying the center. This is one of the few compounds undergoing metal to insulator transition while maintaining a ferromagnetic order [1, 2], established by a Peierls transition [3]. Pressure dependent studies on this compound is fairly limited and the complete phase diagram of this compound is not fully resolved, especially the low temperature / high pressure region [4]. Here, zero field (ZF) and weak-transverse field (wTF) muon spin rotation/relaxation (μSR) data is presented. The obtained paramagnetic (PM) to ferromagnetic (FM) transition temperature differs notably compared to previously published magnetisation measurements. The power of μSR uniquely allow us perform measurements in zero applied field and hereby access the true intrinsic material properties. In detail, the PM to FM transition temperature as a function of pressure is determined from wTF measurements. Moreover, ZF data establish a novel low temperature/high pressure transition between two different magnetically ordered states, which was determined to be FM and antiferromagnetic (AF), respectively. Finally, neutron diffraction has recently been conducted in order to elucidate the detailed nature of the complex phase diagram.

This research was supported by Marie Skłodowska Curie Action, International Career Grant through the European Union, Swedish Research Council (VR), Grant No. INCA- 2014-6426, the Carl Tryggers foundation for Scientific Research (CTS-16:324), the Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan, KAKENHI Grant No. 23108003 and Japan Society for the Promotion Science (JSPS) KAKENHI Grant No. 26286084.

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P31 - Resonant Inelastic X-ray Scattering investigations on correlated electron materials

2. Electronic structure and strongly correlated electron systems including superconductivity

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Resonant Inelastic X-ray scattering (RIXS) is a powerful spectroscopy tool to investigate low energy excitations in correlated materials. Excitations of charge, spin, orbitals and lattice give rise to low energy excitations and interplay of these leads to emergent properties. Some of these emergent properties are metal to insulator transition, superconductivity, topological insulators and many more. During the past decade there has been numerous RIXS studies done on correlated materials especially high temperature superconductors. High resolution RIXS makes it possible to study these low energy excitations such as magnons [1, 2] and orbitons, which gives information about emergent properties. VERITAS beamline at MAX IV synchrotron (Lund, Sweden) has been designed with the aim to further refine the RIXS energy resolution. The beamline and spectrometer resolution (>35 000 resolving power), the capability to cool down to 4K (cryo-cooler) and the ability to change the scattering angle in the horizontal plane from 30 to 150 degrees (Q-chamber) [3] will able to access low-energy excitations in correlated materials with unprecedented quality. Furthermore, a goniometer supplement the Q-chamber, which permits crystal planes orientation and the mapping of dispersions over Brillouin zones.

Several projects on correlated materials will be investigated included the study of the hollandite K2Cr8O16 [4], spinel superconducting thin-films LiTi2O4 [5] and quasi two-dimensional Sr2Cu(BO3)2 [6]. K2Cr8O16 exhibits a metal to insulator (MI) transition preserving the ferromagnetic phase above and below the MI transition. RIXS will be used to investigate magnetic excitations, and orbital hybridization in this system. Molecular hybridization in LiTi2O4 will also be investigated below and above the superconducting transition. Sr2Cu(BO3)2 is a quasi two-dimensional material with an antiferromagnetic ground state characterized as Shastry-Sutherland square lattice. Preliminary M-edge RIXS (74 eV) investigations on Sr2Cu(BO3)2 show dd excitations at 2 eV and charge transfer excitations at 6 eV. Due to the different configuration of the Cu ions in crystal there is a splitting in dd excitation. Further RIXS investigations of these compounds will be carried out.

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P32 - Striped charge density wave phase in niobium diselenide: anisotropy from isotropic strain

2. Electronic structure and strongly correlated electron systems including superconductivity

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The author has chosen not to publicise the abstract.

Field 5

Field 6

P33 - The magnetic order in half-doped La1.5Ca0.5CoO4 by resonant magnetic x-ray scattering

2. Electronic structure and strongly correlated electron systems including superconductivity

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In the $La_{2-x}Ca_xCoO_4$ series, spin and charge ordered phases coexist in a wide hole-carrier concentration range around x=0.5. The half-doped compound exhibits charge-order characterized by super-lattice reflections at $\mathbf{q}_{CO}$= (1/2 1/2 *l*) *l*=integer (*tetragonal cell*) observed by neutron scattering and resonant x-ray scattering [1-3]. However, the (1/4 1/4 0) orbital order-kind reflection, observed in isostructural manganites, was not found. A clear magnetic anisotropy within the *ab* plane seen in magnetic susceptibility motivated the investigation of the correlation between the magnetic structure and a possible orbital ordering. Resonant soft x-ray scattering (RSXS) is a powerful technique for the simultaneous determination of magnetically ordered structures and the local electronic structure at an element-selective level in single crystals and thin films [4]. When applied on $La_{1.5}Ca_{0.5}CoO_4$ (LCCO), $\mathbf{q}_{M1}$= (1/4 1/4 1/2) and $\mathbf{q}_{M2}$= (1/4 1/4 1) super-lattice reflections were detected [5]. We performed a *full polarization analysis* of the resonant scattering intensities (i.e. their dependence on the incident and scattered beam polarization) to determine the – local anisotropy or magnetic – origin of these reflections. We also found the $\mathbf{q}_{M3}$= (1/4 1/4 0) f*orbidden* reflection [7]; all three types of reflections are visible only below T_N~50 K. Looking at energy dependences, the tiny L_2:L_3 ratio of RSXS intensities in all cases denotes a large orbital magnetic moment at Co ions and an overall profile that points to Co^{2+} cations as the main responsible for the antiferromagnetic order [5, 7]. In addition, the full polarization analysis within the frame of the x-ray magnetic scattering theory [6] allowed us refining the orientation of Co magnetic moments in LCCO, which turn out to lie close to or along the tetragonal [110] direction. Finally, our results indicate that all three reflections have a magnetic character and that they respond to the same magnetic phase, ruling out the possibility of different coexisting magnetic domains below T_N.

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P34 - The spin blockade in GdBaCo2O5.5 cobaltite at phase transition “metal-insulator”

2. Electronic structure and strongly correlated electron systems including superconductivity

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Perspectives of using the complex oxides as oxygen-permeable membrane materials and high-temperature fuel cell electrodes define the high relevance of complex study of their physical and, in particular, the electrical transport properties. Transport properties of cobaltites are closely associated with their magnetic order. The interest to the study of oxygen-deficient rare earth cobaltites $RBaCo2O_{5+\delta}$ (here R - lanthanides or yttrium, $0 \leq \delta \leq 1$) initially appeared as to a new class of the compounds undergoing a giant magnetoresistive effect. From the viewpoint of the study of phase transitions the most interesting are the compounds with $\delta = 0.5$, in which all cobalt ions have a single valency Co^{3+}, i.e. charge disorder and phase separation are absent. $GdBaCo_2O_{5.53}$ can be regarded as a typical representative of the ordered oxygen-deficit cobaltites $RBaCo_2O_{5.5}$. Polycrystalline samples were synthesized by the conventional technology of solid state reactions in air. The sharp X-ray diffraction peaks corresponding to the orthorhombic Pmmm-group, showed good crystallization. No secondary phases are detected.

Infraslow thermal relaxation of conductivity with characteristic times 10^4c have been detected during investigation of the phase transition metal - insulator (M↔I) in polycrystalline cobaltite $GdBaCo_2O_{5.5}$. That leads to a strong dependence of the shape of the temperature hysteresis loop on the temperature change rate or even to fluctuation spontaneous transitions from the metastable to absolute stable state. The asymmetry of the hysteresis loop expansion is related with the blocking of M phase nuclei. The spin blockade mechanism, which describes the transition from hopping conductivity at $T < T_{MI}$ to the band conductivity at $T > T_{MI}$, is used to explain of complicated kinetics of 1-th order M↔I transition.

P35 - “Unparticle” S=1 pseudospin description of unusual electron states in cuprates

2. Electronic structure and strongly correlated electron systems including superconductivity

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The phase T-x diagram of the doped quasi-2D cuprates is full of puzzles, which clearly manifest the breakdown of the conventional Fermi-liquid picture. We argue that principal features of parent cuprates, which makes them the basis for HTSC are anomalous proximity to the “polarization catastrophe” [1] and strong electron-lattice polarization effects leading to anomalously small magnitude of a “thermal” charge transfer (CT) gap, or the electron-hole (EH) dimer formation energy: U_{th} » 0.4 eV [2]. The EH dimers are (meta)stable coupled electron $[CuO_4]^{7-}$ and hole $[CuO_4]^{5-}$ centers with a “two-particle” interchange which look like a peculiar “quanta” of the diagonal site and/or bond charge order and off-diagonal (superfluid) order. Giant polarizability makes them as main candidates to resolve the polarization catastroph especially under non-isovalent substitution as the system of EH-dimers provides an effective screening of the impurity electric potential. Such a substitution shifts the phase equilibrium in the direction of condensation of the EH-dimers and the formation of an inhomogeneous mixed valence system whose low-energy physics can be described as that of a system of charge triplets $[CuO_4]^{7-}$, $[CuO_4]^{6-}$, $[CuO_4]^{5-}$ (nominally $Cu^{1+,2+,3+}$, respectively) [2]. In a limit of large negative U we arrive at a system of only electron and hole centers we refer to as an EH-liquid, which is equivalent to a system of composite local (hard-core) bosons, which manifests both charge order (CO) and bosonic superfluidity (SF). Interestingly, the T-x phase diagram of cuprates is very similar to that of the EH-liquid,”disfigured” by coexistence with parent Cu^{2+}-centers and itinerant holes. Strictly speaking, the system of charge triplets as many-electron strongly correlated atomic species in doped cuprates is just like the «boson-fermion» system, however, it does not admit a conventional particle interpretation [3]. We have introduced a minimal model to describe the charge degree of freedom in cuprates with the on-site Hilbert space reduced to a charge triplet formed by the three effective valence centers $[CuO_4]^{7-,6-,5-}$ (nominally $Cu^{1+,2+,3+}$), and made use of the S=1 pseudospin formalism [2]. Effective pseudospin Hamiltonian, resembling that of S=1 anisotropic spin-magnetic system, does include on-site and inter-site correlations, the three types of correlated “one-particle” and a “two-particle” transport. Making use of a spin-magnetic analogy appears to be a very instructive tool for describing the phase diagram and topological defects in cuprates. The “unparticle” representation implying the low-energy on-site states are approached in terms of combinations of strongly correlated atomic-like electron configurations, rather than approximately independent electrons, has been shown to resolve many qualitative mysteries of the cuprates. The pseudogap regime is governed by the on-site and inter-site correlations, which fall heavily with doping [4] in favor of kinetic energy effects such as bosonic superconductivity, supported by the coexistence of electron and hole centers, and Fermi-type behavior.

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3. Frustrated and disordered magnetism, artificial spin ice

P36 - Can we probe in real space the whole phase digram of the kagome dipolar spin ice?

3. Frustrated and disordered magnetism, artificial spin ice

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The author has chosen not to publicise the abstract.

Field 5

Field 6

P37 - Co-existence of long-range order and cooperative paramagnetism in multiferroic hexagonal YMnO3

3. Frustrated and disordered magnetism, artificial spin ice

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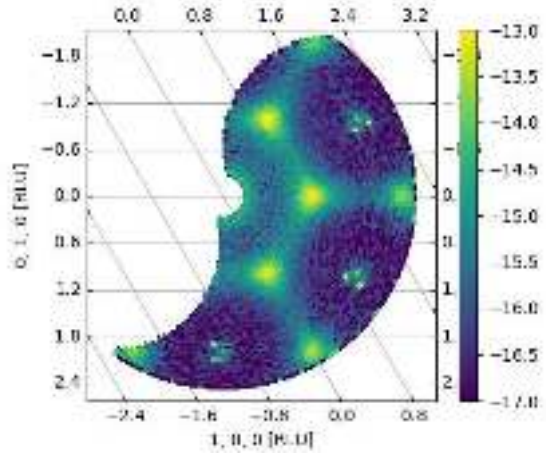
Geometrically frustrated magnets play host to a number of exotic phenomena. Many different geometrical motifs exist for frustrated magnets, but perhaps the most widely studied is the two-dimensional triangular lattice antiferromagnet. Important physical realisations of this system come from the hexagonal rare-earth manganites, the most studied of which is h-$YMnO_3$. We have studied the diffuse magnetic dynamics of h-$YMnO_3$ with the novel inelastic neutron spectrometer CAMEA (PSI, CH), and we find strongly directional diffuse scattering above the magnetic ordering temperature, indicative of a cooperative paramagnetic phase, as shown in the figure for T = 100 K and . This signal is purely dynamic, and without any characteristic energy scale. Curiously, this signal persists below the ordering temperature of T_N = 70 K down to roughly T^* = 30 K, suggesting co-existence of correlated disorder and long-range order for a large temperature range. We use the observation of co-existence of cooperative paramagnetism to explain properties of h-$YMnO_3$, including an anomalous thermal conductivity previously reported to take place above T^*.



P38 - Correlation functions of the 1D dilute Ising model

3. Frustrated and disordered magnetism, artificial spin ice

Yury Panov[1] , *Alexander Moskvin*[1]
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The dilute Ising model is one of the basic models in the theory of magnetic systems with quenched or annealed disorder. The grand partition function of the 1D dilute Ising model was found by Hintermann and Rys [1]. Here we investigate the exact solutions for the spin-spin, spin-impurity and impurity-impurity correlation functions of the 1D dilute Ising model at the fixed impurities density and for all possible values of the spin exchange and the impurities interaction constants. We present an explicit expression for the impurity contribution to the spin correlation length and the distribution function for the length of impurity clusters at the fixed impurities density. We compare our findings for the 1D dilute Ising model with 2D spin-pseudospin model [2]. In the antiferromagnetic phase of the 2D spin-pseudospin system the phase separation was found for the strong exchange case. It corresponds to some critical phenomenon in the 1D dilute Ising system when the compressibility has non-analytic behavior at low temperatures. We show that the critical temperature in the 1D case can be related to the maximum change rate of the impurity-impurity correlator for the nearest neighbors with the temperature and we obtained the expression for this critical temperature.

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P39 - Dielectric response of zig-zag spin chain β-TeVO4

3. Frustrated and disordered magnetism, artificial spin ice

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Materials in which magnetic orderings induce ferroelectricity are promising candidates for magnetoelectric effect (ME). On one hand, it provides an opportunity to explore fundamental interactions between charges, spin, orbital and lattice degrees of freedom. On the other hand, ME enables new directions for development of novel devices. Although bulk, non-composite magnetoelectric materials seem to be rare and elusive, one promising way to achieve the ME effect is through spiral magnetic orders which can allow the existence of electric dipoles by breaking the space inversion symmetry [1].

The quasi-one-dimensional quantum magnet β-$TeVO_4$ is a zig-zag spin chain system with anisotropic interactions between spins and a spiral ordered ground state [2,3]. Its phase diagram is complex: firstly, at T_{N1}=4.65 K the system paramagnetic phase gives way to an incommensurate spin-density wave in which spins are collinear. Then, below T_{N2}=3.28 K a spin stripe phase is observed [3,4]. This phase develops as a superposition of two spin density waves with a small difference in modulation and orthogonal direction of spin. Finally, at T_{N3}=2.28 K the difference between wave vectors disappears and the vector chiral ground state is established [5]. Most interestingly, at T_{N3} there are tantalizing indications of emergent electric dipoles, the nature and mechanism of which are still not resolved.

In this work we present the dielectric response of β-$TeVO_4$ single crystal samples in the static limit at low temperatures and in the presence of external magnetic field. The currently available magnetic phase diagram will be discussed in the context of dielectric properties, and of low-temperature magnetic ordering as a potentially multiferroic phase.

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P40 - Dynamical octupole structure factor of frustrated ferromagnetic chain

3. Frustrated and disordered magnetism, artificial spin ice

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In a spin-1/2 J_1-J_2 Heisenberg chain with competing ferromagnetic J_1 and antiferromagnetic J_2 in an applied magnetic field, there appear a series of spin multipole liquid ground states, i.e., quadrupole, octupole, hexadecapole, etc [1,2]. To clarify magnetic and transport properties in the quadrupole state, we have studied spin and quadrupole excitation spectra [3,4,5] and spin Drude weight [6] by exploiting numerical methods. We have argued that low-energy excitations are governed by bound two-magnon pairs, so that magnon pairs would carry spin current. In the present work, to extend our focus to the octupole regime, we investigate octupole excitation spectra. We observe a gapless mode according to quasi-long-range antiferro-octupole correlations. We envisage that bound three-magnon clusters would contribute to the spin transport. We will report detailed analyses of the dependence on exchange coupling parameters and magnetic field, and discuss the relationship between magnetic and transport properties.

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P42 - Experimental study of BPCB in TLL phase

3. Frustrated and disordered magnetism, artificial spin ice

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Atiferromagnetically coupled even-numbered spin ladder demonstrate spin liquid behavior and have no long range order down to lowest temperatures [1]. At fields $H_{c1}<H< H_{c2}$ (H_{c1}, H_{c2} – the first and the second critical fields) spin ladder system could be described by Tomonaga-Luttinger liquid (TLL) phase [2].

We report here observation of ESR absorption in TLL phase of a spin ladder system. We have measured ESR in $(C_5H_{12}N)_2CuBr_4$ (BPCB) at 450 mK (fig. 1). BPCB is a strong-rung spin ladder magnet with an energy gap Δ=9.5 K. Triplet excitations are freezing out at T=450 mK because of energy gap. Detected ESR absorption signals in field between H_{c1} and H_{c2} corresponds to TTL phase [3]. ESR signal vanishes with heating (see right panel fig. 1). Frequency-field dependence was fitted by equation $(\delta^2+(g\mu_B(H-H^*))^2)^{1/2}$ with gap about 20 GHz, $H^*=(H_{c1}+H_{c2})/2$ and effective g-factor 3.32.

Softening of excitations at H* is predicted by mapping of spin ladder in the magnetic field on XXZ spin chain [2, 4]. This mapping, however, does not explain gap δ and g-factor value, which probably originate from anisotropic spin-spin interactions [5].

Work was supported by RSF grant No 17-12-01505 and also by Program of fundamental studies of HSE.

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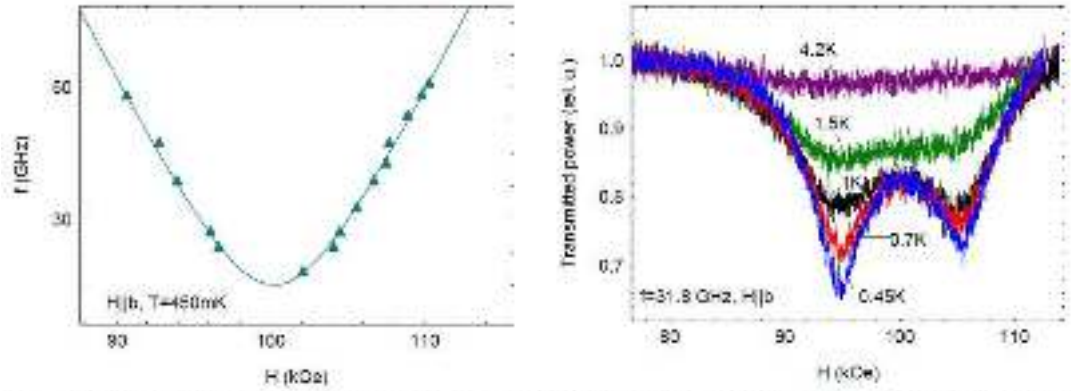

Fig. 1 Left panel: Frequency-field dependence at temperature T=450 mK, right panel: temperature dependence for frequency f =31.8 GHz.

P43 - Exploring mixed valence states and its underlying physics in an iridate: Ba3CoIr2O9

3. Frustrated and disordered magnetism, artificial spin ice

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The author has chosen not to publicise the abstract.

Field 5

Field 6

P44 - Frustrated Pyrochlore Dy2GaSbO7: an unconventional spin ice with enhanced zero point entropy

3. Frustrated and disordered magnetism, artificial spin ice

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Geometrically frustrated pyrochlores with spin-ice properties has Pauling zero-point 'residual' entropy, S_0 =1.67 J/K mol due to six fold '2-in, 2-out' spin-ice configuration out of sixteen configurations per tetrahedron unit and therefore the measured entropy becomes $\Delta S \approx 4.1$ J/(mol K) for a spin-1/2 system. Dy based pyrochlores showed conventional spin ice properties due to large magnetic moment of Dy^{3+} ions (hence possess large dipolar interactions) and strong crystal-field anisotropy. We showed that Dy_2GaSbO_7 has a spin ice ground state that is similar to its titanate analogue $Dy_2Ti_2O_7$, but with enhanced zero point entropy. We report here the measurements of dc and ac magnetization, and heat capacity of Dy_2GaSbO_7 at zero field. Curie-Weiss fit to the dc susceptibility yields positive Curie-Weiss temperature, θ_{CW} = 1.61 K indicative of ferromagnetic nearest-neighbour interactions among Dy^{3+} ions and effective magnetic moment μ_{eff} = 10.013 μ_B/Dy. The magnetization of Dy_2GaSbO_7 at 2 K saturates to the value of 5.06 μ_B/Dy, which is half of the free ion effective moment. Isothermal magnetization data can be expressed by a local easy axis anisotropy at Dy site along the <111> D_{3d} trigonal axes of the tetrahedral unit appropriate for an effective S-1/2 system. AC magnetic susceptibility χ_{ac}(T) data show distinct anomalies in its imaginary (χ") part at lower temperature, T_s ~3 K, indicating spin ice- like freezing of Dy^{3+} ions in Dy_2GaSbO_7 , as also observed in canonical spin ice systems e.g. $Dy_2Ti_2O_7$, Dy_2NbScO_7, $Dy_2Sn_{2-x}Sb_xO_7$ [1-2]. To further investigate the unique behavior of Dy_2GaSbO_7 the magnetic entropy has been determined after subtracting off lattice specific heat from the zero field specific heat data. The Schottky specific heat contribution is found to be negligible below 20K due to large gap ($\Delta_g \approx$ 200K) between the ground and the first excited Kramers doublets of Dy^{3+} in Dy_2GaSbO_7. The magnetic entropy of Dy^{3+} at zero field reaches to 2.9 JK^{-1}/ (mol-Dy) around 15K, which is lower than the conventional spin ice value. This reduction may be associated with the increase in residual entropy if we assume that any four (excluding six '2-in, 2-out' configurations) of sixteen configurations are energetically forbidden and hence only 12 configurations are available to the spins in tetrahedron. Consequently residual entropy becomes 2.88 J/(mol K) and entropy recovered at zero field is ΔS = (5.76-2.88) =2.88 J/(mol K). Structural and crystal field investigation showed that observed divergence from canonical spin ice behavior for Dy_2GaSbO_7 may be attributed to its different axial distortion and chemical pressure effect at Dy site due to larger $Ga^{3+}Sb^{5+}$ ions compared to its sister compound $Dy_2Ti_2O_7$.

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P45 - Magnetic fluctuations in a magnetic metamaterial

3. Frustrated and disordered magnetism, artificial spin ice

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In recent years, artificial spin systems, consisting of elongated single-domain ferromagnetic nanomagnets placed on the nodes of two-dimensional lattices and coupled via their dipolar magnetic fields, have been used to address open questions in frustrated magnetism. However, the imaging techniques so far used, are severely constrained in terms of temporal and spatial resolution. Recently resonant x-ray scattering has provided a means to go beyond such limitations and has shown itself as a powerful alternative method to probe the magnetic configuration in artificial spin systems [1,2]. A system that recently attracted significant attention is the artificial spin ice in the square geometry (Fig. 1), which is known to order antiferromagnetically. In recent X-ray Photon Correlation Spectroscopy (XPCS) experiments on similar arrays in which the nanomagnets are only weakly interacting glassy dynamics were observed [3] while, in another XPCS study on strongly interacting nanomagnets, anomalous features in the dynamics for long time lags were seen [4]. In particular, the latter results suggest the presence of a crossover from a ballistic to free diffusion regime in the motion of the magnetic domain boundaries. Similarly, using XPCS analysis on a square lattice of a strongly interacting nanomagnets, we have analyzed the scattering data for a range of temperatures with the aim to quantify the thermal magnetic moment dynamics.

In our data, we observe reentrant effects which are not expected for a system with glassy behavior. The interaction between the nanomagnets therefore strongly affect the dynamics of the system. With further analysis of the data, we aim to identify the nature of fluctuations for our model system, which may, for example, be a result of critical or depinning dynamics.

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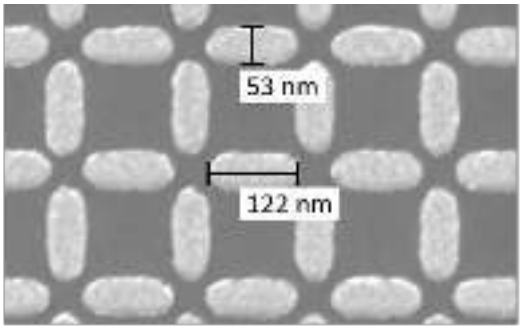

Fig.1. Scanning electron microscopy image of the two-dimensional array of the monodomain nanomagnets (light grey) on a silicon chip (dark grey).

P46 - Magnetic order and energy-scale hierarchy in artificial spin-ice structures

3. Frustrated and disordered magnetism, artificial spin ice

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The influence of different energy scales and their interplay is essential to explain and predict the properties of many physical systems. Here, we present results on the investigations of the magnetic order in thermalized artificial spin-ice structures[1,2], in particular the Shakti and the modified Shakti lattice[3,4,5]. These lattices have different activation energies for the interacting Ising-like elements.[6] The Shakti lattice consists of short and long Ising-like elements, while the modified Shakti lattice has only short elements. The different thermally active temperature regions for these elements are schematically shown in the figure below, emphasizing the two different energy scales present in these lattices. We image the thermally equilibrated magnetic states of the nanostructures using synchrotron-based photoemmision electron microscopy employing the x-ray magnetic circular dichroism to extract the magnetic orientation of each element. By comparing results obtained from structures with one or two different activation energies, we demonstrate a clear impact on the resulting magnetic order. The differences are obtained by the analysis of the magnetic spin structure factors, in which the role of the activation energies is manifested by distinct short-range order. These results highlight the potential of artificial spin-ice structures to serve as model systems for designing various energy-scale hierarchies and investigating their impact on collective dynamics and magnetic order.

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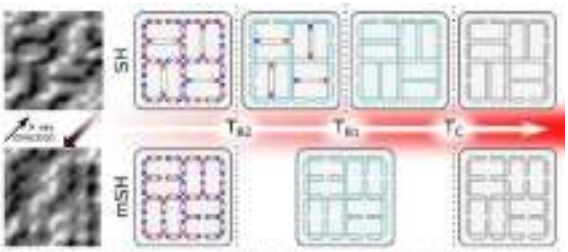

Figure: Representation of the different temperature regimes in which the Shakti (SH) and the modified Shakti (mSH) lattice are thermally active. Above the Curie-temperature, T_C, all islands are paramagnetic (light grey), below this temperature all islands are superparamagnetic (light blue). Below the blocking temperature of the long islands, T_{B1}, the long islands are frozen in and will not alter their magnetization direction during the measurement time. Below T_{B2} all islands are frozen in, with a blue magnetic north and a red magnetic south pole indicating their magnetization direction. At this temperature the PEEM measurements have been carried out, one exemplary PEEM-image is shown on the left for SH and mSH lattice.

P47 - Magnetic spin correlations in the one-dimensional frustrated spin-chain system Ca3Co2O6

3. Frustrated and disordered magnetism, artificial spin ice

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The prototypical quasi-one-dimensional (Q1D) compound $Ca_3Co_2O_6$ belongs to the *R*-3*c* space group and its rhombohedral structure consists of one-dimensional Co-O chains along the c-axis separated by the Ca ions. The Q1D cobalt oxides are one of the more intriguing groups of compounds. They display extremely complex magnetic behaviour due to the competition between 1D intrachain ferromagnetic (FM) and 2D interchain antiferromagnetic (AF) interactions. In combination with the fact that the chains form a triangular lattice in the ab-plane, yields a very intriguing 1D-system with geometrical frustration and strong uniaxial anisotropy. This compound has been investigated by many different experimental techniques but there are still a large number of unresolved issues. For instance, it is expected that a long-range (LR) 1D- FM order should exist for $T = 100$-150 K. In this work we present a combination of ZF and high-TF μSR measurements **[1]**, together with a magnetization and neutron scattering investigation. Our m^+SR Knight-shift measurements clearly show an anomaly at $T = 140$ K that can be connected to the onset of a LR 1D-FM order. Further, we propose that in the low-temperature regime, a competing Q1D ferrimagnetic order co-exist within a LR AF phase, which has been confirmed by our neutron scattering studies **[2]**.

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This research is funded by Swedish Foundation for Strategic Research (SSF) within the Swedish national graduate school in neutron scattering (SwedNess), a Marie Skłodowska-Curie Action, International Career Grant through the European Commission and Swedish Research Council, VR (INCA, Dnr. 2014-6426), a VR neutron project grant (BIFROST, Dnr. 2016-06955), a VR Starting Grant (Dnr. 2017-05078) as well as Carl Tryggers Foundation for Scientific Research (CTS-18:272).

P48 - NMR study of spin dynamics in the alternating chain system with defects Li3Cu2SbO6

3. Frustrated and disordered magnetism, artificial spin ice

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Honeycomb oxide system Li3Cu2SbO6 is composed of Cu2SbO6 layers with Li ions between them. In the related compound, such as Na2Cu2TeO6 the interplay of particular orbital arrangement, lattice distortion and frustration causes quasi-1D magnetic structures or weakly interacting magnetic dimers but not a 2D hexagonal structure. This leads to a non-magnetic ground state with a spin-gap behavior. In Li3Cu2SbO6 the presence of Li-Cu site inversion creates a significant amount of in-plane defects of magnetic structure that cuts the spin-chains to the finite size fragments. It makes it difficult to interpret the results of measurements of bulk magnetic properties obtained in previous studies within the framework of the alternating FM-AFM or AF-AF spin chain model. The nuclear magnetic resonance being a local method allows to separate non-gapped and gapped contributions to the magnetic properties. Nuclear magnetic resonance and thermodynamic experiments on the Li3Cu2SbO6 powder sample were performed in a wide range of temperatures in different magnetic fields. The obtained experimental results, treated within the framework of a theoretical model of a fragmented chain, allowed to obtain an acceptable description of the system.

The work was supported by grant RFBR 18-02-00664

P49 - Observation of long-range magnetic order in dipolar-coupled nanodisk arrays

3. Frustrated and disordered magnetism, artificial spin ice

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Artificial magnetic materials in the form of arrays of single-domain nanomagnets are attractive for both fundamental studies and device applications as they can be fabricated with properties determined by the constituent nanomagnet elements. The ground-state magnetization configuration in such systems is determined by the dipolar interaction,[1] and can be described in the framework of 'supermagnetism'.[2] In particular, monodomain nanodisks on hexagonal and square arrays are predicted to exhibit superferromagnetic[3] and superantiferromagnetic order.[4] Recent experimental data complies with the theoretical predictions,[5] but does not show the magnetic order directly.

In this study, we fabricate arrays of ferromagnetic permalloy nanodisks using state-of-the-art electron beam lithography and use soft x-ray spectromicroscopy to image their magnetization. The spatially resolved magnetization maps show long-range magnetic order in agreement with the theoretical predictions. We believe that this conceptually straightforward investigation of magnetic arrays will stimulate further studies of dipolar-coupled systems with long-range order.

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P50 - Phase diagram of the Heisenberg model on a bcc lattice with the competing Interactions

3. Frustrated and disordered magnetism, artificial spin ice

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The study of phase transitions (PT) and critical phenomena of frustrated spin systems is one of the topical issues of the condensed matter physics. It is believed that frustrations, as a result of competing interactions, are a source of degeneration and disorder, which lead to the arising of new and interesting physical phenomena. Frustrated spin systems are characterized by unusual magnetic properties, and have a rich picture of phases and PT, caused by strong degeneration and high sensitivity to different external disturbance. Moreover, accounting the interaction of the second nearest neighbors in such systems can lead to a change in the order of PT. The characteristics of PT at different values of the ratio of exchange interactions between the first (J_1) and second nearest neighbors (J_2) are known only in general terms.

In the present work, on the basis of the Monte Carlo method replica algorithm, we investigate the influence of the exchange interaction competition on the PT and the critical properties of the three-dimensional Heisenberg antiferromagnetic model on the body-centered cubic (bcc) lattice.

The Hamiltonian of the Heisenberg J_1-J_2 antiferromagnetic model on a bcc lattice can be represented as follows:

$$H=-J_1\Sigma(S_i\cdot S_j)-J_2\Sigma(S_i\cdot S_l) \qquad (1)$$

where $|S_i|$ - three-component unit vector $S_i=(S_i^x,S_i^y,S_i^z)$. The first term in eq. (1) describes the exchange interaction of the nearest neighbors with the magnitude $J_1<0$ and the second term describes the exchange interaction of the next nearest neighbors with the magnitude $J_2<0$. Calculations were carried out for systems with periodic boundary conditions and linear dimensions of $2\times L\times L\times L=N$, $L=12\div 90$, were L is measured in unit cell size. The exchange interactions ratio $r=J_2/J_1$ was changed in the [0.0, 1.0] interval with a step $\Delta r=0.1$.

The PT order for different ratios of the interaction between the J_1 and J_2 have been determined by means of the Binder cumulant method and the histogram analysis of Monte Carlo method. Phase diagram for the critical temperature dependence on the magnitude of interaction of the second nearest neighbors has been constructed.

Fig. 1 depicts the phase diagram for the T_N critical temperature dependence on the next-nearest neighbor interaction value r. As one approach the point where the three phases coexist, the phase transition temperature shifts toward lower temperatures. For the model under consideration, for $r=2/3$, the system has a minimum phase transition temperature $k_BT/J_1=0.670(1)$. In the diagram, we see that at the point $r=2/3$ three different phases intersect: AF1 - Neel phase, PM - paramagnetic phase and AF2 - collinear phase. In this model, transition from AF1 to AF2 ordering is due to a change in the structure of the ground state.

The results of this study show that in the $0.0\le r\le 0.6$ and $0.8\le r\le 1.0$ intervals the PT of the second kind has been observed. For the first time, a region of ($2/3<r\le 0.75$) has been found in the diagram, where the transition from the antiferromagnetic phase to the paramagnetic phase is a first-order transition (shown in Fig. 6 in red). It was found that for the case of $r=2/3$, a second order phase transition has been observed.

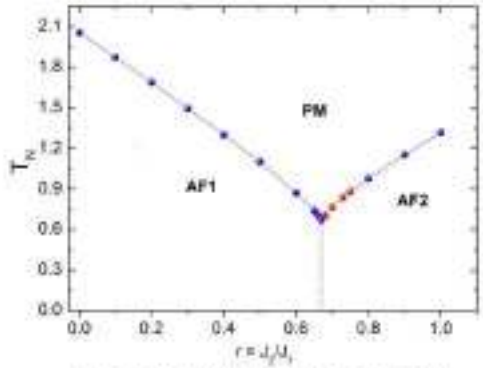

Fig. 1. Phase diagram of the critical temperature versus the next-nearest interactions

P51 - Reducing the superparamagnetic blocking temperature of nanomagnets using a heavy-metal interface

3. Frustrated and disordered magnetism, artificial spin ice

Kevin Hofhuis[1, 2] , *Hanu Arava*[1, 2], *Naëmi Leo*[1, 2, 3], *Aleš Hrabec*[1, 2, 4], *Zhaochu Luo*[1, 2], *Jaianth Vijayakumar*[5], *Sergii Parchenko*[5], *Armin Kleibert*[5], *Laura Jane Heyderman*[1, 2]

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The author has chosen not to publicise the abstract.

Field 5

Field 6

P52 - Spin liquids, spin glasses and ferrimagnets with the cubic β-Mn structure

3. Frustrated and disordered magnetism, artificial spin ice

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The spin liquid is strange state of matter which is thought to exhibit a quantum phase transition at T = 0 to an unusual disordered collective magnetic state. From a chemical point of view, the simplest, elemental example is βMn [1,2]. It is the stable phase of manganese above 725°C, and it can be stabilized at room temperature after arc melting. The space group is $P4_132$, with two occupied sites 8*c* and 12*d* in the 20-atom cubic unit cell ($a_0 = 615$ pm) is illustrated in the figure below. It is believed that the Mn on 8*c* sites, with an average Mn-Mn nearest-neighbour distance of 247 pm is nonmagnetic, whereas that on 12*d* sites average Mn-Mn nearest-neighbour distance of 260 pm with carries a moment, but the topology of these sites, which form linked triangles, is such that the antiferromagnetic nearest-neighbour interactions are completely frustrated [1].

Recently, we made a surprising discovery; When we prepared a Mn_3Al_2 alloy, hoping that the nonmagnetic Al would occupy 8*c* positions, we found that the alloy was strongly ferromagnetic, with a moment of 1.3 μ_B per formula, and a Curie temperature of about 600 K. A similar change to ferromagnetism was observed in Mn_3Fe_2, where the iron is found by Mossbauer spectroscopy to be nonmagnetic at room temperature. Alloys with less Al are were reported by Nakamura et al [1] to be spin glasses with a spin freezing transition below 40 K. We find a strong para-process in the magnetization of all compositions, and ferromagnetic order in $Mn_{5-x}Al_x$ when $2 < x < 1$.

Our preliminary results based on density functional theory (DFT) and a fixed spin moment (FSM) approach reveals that magnetism in βMn is very sensitive to hydrostatic pressure. Fig. 1 shows that at the equilibrium lattice parameter, there exists an unusually shallow energy plateau between 0 and about 0.35 μ_B/atom that is consistent with the observed para process. However, the magnetic energy landscape also suggests stable magnetic states for a 3% lattice expansion, consistent with our finding that 40 % Al substitution increases the lattice parameter a_0 of the alloy from 615 pm to 637 pm. Relaxation of the frustration of the 12*d* site moments by Al or Fe is also expected to stabilize the net ferromagnetic or ferrimagnetic moment.

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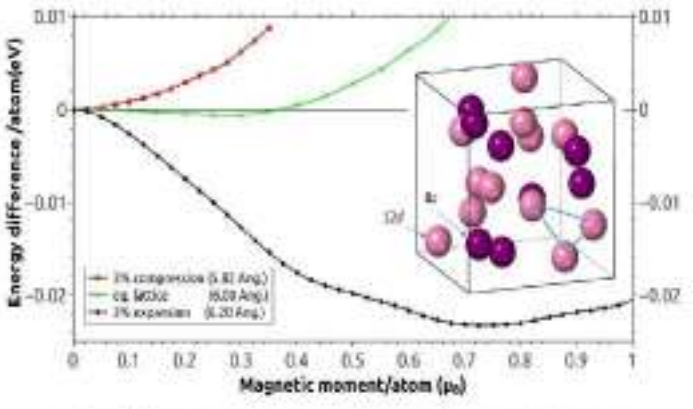

Figure 1. Magnetic energy landscape of βMn from fixed spin moment calculations. The inset shows the crystal structure with a triangle of 12d Mn atoms highlighted.

P53 - Thermally Active Square Artificial Spin Ice Probed by A.C. Susceptibility

3. Frustrated and disordered magnetism, artificial spin ice

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Throughout the last decades, the collective behaviour of ensembles of strongly interacting single-domain magnetic nanoparticles has been a matter of considerable interest[1,2]. Dipolar coupled arrays of single domain magnetic islands – mesospins[3] – fabricated by nanolithography[4] can serve as model systems also exhibiting collective behaviour. These model systems, like Artificial Spin Ice (ASI), provide an experimental framework where the geometry and interaction strength between mesospins can be designed as desired. By a deliberate choice in materials composition that allows for thermal fluctuations of the mesospins below the Curie temperature of the material, ASI's can further serve as an ideal platform to study thermal dynamics and thermodynamic transitions in frustrated systems[5-8].

To explore the magnetization dynamics of thermally active square ASI, temperature dependent AC susceptibility, a technique well known for probing relaxation dynamics in magnetic particle ensembles and spin glasses, is adapted. This non-invasive technique, based on the Magneto-Optical Kerr effect and a small magnetic AC field, allows for frequency and temperature dependent studies on a laboratory scale. We find a cooperative freezing of the mesospins well below Curie temperature of the material, which is marked by a broad frequency dependent peak in the real and imaginary part of the AC susceptibility as shown in Fig 1. A comparison between ASI arrays with different lattice spacings, i.e. different gap sizes between the mesospins, reveals a systematic increase of the freezing temperature with stronger interactions. An analysis using the Vogel-Fulcher-Tammann (VFT) law[9] allows for the extraction of the energy barriers as well as the freezing temperatures of the arrays. The experimentally determined energies are found to be in good agreement with micromagnetic estimates. The AC susceptibility technique can serve as an excellent tool for the characterization of thermal dynamics, collective behaviour and thermodynamic phase transitions in magnetic metamaterials[10,11] such as ASIs[12,13].

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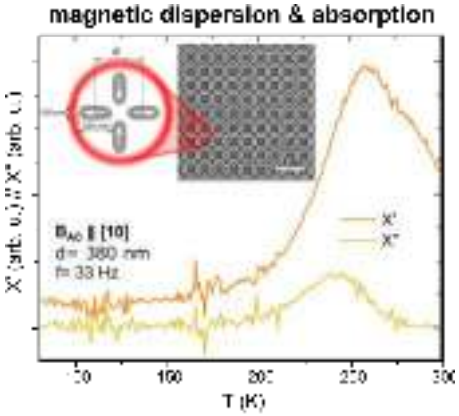

FIG. 1. A broad peak in χ'(T) and χ''(T) indicates the onset of thermal mesospin dynamics, well below the [illegible] ordering temperature of the islands.

4. Magnetism in carbon-based and organic materials

P54 - Effect of light polarisation and magnetisation on the photocurrent of MnOx/C60/Co

4. Magnetism in carbon-based and organic materials

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Molecular semiconductors offer several advantages over conventional crystalline semiconductors, such as simple engineering of mechanical flexibility, big area coverage, low cost and lightweight (1). On the other hand, the difficulty to obtain reproducible results and the generally low carrier mobility in these materials have hampered the progress of molecular spintronics (2, 3). Spin dependent charge transfer, orbital hybridisation, band broadening, Fermi level pinning and interdiffusion may all play a role in the behaviour of hybrid devices. Nevertheless, significant progress in the field can be achieved by taking conceptual steps and design changes that make use of the novel functionalities emerging at the molecular interface, rather than mimicking the behaviour of standard devices. This is the case in particular for the optoelectronic control of spin polarisation and spin currents (4-7). Here, we show the spin and light-polarisation dependent photocurrents generated in manganese oxide-C_{60} junctions with cobalt electrodes: Co/C_{60}/MnOx. During the experiments, we measure the photovoltaic response with magnetic fields applied either in-plane or out-of-plane (Figure 1) to and with different alignments for the light polarisation (Figure 2). These devices can be used as self-powered magnetic and/or light polarisation sensors, and they provide information about the spin-dependent trapping mechanisms at molecular-metal oxide interface.

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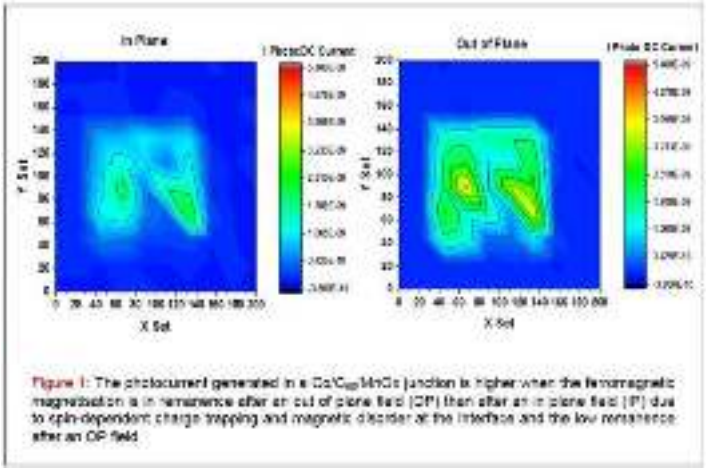

Figure 1: The photocurrent generated in a Co/Co_{50}MnGa junction is higher when the ferromagnetic magnetization is in remanence after an out of plane field (OP) than after an in plane field (IP) due to spin-dependent charge trapping and magnetic disorder at the interface and the low remanence after an OP field.

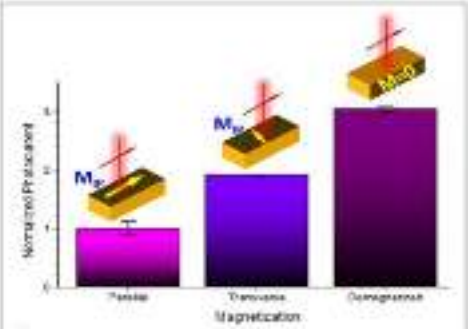

Figure 2: When considering the relationship between the light and spin polarization, lower photocurrents are obtained when the light polarization is parallel to the spin (magnetization) directions than when they are perpendicular. However, the highest photocurrent are obtained when the junction demagnetized.

P55 - Electronic and magnetic properties of phtalocyanine molecules on rare-earth noble-metal surfaces

4. Magnetism in carbon-based and organic materials

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Fundamental knowledge of magnetic and electronic interaction phenomena that takes place at the hybrid metalorganic interface is decisive to explore the possibility to create highly spin-polarized spinterfaces to enhance the performance of organic spintronic devices [1]. To this end, tailoring magnetic properties on structurally robust substrates is crucial. The survival of the long-range magnetic order upon interface formation is a basic requirement for one application type that intent to maintain the substrate magnetism and that is the reason why, besides structural stability and chemical inertness, substrate materials with strong ferromagnetism, i.e., high Curie temperatures T_C are sought. For the survival of the magnetism of single molecular magnets, however, strong substrate ferromagnetism supresses all the desired properties of the molecules and there, a different type of magnetic substrates is needed. Rare-earth/noble metal monolayer alloys, grown on noble metal surfaces, possess a big potential as nanostructured magnetic templates with structural stability. Different elements of the lanthanide series have been observed to form surface-confined alloys in Au(111) [2], characterized by a high crystal quality and nanoscale periodic corrugation. In the case of the Gd-Au combination, by varying the Gd coverage, Moiré or trigon patterns can be tuned, which have been shown to drive the self-organized growth of ferromagnetic Co nanodot arrays. Notably, the Gd-Au templates remain structurally stable upon Co growth, allowing to trigger magnetic coupling of the Co nanodot array with the supporting Gd alloy [3].
Given the variety of REs and their exotic magnetism, the observations made on $GdAu_2$ encouraged a thorough search combining different RE elements and noble metals. In this sense, a remarkable high T_c = 85 K in $GdAg_2$ compared to T_c = 19 K in $GdAu_2$ was recently observed [3]. It was show by photoemission experiments and by Density Functional Theory that magnetic coupling is effectively mediated by a noble metal-Gd hybrid s,p-d band giving rise to such a strong increase in T_c. On the other hand, our results of the magnetic properties in $SmAu_2$ reveal completely different behaviour with respect to $GdAu_2$, namely zero magnetic moment in the hard axis, while maintaining a ferromagnetic loop along the in-plane easy axis with a much lower T_c compared to the $GdAu_2$.
Here we will present experimental evidence based on photoemission and X-ray magnetic dichroism experiments that magnetic properties of the substrate and the magnetic molecules are influenced by each other depending on the strength of the magnetic moment of each contributor.

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P56 - Magnetic properties and degradation efficiency of magnetite/ceria due to magnetite transformations

4. Magnetism in carbon-based and organic materials

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New reactive sorbents based on cerium dioxide (ceria) and/or iron oxide/ceria nanoparticles are frequently studied due to their unusual physical and chemical properties. Iron oxides exist in a natural form as minerals and as artificially prepared compounds. Some of iron oxides contain Fe(II) and the other Fe(III) but magnetite contains both Fe(II) and Fe(III) ions in its structure. It has spinel structure and is ferrimagnetically ordered. Cerium exists as a free metal or as oxide in cerous, Ce(III), and ceria, Ce(IV), forms. Ceria is well known to release significant levels of oxygen at low oxygen partial pressures and elevated temperatures. The defects - oxygen vacancies - dominate the electronic, chemical, and physical properties.

Present investigations are focused on synthesis of magnetite/ceria composites, the so called “reactive sorbents”. The used commercial artificial magnetite has particle size between 50 and 100 nm and the ceria is formed during calcination treatment of the cerium carbonate prepared from the commercial $(NO_3)_3.6H_2O$ and NH_4HCO_3 chemicals. Initially, the magnetite is mixed with cerium carbonate in various weight ratios of both components from 100/0 up to 50/50 and the mixtures are subjected to calcination treatments at 500 °C for 2 h in air. All prepared compounds are experimentally studied using X-ray diffraction, Mössbauer spectroscopy, electron microscopy and magnetic measurements at room and low temperatures. Moreover, a decomposition of the organophosphorus pesticide parathion methyl [1,2] was done using this reactive sorbent in order to determine its degradation efficiency.

Rietveld analysis of XRD results of ceria yielded the lattice parameter 0.5412(1) nm and the microdomain size of 9.4 nm. The same characteristics of the input magnetite were 0.8392(1) nm and 47.3 nm, respectively. Nevertheless, the magnetite exposed to the mentioned treatment has transformed into maghemite (29 %), hematite (68 %), and the remaining magnetite (3 %). The same transformations proceeded at all mixtures but with different relative ratios of individual iron oxides. The amount of ceria was in agreement with nominal amount of ceria carbonate in a frame of experimental error.

The experimental results have revealed that the degradation efficiency, expressed by rate constant (mol/h) in dependence on amount of ceria content (%), has increased almost linearly with ceria amount independently on kind of oxide. On the contrary, saturation and remanent magnetizations are highly sensitive to relative ratio of iron oxides. Both magnetic characteristics are low if the amount of hematite prevails over magnetite and maghemite. The reasons for variations of the mutual ratio of iron oxides after calcination of different samples are not clear at present. As concerns the Mössbauer results, the situation is slightly different due to similar hyperfine induction values of maghemite and hematite. The mean hyperfine induction of initial magnetite of 47.6 T is in agreement with literature. This value increases above 50 T due to the increasing fraction of maghemite and hematite.

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P57 - Magnetisation studies of two field-induced Er(III) single molecule magnets

4. Magnetism in carbon-based and organic materials

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Single molecule magnetism (SMM) presents a novel avenue for the pursuit of a bottom up approach to the design of next generation magnets, their molecular origin of magnetism and sensitivity to their chemical environment allows SMMs to be designed and exploited at the molecular level[1]. Applications include proposals for SMMs to be used as qubits and components in spintronic devices [2,3]. Here we present the synthesis and magnetic properties of mononuclear Ln(III) complexes, where two Er(III) complexes exhibit SMM behavior and blocking temperatures of around 40K. We used a synthetic approach and ligand fine-tuning where the ligand field is favorable for the Er(III) compounds to exhibit SMM properties.
Single crystal structure analysis was carried out to obtain structural information on all the presented complexes, see Figures a) and b). The field dependence of the magnetization for both Er(III) compounds were measured at 2, 3 and 5 K; the magnetization curves did not saturate at high fields indicating the presence of significant magnetic anisotropy and/or low-lying excited states. In order to investigate the potential presence of slow relaxation of the magnetization caused by SMM behavior, ac magnetic susceptibility measurements were performed, in applied dc-fields from 0 to 3000 Oe, in attempts to suppress any quantum tunneling of the magnetization (QTM). For both compounds the in-phase and out-of-phase ac susceptibility show field-dependent signals; the optimum field was found to be 500 Oe and this was used for further ac measurements. In both cases, the ac measurements reveal temperature dependent in- and out-of-phase signals with clear maxima up to 3.5 K, see Figures c and d. The maxima of the frequency dependent out-of-phase susceptibility curves were used extract the relaxation time as a function of temperature.

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P58 - Spin physics at the interface of molecules and inorganic substrates.

4. Magnetism in carbon-based and organic materials

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In molecular spintronics one deals with systems, combining molecules in contact with an inorganic substrate, where one at least of the component is magnetic. The physical properties of these systems is strongly governed by interfacial effect and notions such as spinterface [1] or orbital-matching are essential to understand the device behaviour. These interfacial effects can play in either way: modify magnetic properties of a substrate or conversely influence the magnetism of the molecular layer. These notions can be used to analyse but hopefully also serve to devise strategies for the design of new materials or devices.

I will illustrate these concepts on various relevant systems. I will first consider the case of nonmagnetic molecules in contact with a magnetic substrate: I will how the magnetic anisotropy can be tuned at a ferromagnetic/molecule interface [2]. I will then consider magnetic molecules deposited on a non-magnetic substrate and show recent results obtained with spin-crossover molecules forming a well-organized lattice on a gold surface while keeping their switching ability [3].

This work is the fruit of various collaborations with experimental and theoretical groups and has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No [766726], the Indo-French Centre for the Promotion of Advanced Research (CEFIPRA).

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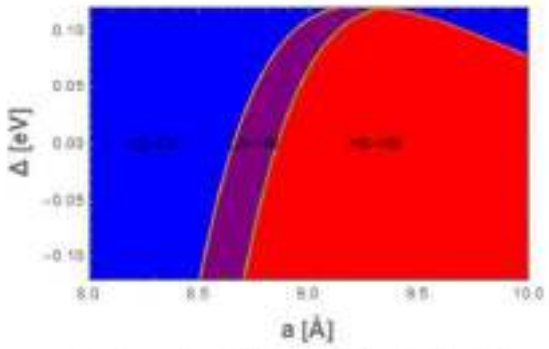

Phase diagram for spin states as a function of the fixed distance a between molecules and the difference of energy between HS and LS in gas phase. It is calculated for a 1D toy model taking into account an interaction potential V inter extracted from DFT calculations.

5. Magnetorecording media, magnetic memories and magnetic sensors

P61 - A flexible GMI sensor based on amorphous magnetic wires for detection of surface deformations

5. Magnetorecording media, magnetic memories and magnetic sensors

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New soft materials have recently emerged and can be used to create soft sensors and actuators for new applications in science and engineering such as wearable devices, artificial skin, artificial muscles, and biomimetic robots. Such sensors allow the detection of superficial mechanical strains, superficial deformations, in elastic or permanent mode. Such materials include electroactive polymers, ferroelectrics, ionic polymer metal composites (IPMCs), photovoltaics, piezoelectrics, shape memory alloys (SMAs), and thermoelectrics. We have previously shown that giant magneto-impedance (GMI) sensors can be successfully used to detect small movements produced by breathing and heart beats of a resting person on a flexible mattress [1]. In this article, we are presenting a flexible GMI sensor that associates the magnetic properties of the material with its mechanical deformation, allowing to highlight the deformation of some surfaces. Our work focused on the influence of external parameters on the sensor's sensitivity, with the aim to optimize its response as needed by various applications. The sensor consists of a high permeability $Co_{68.18}Fe_{4.32}Si_{12.5}B_{15}$ amorphous magnetic wire around which a detection coil is wound, along with an electronic circuit for excitation signal generation and signal processing. We used wires with lengths between 1 cm and 1 m and diameters from 10 to 30 µm, prepared by in-rotating-water-spinning. The detection coil was wound directly on the sensitive element. By applying a short rectangular pulse current through the amorphous wire, a response signal is obtained in the surrounding pick-up coil. The profile and amplitude of the induced peak is dependent on the amorphous wire diameter, length and composition, the number of turns of the surrounding coil, the intensity of the current pulse applied through the magnetic wire, the external magnetic field and mechanical stress to which the sensitive element is subjected. This behavior is due to the specific properties of the amorphous magnetic wires used as sensitive elements, with very high magnetic permeability (>1.2 x 10^5), as well as to the particular core-shell magnetic domains structure with the inner core magnetized axially and the outer shell circumferentially magnetized. The sensor electronics has been designed to generate current pulses with selectable intensity, duration and frequency and to process the signals provided by the sensing coil adapted to the applications needs. The wire was excited using a pulse current with the duration of 12 s, amplitude of 15 mA and frequency of 35 kHz. We found that the bending sensitivity is the best (600 mV/m^{-1}) for the wire of 30 µm in diameter, independent of the length. This type of flexible sensor can have a wide range of applications in the detection of superficial mechanical strains, superficial deformations or impact deformations on different deformable surfaces.

Work supported by the Romanian Ministry of Research and Innovation under NUCLEU Program – contract no. 33N/2019, project PN 19 28 01 01 and Contract No. 11PFE/16.10.2018.

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P63 - Direct formation of CoFeB/MgO-based magnetic tunnel junction on flexible substrate

5. Magnetorecording media, magnetic memories and magnetic sensors

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By combining the magnetoelastic effect and the giant magnetoresistance (GMR) effect, we made strain direction sensors on a flexible substrate [1,2]. However, because of low GMR ratio ~<6% of the current in-plane (pseudo) spin valves, resistance change caused by the magnetic effects is still comparable to that of normal metal's deformation when applied strain is on the order of 1%. In order to enhance the magnetoresistance ratio, we tried to fabricate CoFeB/MgO-based magnetic tunnel junction (MTJ) directly on a flexible substrate. Since annealing process at over 300℃ is required to obtain high tunnel magnetoresistance (TMR) ratio in CoFeB/MgO-based MTJ, previous flexible CoFeB/MgO-based MTJs have been firstly made on a rigid substrate (including the annealing), and then transferred to flexible substrate [3,4]. Although those flexible MTJs show comparable or higher TMR ratio after the transfer process, it is not clear if the strain applied to the flexible substrate is adequately transmitted to the MTJ, which is an important point for strain sensing devices. Here, we used a polyimide film that has endurance against high temperature annealing, on which we directly fabricated the MTJ by a procedure same as that for rigid substrates [5].

The MTJ formed on the polyimide substrate was annealed at 350℃ for an hour in vacuum. As a result, TMR ratio of ~100% was obtained as shown in Fig. (a), which is higher than the upper limit of the expected value by the Julliere's model. When a tensile strain (ε) is applied to the MTJ, coercivity changes because of the magnetoelastic effect. On the other hand, TMR ratio is almost independent of the strain application at least up to ε = 1.2%. Figure (b) shows current-bias voltage (*I*-*V*) curves at parallel and antiparallel magnetic configurations. As the linear parallel *I*-*V* curve is one of the characteristics of the coherent tunneling through MgO (100), suggesting that crystallization of MgO progressed even on the flexible substrate. Figure (c) shows TMR ratio-*V* curves for ε = 0% and ε = 1.2%. Although resistance decreased for ~6% with ε = 1.2% (not shown) probably because of thickness reduction of the MgO barrier, the TMR ratio-*V* curve remained unchanged. Furthermore, we confirmed that a strain is adequately transmitted to the CoFeB layer regardless of the complex structure of the MTJ by comparing the magnetoelastic properties with the single CoFeB sample formed on a flexible substrate.

The authors thank R. Iguchi, R. Kohno, T. Sekitani, S. Kasai, T. Nagahama, T. Namazu, H. Murayama, Y. Iwasa, Y. Nakagawa, and M. Kawasaki for useful discussion and technical help. This work was partly supported by the JSPS KAKENHI (Grant No. JP17J03125), Murata Manufacturing Co., Ltd.

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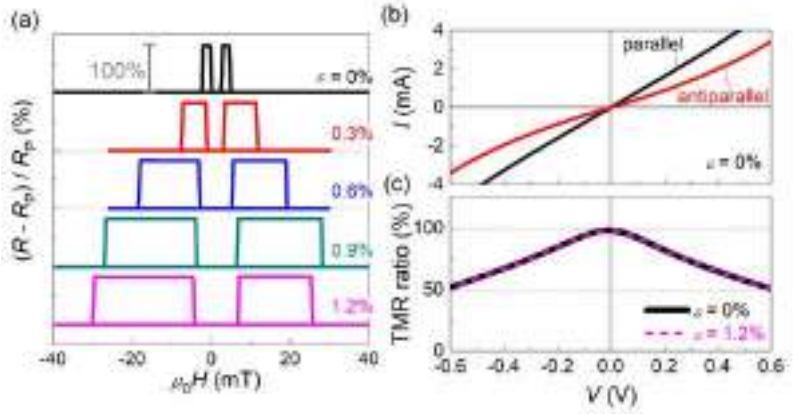
(a)
100%
ε = 0%
0.3%
0.6%
0.9%
1.2%
(R - Rp) / Rp (%)
-40
-20
0
20
40
μ0H (mT)
(b)
parallel
antiparallel
ε = 0%
I (mA)
4
2
0
-2
-4
(c)
TMR ratio (%)
100
50
0
ε = 0%
ε = 1.2%
-0.5
-0.4
-0.2
0.0
0.2
0.4
0.6
V (V)

P64 - Exchange Biased Structures Optimized for Magnetic Nanoparticles Detection

5. Magnetorecording media, magnetic memories and magnetic sensors

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Detection of magnetic nanoparticles (MNPs) used as labels for biosensing applications represents key features in lab-on-a-chip (LOC) devices. Chip-based detection systems using spintronic sensors based on giant magnetoresistance effect (GMR), tunnelling magnetoresistance effect (TMR) or planar Hall effect (PHE) have demonstrated very high sensitivity, low cost and compatibility with integrated circuit technology.
This report demonstrates by micromagnetic modelling and through some experimental results that large-area spintronic sensors can successfully detect low magnetic moments generated by MNPs. The detection method is based on localized reversal nucleation induced by MNPs. The sensing setup used in our simulations and experiments is based on the PHE. The choice is motivated by the relatively large detection area, typical for this setup, large SNR and a very good thermal stability. To find the structures suitable to pattern PHE sensors used for MNPs detection, we deposited exchange biased multilayers of the type Permalloy/NM(x)/IrMn onto 5x5 mm^2 Si substrates. NM denotes nonmagnetic layer as Cu and MgO (0.4 nm). The thickness of the Cu layer was varied between 0 and 0.8 nm. The samples were annealed in magnetic field to define the orientation of the anisotropy and exchange bias fields. The magnetization curves were characterized by VSM. By using typical AMR and PHE setups on these films we obtained precise values for the coercive fields, exchange bias fields and the field sensitivity of the PHE. The measurements were made with the field applied in the film plane both over hard and easy axis of magnetization. For our samples the exchange coupling, H_{EB}, between the Permalloy layer and the antiferromagnetic layer (IrMn) varies between 35 Oe (x=0 nm) and 2 Oe (x=0.8 nm). A field sensitivity of the PHE signal up to 15 µV/Oe was found in our structures for a driving current of 1 mA and x=0.5 nm. When as NM layer we used MgO(0.4 nm), an outstanding sensitivity of 130 µV/Oe was found for a field variation ΔH=2.2 Oe applied in the film plane over the hard axis of magnetization. We found that for structures with low exchange coupling the sensitivity and the width of the linear region can be controlled by applying a polarizing field, up to 100 Oe, perpendicular to the film plane. For detection applications this field can be used, also, to polarize the MNPs placed above the sensor surface. Using this configuration, the MNPs will acquire a high magnetic moment which will interact with the Permalloy layer. The MNPs placed above the sensor surface can nucleate the reversal process in the magnetic layer, increasing the detection sensitivity in terms of magnetic moments. From experimental results regarding field dependences of the PHE for different polarizing fields and micromagnetic simulations for different sensor geometries, the appropriate structure can be selected to build PHE sensors employed in detection of MNPs.

Acknowledgements: *This work was supported by a grant of the Romanian Ministry of Research and Innovation, CCDI-UEFISCDI project number 3PCCDI/2018, within PNCDI III.*

P65 - First Order Reversal Curves of [Ni/Co] modulated Nanowires for 3D memory applications

5. Magnetorecording media, magnetic memories and magnetic sensors

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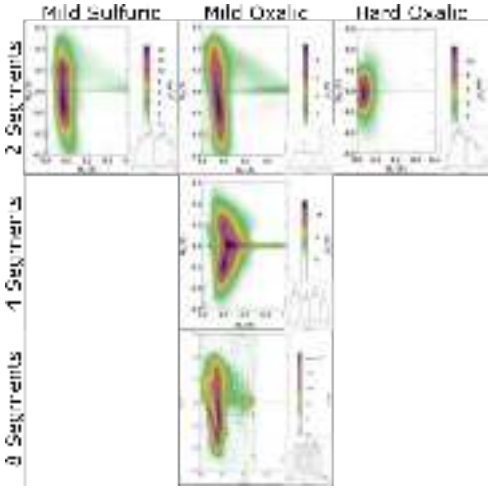
A large and efficient data storage device is described with cylindrical magnetic nanowires fabricated in dense parallel arrays. Inside of the arrays, each nanowire's length is modulated in composition, dividing it into sequential segments of nickel (Ni) and cobalt (Co), each of which holds a one-dimensional magnetization state (bit) independent of their neighbors' bit. Therefore, a large number of modulations and high density of nanowires are achieved for higher data storage capability.

Since inter-wire magnetic interactions may affect individual bit states, it is relevant to study their behavior in commonly used templates. These parallel arrays of nanowires are fabricated by alternating electrodeposition of each metal inside of porous alumina templates. Depending on anodization conditions, the templates display characteristic pore densities (porosity) and diameter (D) to inter-pore distance (D_{int}) ratios: (D/D_{int}). Geometrically, D determines the magnetization state and stray field of each modulated nanowire, and D/D_{int} has an impact on the strength of inter-wire interaction. The impact of this interaction can be studied by varying D/D_{int} ratios and using First Order Reversal Curves (FORC), which provide quantitative measures of such interactions in addition to standard coercive fields.
Here, we perform room temperature FORC studies on arrays of multi-segmented [Ni/Co] nanowires grown in alumina templates anodized under mild sulfuric, mild oxalic and hard oxalic conditions. The characteristic D/D_{int} ratios of these conditions were 0.38, 0.35 and 0.33, respectively, and nanowires of two, four and eight segments were deposited into each template and quantified with energy-dispersive X-ray analysis. To ensure that the observed effects are the result of geometrical changes, the deposited masses of both nickel and cobalt were kept constant, meaning that all nanowires had the same mass, whether two or more segments. In this way, the effect of length and number of segments on the FORC distribution can be studied.

For two-segmented nanowires, the interaction field reduced as the inter-wire distance increased and the ratio of interaction distribution to coercive field increased from 2.1 to 3.6 as D/D_{int} decreased. In addition, the magnetization switching exhibits two interaction field distributions as described in other works. In the case of four segment nanowires, an additional main distribution appears, shifted approximately by 50 mT to higher coercive fields compared to the two segments case. We attribute this new distribution to the higher field required for switching the nickel segment coupled in-between the two cobalt segments. For eight segments, the distributions appear at lower coercive fields, due to the shorter length of the segments. They are related to the switching of one set of segments (nickel) back to saturation assisted by the other set (cobalt) and vice-versa. This indicates that the FORC footprint is highly dependent on the nature of the interactions between sets of segments and their lengths.


Mild Sulfuric
Mild Oxalic
Hard Oxalic
2 Segments
1 Segments
0 Segments

P67 - High Frequency MI in Amorphous Microwires for Magnetic Sensor Applications

5. Magnetorecording media, magnetic memories and magnetic sensors

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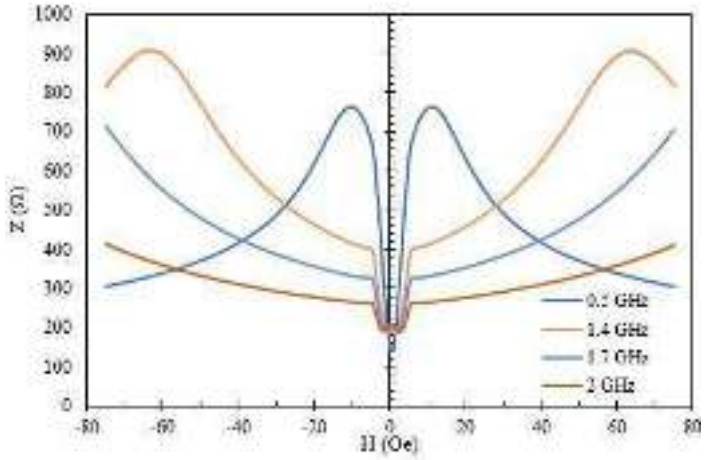
In the past few years, soft ferromagnetic amorphous wires have attracted growing attention in research due to their excellent soft magnetic properties, giant-magnetoimpedance (MI) effect and miniature dimensions. The MI effect which is referred to a large and sensitive change in the complex-valued impedance of a magnetic conductor in the presence of external magnetic field and/or mechanical stress, temperature is of particular interest for the development of various high performance micro-sensor devices. To optimize sensing operation regimes it is important to measure the impedance characteristics of the individual wire which may present considerable problems at higher frequencies in the GHz range. This is related with uncertainties occurring due to calibration of measuring devices (Network Analyzer). In the present work, we suggest a new calibration technique with specially designed microstrip cell for measurement of MI of microwires for frequencies to 6 GHz.

The amorphous microwires of two composition: $Co_{67}Fe_5B_{14}Si_{11}Cr_3$ (sample no.1) and $Co_{66.6}Fe_{4.28}B_{11.51}Si_{14.48}Ni_{14.4}Mo_{1.69}$ (sample no.2) with total diameter of 25.8 and 43 μm and metallic core-diameter of 14.2 and 35.2 μm, respectively, were investigated. An advanced calibration technique with a new microstrip cell specifically designed for measurement of microwire impedance at frequencies ranging from 30 kHz to 6 GHz, was applied. For all samples, the MI was measured in as-prepared state at room temperature without and with applied tensile stress. A characteristic feature of a high frequency MI is that it becomes insensitive to moderate values of magnetic fields if there is no change in the direction of the static magnetization. High frequencies correspond to the “tail” of the ferromagnetic resonance and relatively strong magnetic fields are needed to produce changes in the impedance caused by the frequency dispersion of the permeability. This is demonstrated in Fig. 1 for microwires with a nearly circumferential anisotropy. For a frequency of 2 GHz moderate magnetic fields which are higher than the saturation field do not produce large changes in the impedance. Therefore, in order to design sensing devices based on GHz frequency MI, the external stimuli must produce the re-orientation of static magnetization.

Figure 1. Magnitude of the complex impedance vs magnetic field of amorphous $Co_{66.6}Fe_{4.28}B_{11.51}Si_{14.48}Ni_{14.4}Mo_{1.69}$ *microwires at various frequencies in the GHz range.*



P68 - Low Tc Fe-Cr-Nb-B glassy alloys with variable Cr content for high sensitivity temperature sensors

5. Magnetorecording media, magnetic memories and magnetic sensors

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Sensitive magnetic temperature sensors can be designed by changing the Curie temperature (T_C) of a magnetic material in a controlled manner.

In this work we will present our recent results on the microstructure, magnetic properties and temperature transition of $Fe_{79.7-x}Cr_xNb_{0.3}B_{20}$ (x = 11.5÷13.5 at.%) glassy melt-spun ribbons with T_C ranging from 290 to 330 K, depending on the Cr content (the lower the Cr content the higher the temperature of the ferromagnetic-paramagnetic transition). High resolution imaging and electron diffraction confirm that in the as-quenched state the structure is completely amorphous, independent of the Cr content. Clear indications have been found of Fe and Cr clusters varying from approximately 1-2 nm to 7-8 nm in size with the increase of Cr content from 11.5 to 13 at.%. The Fe and Cr atoms clearly segregate the atomic scale to form nanometer sized clusters, influencing strongly the macroscopic magnetic behavior. The a.c. magnetic susceptibility temperature dependence presented in figure confirms the ferromagnetic-paramagnetic transition at low T_C, and its sudden drop recommends these materials for high sensitivity temperature sensors or hyperthermia applications.

The temperature sensor was constructed by winding of 150 turns of enameled copper wire of 0.07 mm diameter on a glass tube with elliptical section, in which the magnetic core (Fe-Cr-Nb-B magnetic ribbon) was introduced. To be used as a temperature sensor this small coil was inserted in a Colpitts oscillator using an operational amplifier. For the output signal to be rectangular, a pulse generator was set-up using an operational amplifier in comparator configuration. The change in the temperature of the magnetic core induces a very high change rate in the magnetic permeability, hence changes in the coil’s inductance and consequently in the output frequency. Using this configuration, temperature sensors of small dimensions, high sensitivity (0.1–0.025), and good repeatability can be constructed. The proposed sensor can be also used as thermostat for various applications or on-off switches type relays.

Financial support from the Contract No. 11PFE/16.10.2018 and Contract No. 33N/2019 (Project PN 19 28 01 01) funded by the Romanian Ministry of Research and Innovation (MCI) is highly acknowledged.

P69 - Magnetic Field Concentrator with Nanosize Cuts

5. Magnetorecording media, magnetic memories and magnetic sensors

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Ultra-weak magnetic fields with values $B_0 \leq 10^{-9}$ T arising in the physiology of biological elements (neurons, cells, tissues, organs, etc.) need to be registered non-invasively. At present, ultra-weak magnetic fields are measured by various types of magnometers: SQUIDs (Superconducting Quantum Interference Device), quantum magnetometers, fluxgate transducers, etc. For SQUIDs, the threshold sensitivity, that is the minimum recorded magnetic field, is at level of $\delta B_0 \sim 10^{-15}$ T. To improve the basic parameters (in particular, reducing of δB_0) of magnetic field sensors, it is necessary to use magnetic field concentrators. In most magnetic field sensors, high resolution, i.e. low threshold sensitivity $\delta B_0 \sim 10^{-9}$ T , is achieved through the use of superconducting film concentrators.

This paper presents calculations of the magnetic field concentration factor F in planar combined magnetic field sensor, when the active strip of the concentrator is in both nanostructured and non-nanostructured states. While in the inductances of the receiving rings of the concentrator are taken into account.

Optimal active strip nanostructuring of a magnetic field concentrator based on superconducting films allows to further increase the concentration ratio of the device. The magnetically sensitive element was placed between two concentrator rings lying in the same plane without crossing. Calculated concentration coefficients F and F_0 of a planar concentrator with an active strip with nanosize cuts and without them. Different position of the cuts in the active strip of the concentrator were invastigated, as well as different values of the magnetically sensitive element width w_0 and the London penetration depth λ. In the calculations it was assumed that the width of the cut w_p coincides with the distance w_a between the ends of the near concentrator and magnetically sensitive element. The active strip width w_s and width of the superconducting branch were multiples of w_a. It turned out that as w_0 decreases, F_0 increases and F decreases but the total concentration coefficient $F^* = F_0 \times F$ increases. F^* value for a concentrator based on the niobium film (λ ~ 50 nm) is higher than for the concentrator based on films Y-123 or Bi-2223 (λ ~ 250 nm). The considered concentrator with nanosize cuts will increase the efficiency of combined magnetic field sensors, SQUIDs, and other sensors with a resolution of $\delta B_0 \leq 1$ pT.

In modern medicine, relevant biocompatible materials (nanomaterials with ferromagnetic or superparamagnetic particles, carbon nanotubes, etc.), as well as non-invasive diagnosis and control of active implanted devices (artificial heart, various stimulants, measuring blood flow velosity, etc.) are relevant. The sought-after task are likely to be solved using magnetic field sensors with superconducting film magnetic field concentrators with nanostructured active strips.

Aithor is grateful to N.Yu. Shichkin for his help in the calculations. The work was supported by the Ministry of Education and Science of the Russian Federation (Agreement 14.578.21.0234 RFMEFI57817X0234).

P70 - MAGNETOMODULATION SENSOR BASED ON CERAMIC HIGH TEMPERATURE SUPERCONDUCTOR

5. Magnetorecording media, magnetic memories and magnetic sensors

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In many areas of human activity, for example, in electronic compasses, archaeological research, spacecraft, as well as in biomedical applications, magnetic field sensors (MFS) with ultra-low threshold sensitivity $\delta B \leq 1$ nT are in demand. Such MFS are especially important in non-invasive medical diagnostics which require registration of an ultra-weak magnetic field in the range of 1 nT ÷ 10 fT. For example, for a wound diagnosis of heart disease, value δB should be in the region of $\delta B \leq 100$ pT.

The developed ceramic high-temperature superconductors (HTSC) showed the properties of the Josephson medium and the prototypes of the magnetic modulation (MM) sensor of the magnetic field based on them were proposed. They were mainly created on the basis of the HTSC material of the Y-123 systems. They showed an acceptable magnitude sensitivity against a small measurement range $\Delta B = \pm 0.3$ mT.

We investigated the differential MM MFS based on ceramic HTSC material of the system Bi-2223. A magnetically sensitive sensor element served as a cylindrical rod made of ceramic with the length of 10 mm and the diameter of 2 mm. Almost the entire length of the samples (~ 8 mm) tightly wound two coils: an exciting one consisting of two identical encountered included sections of 50 coils (turns) each, and on top of it – a signal one containing 100 coils (turns). MM MFS functioned in the differential mode, which automatically excluded the influence of the odd harmonics of the response on the signal winding. The useful signal was the response (voltage) at the second harmonic. The excitation frequency f varied in the range of 5–50 kHz, and the selectivity of the harmonics provided a selective nanovoltmeter at 40 dB/octave.

It was established that the useful signal U_2 linearly depends on f, while the magnetosensitivity $S = \mathrm{d}U_2/\mathrm{d}B$ grows linearly from f. The experiment recorded: $S \sim 500$ V/T, $\delta B \sim 30$ pT, $\Delta B = \pm 0.7$ mT, in the region of $\Delta B = \pm 15$ mT the dynamic measurement range ~ 120 dB. Estimates showed that with optimal selection, the number of turns, selectivity, the identity of the two parts of the rod, the threshold sensitivity could be reduced significantly and make $\delta B \leq 1$ pT. By the same time, the MM MFS proposed by us is approaching the resolution of HTSC SQUID. Besides, MM MFS has a number of positive properties, for example, direct measurement of the absolute value of the recorded magnetic field is simple to control and is available, while SQUIDs do not possess such properties.

Thus, the investigated differential magnetic modulation magnetic field sensor can compete with HTSC SQUIDs, in particular, in biomedical applications for non-invasive registration of magnetic particles, as well as various implantable devices or artificial organs in biological objects.

This study was supported by the Russian Science Foundation, project No.18-79-10008.

P71 - Properties of Magnetometer Utilizing High-Tc Superconducting Coil and Inductance Modulation Scheme

5. Magnetorecording media, magnetic memories and magnetic sensors

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We have been developing a magnetometer utilizing high-critical-temperature superconducting (HTS) coil and inductance modulation scheme [1]. Figure 1(a) depicts an equivalent circuit of the magnetometer. The magnetometer consists of pickup and input coils made from HTS tape. These two coils are connected with very low joint resistance (R_c << 20 micro Ohm), and form a closed loop. When the signal flux Phi_s with frequency f_s is collected by the pickup coil, signal current I_s flows in the loop. The inductance of the input coil, L_i, is modulated over time by supplying a modulation current I_m to an amorphous magnetic wire (SENCY 120FC20, Aichi Steel) that was inserted into the input coil. Using this this time-dependent inductance, a signal voltage V_s is generated across the terminal P-Q of the input coil, i.e., $V_s = I_s \times (dL_i/dt)$.

We fabricated a prototype of the magnetometer. The coils were made from an HTS tape with width of 2 mm (SF2050, SuperPower). The average diameter, the number of turns and the inductance of the pickup coil were D_p = 25 mm, N_p = 50 and L_p = 65 micro H, respectively. The parameters of the input coil were D_i = 20 mm, N_i = 60 and L_i = 50 micro H, respectively. In order to modulate the inductance L_i, we supplied DC and AC current to the magnetic wire, i.e., $I_m = I_{DC} + I_{AC} \sin(2\pi f_m t)$.

We studied performance of the magnetometer. The magnetometer was cooled with liquid nitrogen, and operation temperature was T = 77 K. It was shown that the magnetometer can measure low-frequency signal fields down to 0.03 Hz without any reduction in responsivity (or the field-to-voltage transfer coefficient). This is because the current I_s becomes independent of the signal frequency f_s when the condition that $2\pi f_s(L_p+L_i) >> R_c$ holds: This condition is satisfied for f_s > 0.03 Hz in the present case. It was also shown that the responsivity increased with increasing I_{AC} or f_m of the modulation current. For example, we obtained the responsivity of 2480 V/T when we used the modulation current with I_{DC} = 76 mA, I_{AC} = 35 mA and f_m = 900 kHz. Figure 1(b) shows the noise spectrum of the magnetometer. As shown, the magnetic field noise was 0.72 pT/Hz$^{1/2}$ above 25 Hz. At low frequencies, the field noise increased with decreasing the frequency, and reached 9 pT/Hz$^{1/2}$ at 1 Hz. The peak noise at 5 Hz will be caused by the vibration noise. We note that low frequency noise changed when different wires were used, indicating that the low frequency noise depends on the quality of the magnetic wire.

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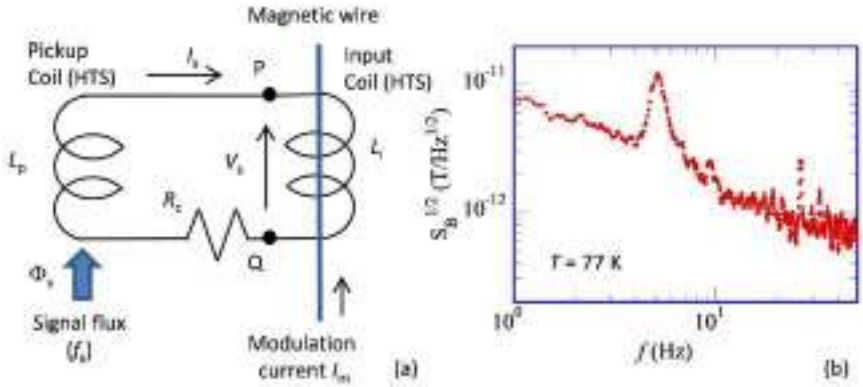

Fig. 1. (a) Equivalent circuit of the magnetometer. (b) Magnetic-field noise spectrum of the magnetometer measured at $T = 77$ K.

P72 - Reducing the switching current with a DMI in ECC nanomagnets with perpendicular anisotropy

5. Magnetorecording media, magnetic memories and magnetic sensors

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The author has chosen not to publicise the abstract.

Field 5

Field 6

P73 - Registration Magnetic Particles in Biological Objects

5. Magnetorecording media, magnetic memories and magnetic sensors

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The life process is accompanied by indexing of super-weak magnetic fields in various parts (organs, muscles, nerves, cells) of the organism. Weak magnetic fields in the human body can also be created by ferromagnetic particles that are captured or intentionally introduced into it. Indeed, micron-, submicron- and nanoscale magnetic particles (MP) are widely used in medical practice, for example, to: improve the contrast of magnetic resonance imaging (MRI), diagnose and treat cancer, targeted drug delivery to certain organs, etc. In particular, spherical MPs coated with active substances are used to isolate DNA and RNA from biological materials. In this case, the nucleic acid is stored with MP much longer than in their absence. The MP magnetization is more than ten million times greater than the magnetization of the medium in the MRI method, therefore, MP will allow you to create a tomography with a small magnetic field of a few mT.

In this regard, we offer estimates of the minimum concentration and the minimum size of magnetic particles, within which modern ultrasensitive magnetic field sensors can register them.

Calculations showed that magnetite MP with specific magnetization 50 $A \cdot m^2/kg$ with characteristic dimensions of 50 nm and concentration $C_V \sim$ 1 vol. ‰ can be detected by magnetic resistance magnetic field sensors, for example, HMR1001 – have threshold sensitivity $\delta B \sim 10^{-9}$ T, at a distance of ≤ 0.1 mm. However, the very same MP c will be detected using SQUID magnetic field sensors or combined magnetic field sensors with an operating temperature of ~ 4 K. It is assumed that these sensors have $\delta B \sim 10^{-15}$ T and will be at a distance of ~ 1cm from MP. These sensors also have the potential to record individual MPs of spherical shape with micron sizes.

It is noted that superparamagnetic particles of iron and carbon nanotubes containing particles of catalytic iron can also be detected only with the help of SQUIDS or combined magnetic field sensors.

Thus, modern supersensitive magnetic field sensors with $\delta B \sim 10^{-15}$ T will allow magnetic particles to be recorded in biological objects. They can be used for non-invasive control of organs, implants, prostheses and vector drug delivery in the right parts of the body.

This study was supported by the Russian Science Foundation, project No.18-79-10008.

P74 - Sensoric application of bistable glass-coated microwires.

5. Magnetorecording media, magnetic memories and magnetic sensors

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Glass-coated microwires are unique group of material that offer some advantages in practical applications. First of all, it is their extremely high added value due to the very efficient production. It allows to produce up to 100 000 sensors from few gram of iron-based master alloy within 10 minutes. Glass-coating provides insulation from electrical short-circuits, from chemically aggressive environment and provides biocompatibility as well. Their dimensions allow introduction inside almost any material without changing its functional properties. Magnetic nature gives advantage of contactless sensing from the distance. High durability (high elasticity because of amorphous nature) increases their wide range of potential applications.

In the present contribution we offer some examples how bistable microwires can be used to sense internal stress in 3D printed materials or how stress dependence of the switching field can be employed for monitoring osteomalacy in medicine.

Understanding correctly magnetic material science allows for adjustment of chemical composition to obtain high sensitivity to various range of applications from technical (temperature range up to 150°C) to medical (temperature range from 35-45°C) using the onset of superparamagnetism in early stage of nanocrystalline phase. We offer the proof of concept for intracranial temperature monitoring using the personalized titanium implants.

This work was supported by Slovak Grant Agency VEGA 1/0053/19 and VEGA 1/0185/18,Slovak Grant Agency grant number APVV-16-0079 and APVV-17-0184.

P76 - Topology optimization of magnetic structures using the adjoint method

5. Magnetorecording media, magnetic memories and magnetic sensors

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In many applications like magnetic sensors, the geometry of involved magnetic structures is crucial with respect to performance. The process of optimizing the geometry of these structures can be very time consuming. Usually the structure's geometry is parameterized with relatively few parameters and the parameter region is investigated until an optimal solution is found. This process is called shape optimization. Another approach is to directly optimize the structure's topology. This increases the degrees of freedom dramatically but aims to find a global optimum. Utilizing the adjoint method, inverse problems, including topology optimization problems can be solved accurately and in a reasonable time frame. We present a method of solving the inverse magnetostatic Maxwell problem to optimize the topology of magnetic structures. The algorithm is based on a hybrid FEM/BEM approach [1] solving the magnetostatic Maxwell problem highly efficient. In contrast to already presented FEM [2] and FD [3] algorithms using a FEM/BEM approach has the advantage that only the regions of interest need to be discretized reducing the degrees of freedom drastically. Our method takes the B/H curve of a hard of soft magnetic material linearized at the working point as input and is able to include external fields generated from electronic sources (e.g.: coils). After optimization, the result is an optimized magnetic structure and its stray field dependent magnetization state.

In order to perform the topology optimization a scalar density function $\rho \in [0, 1]$ is introduced to scale the susceptibility $\chi \rightarrow \rho^p \chi$ and the remanence magnetization $M_r \rightarrow \rho^p M_r$. p here is a parameter penalizing values in the interval (0, 1) to only obtain values at 0 (no material) or 1 (material).

The optimization is performed by minimizing an objective functional $J(\rho)$ for a given problem. The objective functional is minimized iteratively by calculating its gradient $dJ/d\rho$ using the adjoint approach. Additional constraints on the solutions (e.g. volume constraints) can be incorporated by various regularization terms.

We present several examples showcasing the capabilities of our method and compare the results to a method optimizing topologies using fixed magnetization vectors [2]. The examples include the optimization of a quasi-two dimensional, soft magnetic structure maximizing the magnetic flux at a given point (see attached image figure 1). Such a two dimensional flux concentrator or flux guide can be used to improve the efficiency of magnetoresistive sensors [4]. Furthermore, the topology of the tip of a magnetic yolk is optimized to obtain a maximal field in an area inside the yolk's opening (see attached image figure 2).

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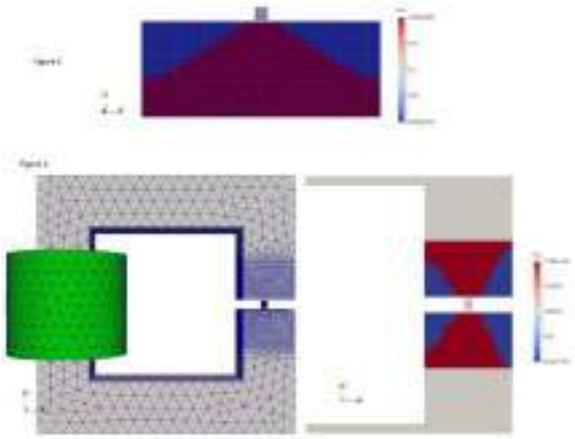

6. Magnetic thin films, multilayers, surface and interfaces

P77 - Amorphous interfaces: extending magnetic exchange coupling to the mesoscale

6. Magnetic thin films, multilayers, surface and interfaces

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Composites and superstructures represent one of the most effective ways to create new materials with improved properties. The degree of integration among the components represents a crucial point that marks the difference between a composite which shows the properties of the original components as independent players, and a genuine new material that exhibits the best qualities of the parent materials or, even better, with new emerging properties. In this framework, the main role is played by the quality of the interfaces between the original phases. Unfortunately, this aspect is just as important as difficult to control, especially due to structural defects which easily degrade interfaces. We deal with the root of the interface problem through the use of a non-conventional approach, namely realizing fully amorphous system. By this choice, we can avoid the defects associated with crystalline interfaces. We have selected $Fe_{89}Zr_{11}$ as a model amorphous material. A thin film (15 nm) of amorphous $Fe_{89}Zr_{11}$ was produced by magnetron sputtering. Later, a regular lattice of amorphous $Fe_{80}Zr_{10}X_{10}$ elements (X = B or C) has been created by means of light ion implantation through a mask, realized by lithographic techniques. Each sample is constituted by $Fe_{80}Zr_{10}X_{10}$ elements with specific shapes (e.g., disks, triangles, squares, sticks), fully embedded in the original amorphous matrix. The implantation does not induce crystallization or any other major structural modification, but it locally creates elements with different magnetic anisotropy, saturation magnetization and Curie temperature with respect to the matrix, i.e., a second magnetic phase [1]. The magnetic coupling between the two phases can extend over an extraordinary long-scale thanks to the absence of sharp interfaces, showing a single phase magnetization reversal, up to a distance of 5 micrometers, far beyond the 200 nm limit expected according to conventional models of exchange coupling [2,3].

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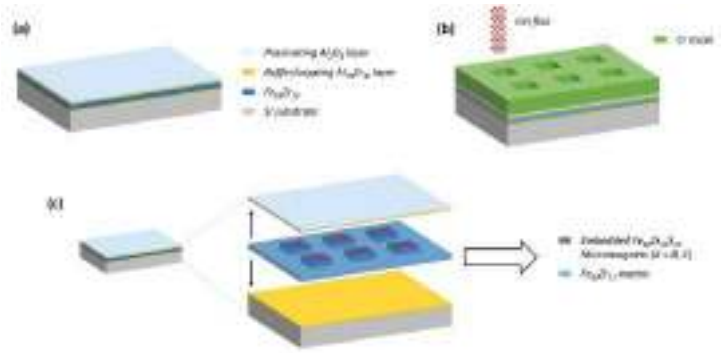

Figure 1. (a) Original as-sputtered sample. (b) Implantation of ions into the unmasked parts of the sample with a lithographically produced Cr mask on top. (c) Exploded view of the final sample (after removal of the mask) with 2D amorphous magnetic elements embedded within the original amorphous matrix.

P78 - An experimental study on magnetic field distribution above a magnetic liquid free surface

6. Magnetic thin films, multilayers, surface and interfaces

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Recently, a numerical evaluation has been reported of the magnetic field distribution above a hexagonally distributed spikes pattern of a magnetic liquid free surface. To support theoretical predictions, as well as numerically obtained results, the measured values of the magnetic field above the magnetic liquid free surface are disclosed in the article. The measurement technique is performed by scanning a magnetic field induction with a Hall sensor at a close distance above the free surface (spikes). The results show that the experimentally obtained magnetic field is distributed in a similar way as a free surface, thus, a quality image of spikes can be reproduced by the magnetically-based technique introduced in the article.

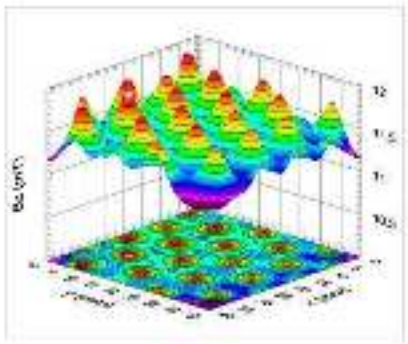

Figure 1. Measured values of a magnetic field (magnetic induction B) above magnetic liquid spikes.

P79 - Anomalous Hall Effect characterisation of magnetic anisotropy in Pt/CoFeB/Ir multilayers

6. Magnetic thin films, multilayers, surface and interfaces

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At the interface of a 5d metal and a thin film 3d ferromagnet such as Pt/Co, the interfacial Dzyaloshinskii-Moriya interaction (DMI) leads to domain walls with a defined chirality and skyrmion-like domains in the ferromagnet that are promising for low-power magnetic memory devices [1]. Furthermore, voltage-control, mediated by strain, of thin film magnetism promises high power efficiency in nanomagnetic devices [2]. Recently, skyrmion bubbles have been imaged and their magnetotransport signature recorded in a Pt/Co/Ir multilayer dot [3,4]. We have also measured the effect of out-of-plane strain on domain wall properties in Pt/Co thin films [5,6]. In this work we investigate multilayers with the following structure: Ta(5)/[Pt(2.3)/$Co_{68}Fe_{22}B_{10}$(0.7)/Ir(0.5)]$_n$/Pt(2.3) (thickness in nm) grown on Si/SiOx, Pb($Mg_{1/3}Nb_{2/3}$)O_3–$PbTiO_3$ (PMN-PT) (001) and glass substrates, which show perpendicular magnetic anisotropy (PMA). We study the magnetic anisotropy using a technique based on the Anomalous Hall Effect (AHE) and the strain effect upon multilayers applied by a piezoelectric transducer.

Multilayers with structure [Pt/CoFeB/Ir] $_n$, where n is the number of repeats, were deposited by dc magnetron sputtering. In all cases samples have PMA as shown in Fig.1. (a). For n = 2 the multilayers have square hysteresis loops. However, for n >2, the hysteresis loops become increasingly wasp-waisted due to the increased pinning effect on domain walls. Meanwhile, the anisotropy field $\mu_0 H_k$ is found to decrease as the number of layers increases, regardless of the substrate, as indicated by the decreasing width of the parabolas in each graph in Fig .1.(b). The decrease of the $\mu_0 H_k$ is a consequence of the surface roughness, which increases with each successive layer.

Lastly, we report on the anisotropy measurement of (Pt/CoFeB/Ir) $_5$ thin films grown on glass under strain applied perpendicular to plane using a piezoelectric transducer. A voltage from 0 V to 150 V applied to the transducer generates a maximum strain of ~0.1% [5]. This results in a decrease of the perpendicular magnetic anisotropy in the films up to 10 kJ/m^3.

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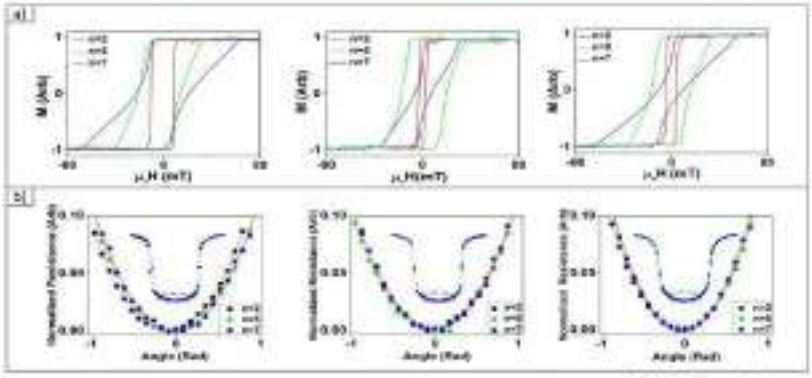

Fig.1. (a) Polar MOKE measurement for Ta/[Pt/CoFeB/Ir]$_x$/Pt multilayers on Si/SiOx, PMN-PT and glass substrates. (b) Normalised anomalous Hall effect the anisotropy decreased as the number of layers increased on all substrates.

P80 - Change of damping constant with microstructure in nanocrystalline YIG thin films on Si substrate

6. Magnetic thin films, multilayers, surface and interfaces

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The author has chosen not to publicise the abstract.

Field 5

Field 6

P81 - Characterisation of Magnetostriction with Observation of Magnetic Ripple using Lorentz TEM

6. Magnetic thin films, multilayers, surface and interfaces

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The effect of magnetostriction is an important, though less intensively studied, effect in magnetic data storage technology. Although the presence of magnetostriction in device materials may be small it is recognised as important and previous bulk measurement techniques that it can have a significant effect on the magnetic properties particularly in the presence of tensile and compressive forces [1]. The effects of magnetostriction for materials without such applied external stresses but under normal operating conditions are less well understood and we are interested in a micromagnetic study to investigate this from an experimental and modelling perspective.

We have chosen to study one of the most commonly used materials in data recording, permalloy with a composition around the varying around the 80/20 nickel to iron ratio. The reason for choosing this value if that the magnetostriction constant changes from negative to positive around this composition as the elemental ratio changes. We aim to identify the subtle effects magnetostriction has on continuous thin films of permalloy with five different compositions by studying their micromagnetic behaviour. Experimentally we have studied the effect of magnetostriction in observed magnetic ripple using Lorentz transmission electron microscopy (LTEM) [2]. This nano-scale visualisation of the magnetisation ripple structure allows for not only the mapping of hysteresis behaviour, but quantitative characterisation of the material [3]. For the first time, we can quantitively asses the magnetic effect magnetostriction has on the hysteresis behaviour of these samples, without the need for external straining. Simulations can be performed in conjunction these studies using the package Mumax3 [4], in order to compare simulated with experimental results.

Keywords: Magnetic materials, polycrystalline, Lorentz microscopy, magnetostriction, magnetisation ripple, anisotropy.

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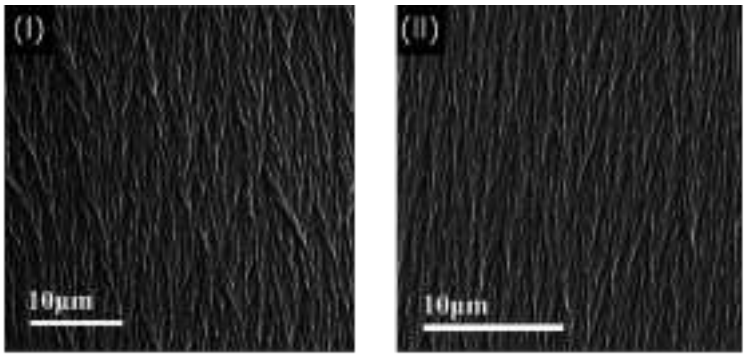

Figure 1: 80/20 NiFe Lorentz TEM results of (i) experimental, and (ii) Mumax3 simulation, demonstrating magnetisation ripple at zero field. These images can be analysed to investigate how the magnetisation ripple values change with different magnetostrictive values, throughout the hysteresis sequence.

P82 - Conducting LaVO3/SrTiO3 Interface: Is Cationic Stoichiometry Mandatory?

6. Magnetic thin films, multilayers, surface and interfaces

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The origin of the conductivity at the interface of two insulating perovskite oxides has been a matter of intensive studies. The conductivity generated at the interface of insulating $LaVO_3$ (LVO) and $SrTiO_3$ (STO) has been explained in terms of polar catastrophe. Here we grow LVO films on (001) TiO_2-terminated STO substrate employing pulsed laser deposition technique and demonstrate a transition from conducting to insulating interface by changing the La-stoichiometry by only 1 %, whereby such transitions take place for La-deficient films. Moreover, the cation non-stoichiometry of La-deficient LVO film has negligible effect on both carrier density and mobility of the charge carriers. Our observation suggests a revisit to the explanation of possible origin of such conductivity beyond the polar catastrophe scenario and can be instrumental in search for novel conducting interfaces.

P83 - Control of magnetic structure in Co/Pd superlattices with Dzyaloshinskii-Moriya interaction

6. Magnetic thin films, multilayers, surface and interfaces

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Structural and magnetic properties of symmetric crystalline [Co(d_{Co})/Pd(2 nm)]$_5$ superlattices were investigated depending on the thickness of Co layers. [Co/Pd(111)]$_5$ superlattices were epitaxially grown on Si(111) substrate with Cu buffer layer. The thickness of Co layers d_{Co} was varied from 0.8 to 1.6 nm. We have analyzed strain distribution in Co and found that Co layers are strained much larger at the bottom than at the top. This fact is explained by the epitaxial growth of Co on Pd and gradual strain relaxation despite the large 9.6% lattice mismatch between Co and Pd. We have shown that the profile of strain relaxation in the each Co layer of the [Co(d_{Co})/Pd(2 nm)]$_5$ superlattices is nearly the same.

A strong dependence of the magnetization reversal processes and magnetic structure in the [Co/Pd(111)]$_5$ crystalline superlattices on the Co layers thickness was observed. The dependence of perpendicular magnetic anisotropy (PMA) on the thickness of Co layers obeys the usual 1/d_{Co} law. The shape of the out-of-plane hysteresis loops strongly depends on the Co thickness. With increasing of the Co thickness they elongate towards magnetic field axis and remind vortex hysteresis loops in magnetic nanodots. The samples with relatively strong PMA self-demagnetize in the absence of the magnetic field. One possible explanation of the self-demagnetizing phenomenon of the samples with relatively strong PMA may be presence of uncompensated interface Dzyaloshinskii-Moriya interaction (DMI) in this system.

We evaluated the effective energy of the DMI, D_{eff} in this system by comparing the periods of the experimentally obtained and simulated demagnetized labyrinth domain structures as in [1]. It appeared that D_{eff} practically does not depend on the thickness of Co layers in [Co/Pd]$_5$ superlattices. It slightly increases from 2.2 to 2.5 mJ/m^2 if d_{Co} changes from 0.8 to 1.6 nm. Magnetic structure, skyrmion stability, sizes of stripe domains and skyrmions are determined mainly by relation of PMA and DMI energies. Since PMA decreases but DMI remains nearly the same with increase of d_{Co} the magnetic structure in the [Co/Pd]$_5$ superlattices may be precisely controlled. In thin [Co(0.8 nm)/Pd]$_5$ superlattices stable isolated skyrmions may be stabilized in zero magnetic field (fig. 1(a)). Increasing of d_{Co} to 1.2 nm leads to self-demagnetization of the samples and spontaneous nucleation of labyrinth domains and skyrmions in the remanent state (fig. 1(b)). The sizes of the stripe domains and skyrmions decrease with further increasing of Co layer thickness (fig. 1(c)). Taking into account results of our previous work, in which we have established the possibility of controlling the effective DMI energy in [Co/Pd]$_N$ superlattices by variation of the number of Co/Pd bilayers [2], it may be concluded that epitaxial Co/Pd(111) system is perspective and very flexible system for Neel-skyrmions investigation.

The reported study was partially funded by RFBR under the research projects № 18-02-00205, 18-32-20057 and by the Grant program of the Russian President (MK-5021.2018.2).

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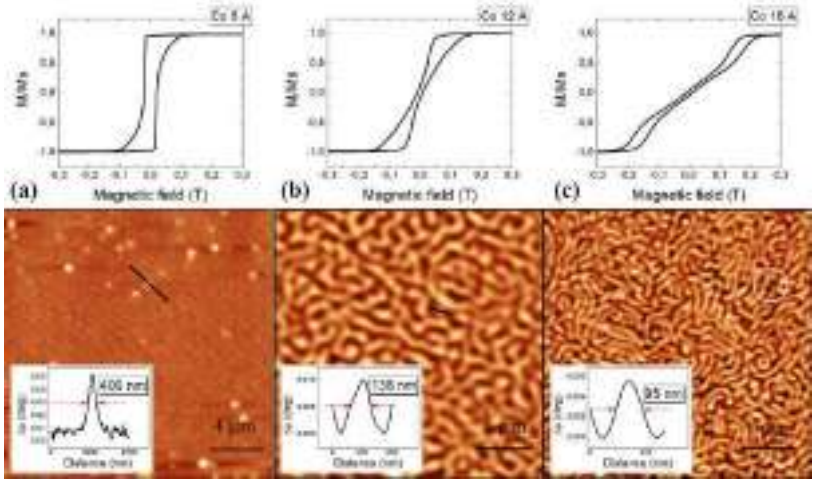
Co 8 Å
Co 12 Å
Co 16 Å
(a)
(b)
(c)
Magnetic field (T)
Magnetic field (T)
Magnetic field (T)
400 nm
138 nm
95 nm

P84 - Controlling microscopic properties of polycristalline exchange bias thin films

6. Magnetic thin films, multilayers, surface and interfaces

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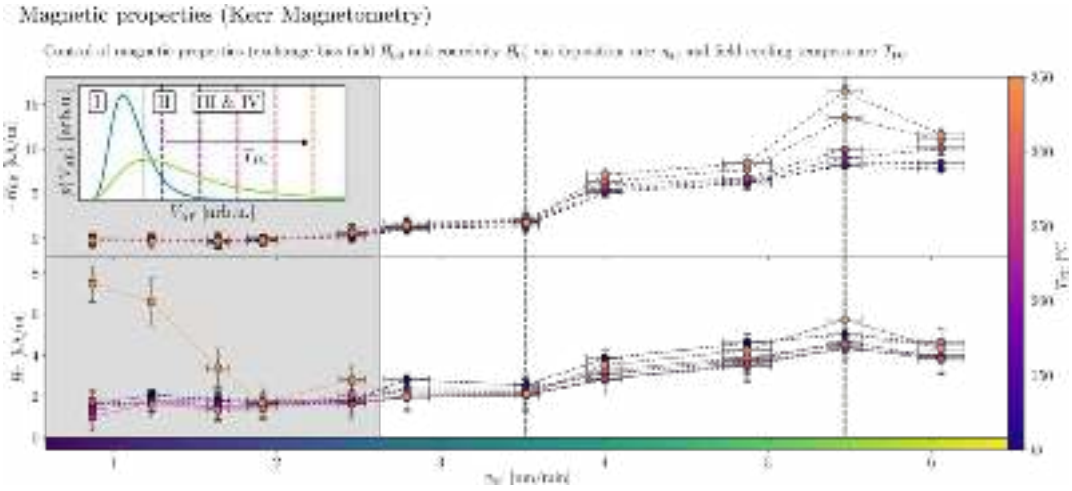
The exchange bias (EB) is a magnetic phenomenon which occurs in thin films, when an antiferromagnet (AF) and a ferromagnet (F) are combined. The effect manifests itself as a shift (unidirectional anisotropy) and broadening of the ferromagnetic hysteresis loop resulting from exchange interaction taking place at the common interface between the AF and F layer. For polycrystalline EB films fabricated by sputter-deposition, the macroscopic magnetic properties evolve from a complex interplay of different individual magnetic anisotropies which are directly connected to the grain size distribution, crystallite texture and interface structure of the layer system. These structural characteristics can be addressed e.g. via deposition parameters or manipulated during a thermal activation procedure in an external magnetic field. The former defines different classes of AF grains that are formed during deposition and how these grains affect the F during the magnetization reversal while the latter steers the coupling of a specific set of grains in respect to their thermal stability. Angular-resolved magnetization curves acquired by Kerr magnetometry are compared with an extended Stoner-Wohlfarth model, which allows for the quantification of material properties in dependence of the layer thickness, deposition parameters and the field cooling temperature, supporting common structure zone models. The obtained results demonstrate, that the EB shift only occurs beyond a certain threshold deposition rate for the AF layer, where the strength of the EB field can be systematically varied by further increasing the deposition rate. Field cooling at various temperatures allows for selectively tuning the contribution of different AF grain classes to both the coercive field and the EB. Furthermore, variation of the AF layer thickness reveals an additional degree of freedom to manipulate the thermal stability of involved AF grains.



P85 - Controlling the crystalline and magnetic texture in sputtered Fe0.89Ga0.11 thin films

6. Magnetic thin films, multilayers, surface and interfaces

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In this work we present a careful study on the relationship between the magnetic and structural properties of a highly magnetostrictive $Fe_{0.89}Ga_{0.11}$ (Fe-Ga) alloy deposited onto glass, Si and MgO substrates. Thin films with a nominal thickness of 200 nm were fabricated by dc magnetron sputtering on glass and on single-crystals of naturally oxidized Si(100) and MgO(100). The samples were deposited from a 3.8-cm diameter Fe-Ga alloy target with a Ga nominal atomic composition, x = 0.17. The annealing procedure consisted in increasing the sample temperature to 250 C, holding during 2 hours in the growing chamber and, then, cooling down to room temperature in 2 hours. The Fe and Ga concentration in the target and the films was determined by means of X-ray photoelectron spectroscopy (XPS), Rutherford backscattering (RBS), energy dispersive X-ray spectrometry (EDX) and particle induced X-ray emission (PIXE). The structure of Fe-Ga films was also studied by X-ray diffractometry performing conventional Bragg-Brentano theta-2thea scans using an eulerian cradle for the determination of the interplanar distances. The crystallographic texture of the samples was obtained for the (110), (200) and (211) reflections.
The magnetometry study was performed by a superconducting quantum interference device (SQUID) and a vibration sample magnetometer (VSM) with an applied field H along several in-plane angles. Magnetic anisotropies were determined by ferromagnetic resonance (FMR) at a excitation frequency 24 GHz (K-band). For this purpose, we performed angular measurements in the film plane with the aim of obtaining the relationship between the resonance field at different in-plane film directions. All the magnetic measurements were done at room temperature.

Fe-Ga thin films grown on three different substrates, i.e., glass, Si and MgO with the goal of obtaining different magnetic Fe-Ga behaviors by changing the crystalline Fe-Ga texture. As expected, the structural study shows that the Fe-Ga texture depends on the substrate. Fe-Ga on glass grows without any preferential direction. FeGa/Si(100) presents a small textured volume fraction, with the {113} family plane directions perpendicular to the film surface. Finally, the MgO crystalline structure determines an epitaxial growth of the Fe-Ga with (100) planes parallel to the substrate surface showing a very good monocrystallinity. When Fe-Ga/MgO(100) is annealed, an additional texture is detected with the (110) plane parallel to the film surface. Magnetometry and ferromagnetic resonance (FMR) show that the magnetic behavior is closely related to the structural observed textures. Furthermore, the structural analysis allowed us to get a deeper understanding of the magnetic behavior.

This work shows that the ability of controling the crystalline texture in ferromagnetic materials gives the possibility of obtaining different magnetic behaviors. This is particularly important in highly magnetostrictive materials, such as Fe-Ga, because it allows to tune their magnetoelastic properties in order to be used in straintronics magnetic devices.

P86 - Determination of the morphology of epitaxial Fe/MgO granular multilayers by magnetometric technique

6. Magnetic thin films, multilayers, surface and interfaces

A. Vovk[1] , *A. García-García[1], Y.G. Pogorelov[1], J.A. Pardo[2, 3, 4], P. Štrichovanec[4], C. Magén[4, 5],* ***P. A. Algarabel***[4, 5]*, J.P. Araujo[1], G.N. Kakazei[1]*

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Magnetic discontinuous metal insulator multilayers (DMIMs) attract a lot of attention due to their potential applications as sensors with advanced response to magnetic field and memristors. DMIMs represent a special type of nanostructures where magnetic particles are arranged in layers (not distributed randomly over the volume as in the case of granular metal-insulator mixtures) and thus are considered as model systems for the magnetic interactions in 2-dimensional case and percolation studies. It is known that, due to big difference in surface free energy of metals and insulators leads to non-wetting, and, in diluted regime, metallic particles of a few nanometters size encapsulated in the insulator matrix are formed. Recently we have grown epitaxial Fe/MgO DMIMs on MgO(001) single crystal substrates at different deposition conditions [1].

The determination of particles size and shape in the case of nanostructured films is not a trivial task. Well established experimental techniques for structural characterization suffer serious setbacks in this case. Both, convenient X-ray diffraction (XRD) and X-ray reflectivity are not very informative for the particles of a few nm in size and when the layer has discontinuous nature. Cross-section TEM does not provide information about the shape and size of particles in the individual layer due to superposition of granules over the sample thickness. Meanwhile deposition of the three-layer insulator/metal/insulator reference films on carbon covered TEM grids does not reproduce conditions of the epitaxial growth on single-crystal substrates. Thus, complementary magnetic studies become of great importance for the evaluation of granular sizes and shapes in DMIMs.

In this work, the morphology of Fe nanoparticles in Fe/MgO epitaxial DMIMs has been obtained combining TEM investigations and magnetic measurements [2]. A simple model that allows determination of magnetic nanoparticles sizes was developed and tested for disc (2D) shaped particles. A comparison of the modelling results for spherical and disc-shaped particles is presented and discussed in the framework of the experimental results. The comparison of the fitting results for magnetic isotherms and the direct experimental confirmation that Fe nanoparticles are confined in layers of ~1nm thickness strongly suggests that for epitaxially grown DMIMs disc-shaped particles are formed. The modeling procedure proposed here could serve as a basis for future investigations on particle size distribution for DMIMs. Moreover, this research demonstrates that modifying the growth conditions it is possible to control the geometrical parameters of the disc-shaped nanoparticles: the thickness of the magnetic layer allow us to determine the thickness of the disc and the growth temperature its diameter, opening the possibility to engineer heterogeneous nanostructures with desired magnetic and magnetotransport properties.

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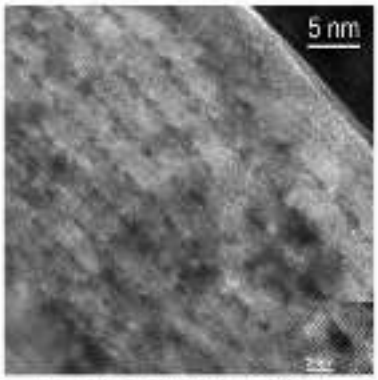

TEM cross-section image of the [Fe (0.6 nm)/MgO (3 nm)]$_{10}$ BVAM deposited at 523 on MgO (001). Thin layers of Fe particles (darker contrast) are sandwiched between MgO layers (brighter contrast). Inset is a close-up image of a Fe particle.

P87 - Dipolar stabilized bubble-like skyrmions in Fe/Gd multilayers

6. Magnetic thin films, multilayers, surface and interfaces

Michael Heigl[1] , *Ping Che*[2], *Edoardo Catapano*[2], *Marek Vaňatka*[3], *Zahra Inanloo Maranloo*[4], *Peter Böni*[4], *Michal Urbánek*[3], *Dirk Grundler*[2], *Manfred Albrecht*[1]

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Magnetic skyrmions are topologically nontrivial chiral spin textures. Most skyrmion structures studied in today's research are stabilized by the Dzyaloshinskii-Moriya interaction. In this work, we present a topologically similar spin structure in ferrimagnetic Fe(Co)/Gd multilayers stabilized by the competition of long-range dipolar energy in a thin film and domain wall energy [1]. These chiral bubbles can be also described as dipolar stabilized skyrmions [2].

The Fe(Co)/Gd multilayers were magnetron deposited at room temperature with up to 80 bilayers and varying individual layer thicknesses. The magnetic moment of the 3d-transition metals and the Gd layers are coupled antiparallel with the Gd moment being dominant over the whole temperature range.
First, the structural properties of the films were investigated by X-ray reflectivity measurements and cross-section transmission electron microscopy. Both suggest a highly intermixed system. Still revealing a periodic modulation in composition along the growth direction. However, a co-sputtered homogeneous alloy with the same overall composition doesn't show the same properties.
The static magnetic properties were studied dependent on composition, strain, magnetic field and temperature by SQUID magnetometry, Lorentz transmission microscopy (LTEM), and magnetic force microscopy (MFM). The system shows a decrease in out-of-plane magnetic anisotropy and an increase in the magnetic moment for thicker Gd layers which leads to a shift of the stability range of the skyrmion phase to higher temperatures. The formation of the skyrmions was directly observed at room temperature via field dependent MFM [Fig. 1] and LTEM. The size of the observed skyrmions is in the range of 100 nm. For higher fields, the system forms a quasi-ordered hexagonal skyrmion lattice with a periodicity of about 200 nm.
Additionally, the dynamic response of the skyrmion system was investigated by VNA ferromagnetic resonance measurements. Excited by out-of-plane rf fields, we identify different localized spin-wave excitations for the skyrmions and stripe domains that are analogue to [3].

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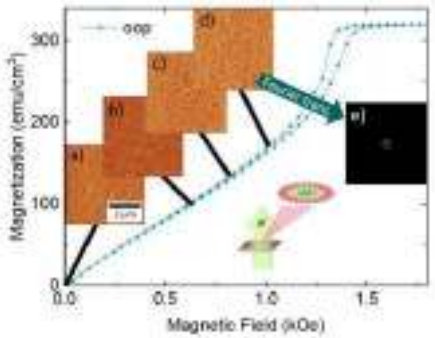

Fig. 1. Out-of-plane (oop) M-H hysteresis loop of a Fe/Gd multilayer with corresponding MFM images taken at room temperature. (a) Stripe domain state at zero field. (b) Stripes with a magnetic moment parallel to field grow. (c) Stripes opposite to field collapse into cylindrical domains and skyrmions start to form (100 nm diameter). (d) Skyrmions arrange into a hexagonal lattice (see (e) Fourier transform). Sample saturates at 1.5 kOe.

P88 - Double magnetic proximity induced magnetization profile in an Fe/Fe0.30V0.70 superlattice

6. Magnetic thin films, multilayers, surface and interfaces

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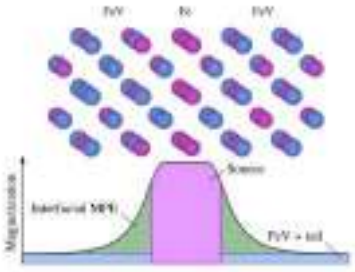
The magnetic proximity effect (MPE) occurs as a region of enhanced magnetization typically at an interface between two ferromagnets or between a ferromagnet and non-magnetic material. Furthermore, double magnetic proximity effect is a combination of a finite size effect and an MPE resulting in a situation where a component is magnetic only because the other component is exerting MPE on it but, at the same time, the same holds for the other component as well. The aim of tuning MPE is to have full control of the interface phenomena in magnetic heterostructures. MPE is often accompanied by exchange bias, it is involved in the generation of spin currents in non-magnetic metals and can be used to, for example, push up the ordering temperature of dilute magnetic semiconductors.

In this work, the double magnetic proximity effect in an $Fe/Fe_{0.30}V_{0.70}$ superlattice is studied by a direct measurement of the magnetization profile using polarized neutron reflectivity. The experimental magnetization profile is shown to qualitatively agree with a profile calculated with density functional theory. The profile is divided into a short range interfacial part and a long range tail. The interfacial part is explained by charge transfer and induced magnetization that comes from the high magnetic susceptibility of the alloy above its intrinsic ordering temperature. The tail of the MPE is caused by the inhomogeneous nature of the FeV alloy resulting in an extended network of connected magnetic atoms. The long range tail in the magnetization persists up to 170% above the intrinsic ordering temperature of the FeV alloy.

The observed effects can be used to design systems with a direct exchange coupling between layers over long distances through a network of connected atoms. At the same time, the magnetic material can be tuned to have a very small energy product.



A schematic of the sample structure (top) showing 1 ML of Fe inserted inside an FeV alloy. A schematic of the magnetization profile (bottom) of the structure. The profile has been divided into regions that mark the different parts of the MPE.

P89 - Dzyaloshinskii-Moriya Interaction and Magnetic Anisotropy in Ultrathin cobalt films

6. Magnetic thin films, multilayers, surface and interfaces

Anuj Dhiman[1] , *Michal Matczak*[1, 2], *Ryszard Gieniusz*[1], *Iosif Sveklo*[1], *Zbigniew Kurant*[1], *Urszula Guzowska*[1], *Feliks Stobiecki*[2], *Andrzej Maziewski*[1]

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ABSTRACT:

The interfacial Dzyaloshinskii-Moriya interaction (IDMI) has become an eminent tool in magnetism due to its potential application in stabilizing chiral domain structure and magnetic skyrmions[1]. The IDMI and surface magnetic anisotropy are both directly co-related with the magnitude of spin-orbit coupling. Investigations were performed on ultrathin cobalt wedges and flat films (with Co thicknesses $0<d_{Co}<4$nm) surrounded by Ir and Pt layers. Nanostructures were deposited by magnetron sputtering on naturally oxidized Si substrates with Ta/Au buffer. For DMI constant D studies we have employed Brillouin Light Scattering (BLS) spectroscopy in backscattering geometry. The spin waves propagating along in-plane direction perpendicular to the applied magnetic field (Damon-Eshbach configuration) were investigated. The values of D were calculated from measurement of frequency differences $\Delta f(d_{Co})$ between Stokes and anti-Stokes spin wave frequencies. Magnetization curves were measured using magneto-optical polar Kerr effect (PMOKE) as a function of crossed in-plane and perpendicular applied magnetic fields. Magnetic anisotropy fields $H_A(d_{Co})$ were determined fitting these curves in single domain model. While decreasing Co thickness we observed both parameters $\Delta f(d_{Co}) \sim D$ and $H_A(d_{Co})$ first increase linearly (upto ~1.1nm) in a usual manner and then after achieving a maxima both decreases (for d_{Co} below ~1.1nm). Result will be discussed with ones from literature [2-6].

Acknowledgement: Supported by Polish National Science Center projects: DEC-2016/23/G/ST3/04196 Beethoven and UMO-2018/28/C/ST5/00308 SONATINA.

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P90 - Dzyaloshinskii-Moriya interaction in Pt/Co/Ta multilayers with engineered interfacial roughness

6. Magnetic thin films, multilayers, surface and interfaces

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The Dzyaloshinskii-Moriya Interaction (DMI) determines the type and symmetry of non-uniform magnetic structures. The DMI comes from the spin-orbit-interaction and arises as a result of broken inversion symmetry in bulk magnetic crystals with low symmetry or at interfaces between a ferromagnet and a nonmagnetic material with strong spin-orbit coupling. DMI is important for spintronics as it stabilizes Néel domain walls with high velocities under current excitation and stabilizes magnetic skyrmions which are potential candidates for new data storage and processing technologies. As that DMI depends on the symmetry of the system, interfacial roughness further breaks the symmetry at the interface in a heterostructure. Here, we describe how controlled induced interfacial roughness can be used to tailor the DMI in model Pt/Co/Ta thin-film multilayer structures.

In thin-films, the effect of the DMI is to act as an in-plane magnetic field. This influences both the slow, field-driven, dynamics of magnetic domain walls, and the faster, thermally driven, motion of spin-wave excitations. Magneto-optic Kerr effect (MOKE) microscopy is used to quantify the strength of the DMI indirectly (figure, left) via the asymmetric growth of bubble-like domains. Brillouin Light Scattering (BLS) is also used to directly quantify the DMI from the asymmetry induced in the spin-wave dispersion. The influence of engineered interface roughness on DMI as measured by BLS is shown in the figure (right).

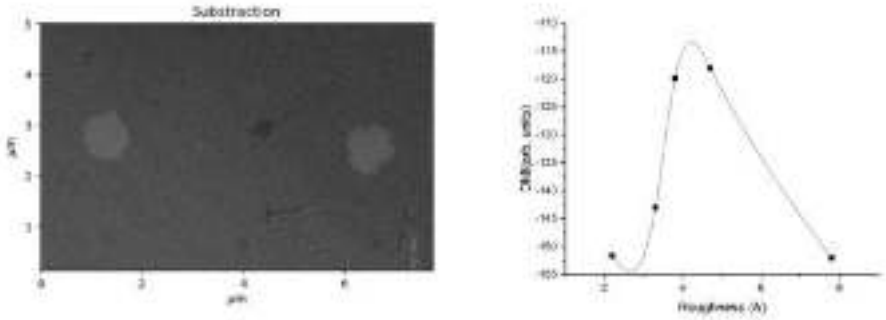

Figure: Magnetic Domain Bubbles in Pt/Co/Pt multilayer (left) using MOKE microscopy, and (right) DMI strength versus induced interface roughness in Pt/Co/Ta measured by BLS.

P91 - Dzyaloshinskii-Moriya interaction in symmetric multilayers with different numbers of Co/Pd bilayers

6. Magnetic thin films, multilayers, surface and interfaces

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Heavy metal/ferromagnetic superlattices are of great interest since Néel skyrmions may be stabilized in them due to an interfacial Dzyaloshinskii-Moriya interaction (DMI) even at room temperature. Here we report on evidence of the strong DMI in symmetric epitaxial $[Co/Pd(111)]_N$ superlattices with high perpendicular magnetic anisotropy. The structural and magnetic properties of epitaxial Si/Cu/Pd/$[Co(0.8\ nm)/Pd(2\ nm)]_N$ superlattices were investigated dependent on the period of superlattices varied from 1 to 20. The bottom interfaces of the Co layers are more greatly strained (9.2%) as compared to the top Co interfaces (3.3%). Asymmetry of the strains is conserved in all Co layers independently of their number. The roughness of the interfaces increases almost linearly from the bottom to the top of the whole structures. Perpendicular magnetic anisotropy does not significantly depend on the period of the superlattices.

A strong negative DMI was found in N1-N4 Co/Pd samples by measuring the asymmetrical velocity of the domain walls propagation in the simultaneous presence of in- and out-of-plane magnetic fields [1]. The effective DMI energy was evaluated in N5, N10, and N20 superlattices by comparison of the experimentally measured out-of-plane hysteresis loops and the in-plane demagnetized domain patterns with results of micromagnetic simulations [2].

With increase of the number of bilayers, the magnetostatic energy of the system increases, which results in demagnetization of the samples in the absence of magnetic fields. The effective energy of the perpendicular magnetic anisotropy is independent of the number of bilayers N and fluctuates near the average value of $(8 \pm 1) \times 10^5$ J/m^3.

The domain structures of N5, N10, and N20 superlattices demagnetized by in-plane oriented magnetic field are shown in Figs. 1(a), (b), and 1(c), respectively.

The experimentally measured periodicities of the in-plane demagnetized domain patterns are 600 ± 80 nm for N5, 330 ± 40 nm for N10, and 260 ± 20 nm for N20 superlattices. The dependencies of effective DMI energies on the number of Co/Pd bilayers derived with different values of exchange energies used in the calculations are shown in Fig. 1(d).

An increase of the magnitude of effective DMI energy with increase of the number of Co/Pd bilayers in epitaxial $[Co/Pd(111)]_N$ superlattices was established independently of the value of the exchange constant adopted in the simulations. Growth of the effective DMI constant is rapid in the beginning and tends to saturation with higher periods of $[Co/Pd]_N$ superlattices. The value of exchange energy adopted in the simulations does not influence the trend of the D_{eff} (N) curve in the range of $N \geq 5$. It influences only the quantitative results [3].

The reported study was partially funded by RFBR under the research projects № 18-02-00205, 18-32-20057; by the Grant program of the Russian President (MK-5021.2018.2), and by the Russian Ministry of Science and Higher Education under the state task 3.5178.2017/8.9.

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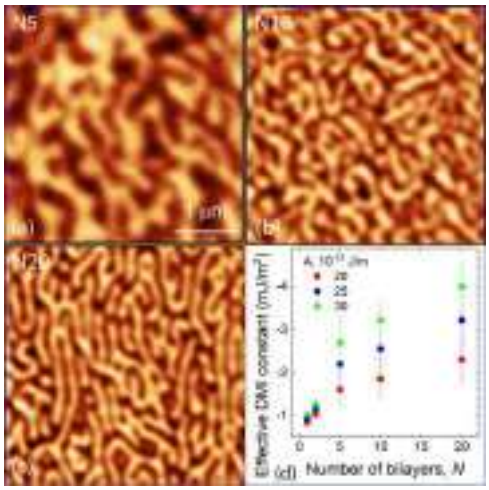
N5
(a)
(b)
N26
(c)
(d)
Number of bilayers, N

P92 - Effect of Disorder on the Gilbert damping of B2 ordered Co2MnAl Full Heusler Alloy Thin Films

6. Magnetic thin films, multilayers, surface and interfaces

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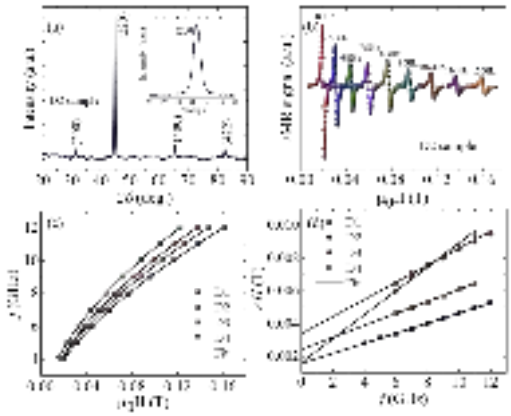
Co-based Heusler alloys are in demand due to their half-metallicity, high spin polarization, high Curie temperature T_C and low damping constant, etc.. Co_2MnAl (CMA) is one of the Co-based full Heusler alloys which exhibits high T_C~697 K and large spin polarization (~78%). CMA has considerable research interest due to its compatibility with the most semiconducting substrates and topological properties. In the present work, the Mn concentration dependent magnetization dynamic properties of *B2* ordered CMA full Heusler alloy are investigated.$Co_{2+x}Mn_{1-x}Al$ (CMA) Heusler alloy thin films grown on Si (100) by varying Co/Mn concentration at fixed growth temperatures (T_s) of 400ºC using DC-magnetron sputtering are investigated. XRD patterns revealed the formation of *B2* ordered phase in the film with exact stoichiometry. Ferromagnetic resonance (FMR) technique is employed to determine the Gilbert damping constant, which is found to be 0.0045±0.0002 for the perfect stoichiometric film which is a record low value in the CMA Heusler alloy thin films. The Co/Mn concentration based tunable Gilbert damping constant in CMA Heusler alloy is investigated and the lowest value of damping constant is found to be 0.0045. The tunability of Gilbert damping provides the opportunity to apply Heusler alloy materials in different fields of the spintronic devices. The low damping constant is inevitably important for spintronic applications.



P93 - Effect of oxygen content on structural and magnetic properties of GCMO films

6. Magnetic thin films, multilayers, surface and interfaces

Azar Beiranvand[1] , *Jussi Tikkanen*[2], *Heikki Palonen*[2], *Hannu Huhtinen*[2], *Petriina Paturi*[3]

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[3] Prof.

The influence of in-situ oxygen and vacuum treatments on low bandwidth manganite, $Gd_{1-x}\ Ca_x\ MnO_3$ (GCMO) films, are investigated in the hole doped (x = 0.4) and electron doped (x = 0.9) regions. The effect of oxygen content is insignificant on Curie temperature, T_C , for both concentrations, but for x = 0.4, the magnetization at 10 K increases in oxygen treated and decreases in vacuum treated samples when compared with the pristine sample. For sample with x = 0.9, the treatments in oxygen and vacuum lead to decrease in magnetization. In addition to earlier obseved usability of x = 0.4, the appearance of charge-ordering state near room temperature in in-situ oxygen annealed x = 0.9 sample makes also this concentration a good candidate for potential spintronic applications.

P94 - Electric-field control of perpendicular magnetic anisotropy and exchange bias in Co/CoOx/HfO2

6. Magnetic thin films, multilayers, surface and interfaces

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Electric field (EF) control of magnetism in 3d transition metals is considered desirable for next-generation electronics technology. Especially, EF effect on magnetic anisotropy (MA) has a great importance on magnetic memory devices in terms of energy-saving for magnetization switching. Many researchers has intensively studied for the enhancement of the efficiency of the voltage-induced MA change (defined as β_S). EF control of exchange bias (EB) is also expected for various spintronic applications, but in most of the studies, EB is controlled by magneto-electric (ME) effect using multiferroic materials. In this presentation, we report the EF effect on MA and EB in all-solid-state capacitor structure with surface-oxidized Co electrode.

From the substrate side, Ta(3.3)/Pt(3.0)/Co(1.0) layers were deposited on Si substrate using rf-sputtering at room temperature (numbers in the parentheses show nominal thicknesses in nanometer orders). After the deposition, the film was exposed to the air for about 10 min to form the naturally-oxidized layer on the Co surface. As a gate insulator, a 45-nm-thick HfO_2 was deposited in an atomic layer deposition chamber at 150℃. Finally Cr/Au counter gate electrode were formed. The sample was patterned into Hall-bar shape. The magnetic property was measured by using anomalous Hall effect under each gate voltage (V_G). Magnetization easy axis in this sample is out-of-plane direction. The coercivity (H_c) and exchange bias field (H_{EB}) was measured by sweeping of the perpendicular magnetic field, and MA was estimated by hard-axis magnetization curves.

[Magnetic anisotropy] H_c and perpendicular MA are increased (reduced) by positive (negative) gate voltage application at 300 K. The sign of MA change is contrary to those in non-oxidized 3*d* transition metals single layer*[1,2]. In addition, β_S is calculated to be ~230 fJ/Vm*[3], which is larger than the value for widely-studied Fe(Co)/Oxide systems*[1,2].

[Exchange bias] At the low temperature (below 200 K), the shift of magnetic hysteresis loop can be observed through out-of-plane field cooling process. This is clearly due to the EB effect generated by the interfacial exchange coupling between ferromagnetic Co spins and antiferromagnetic CoO_x spins. Figure shows H_c and H_{EB} at 50 K as a function of V_G and gate electric field E_G. Both of them is monotonically and reversibly changed by V_G. The sign of H_{EB} modulation cannot be explained by the change in the thickness of Co and CoO_x layer induced by redox reaction. It is concluded this effect is not due to the electrochemical reaction or ME effect but the modulation of interfacial electronic structure, including electron accumulation/depletion at Co/CoO_x interface.

This work was partly supported by JSPS KAKENHI, and Spintronics Research Network of Japan.

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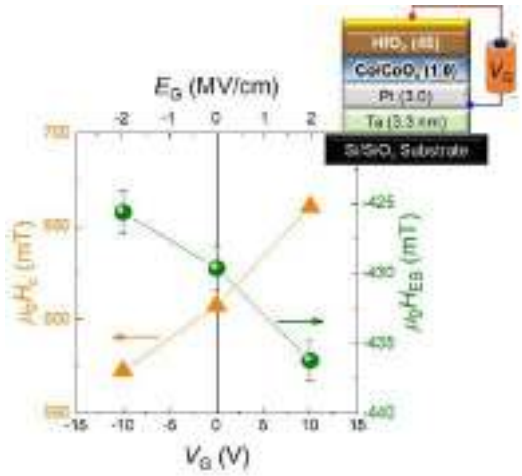
E_G (MV/cm)
-2
-1
0
1
2
V_G
$\mu_0 H_c$ (mT)
$\mu_0 H_{EB}$ (mT)
V_G (V)

P95 - Engineering the magnitude and the sign of the bias field in orthogonally coupled SmCo5-CoFeB films

6. Magnetic thin films, multilayers, surface and interfaces

Alberto Bollero[1] , *Volker Neu[2], Vincent Baltz[3], David Serantes[4], José Luis F. Cuñado[1], Fco. Javier Pedrosa[1], Ester María Palmero[1], Marietta Seifert[2], Ludwig Schultz[2], Bernard Dieny[3], Rafael P. del Real[4], Manuel Vázquez[4], Oksana Chubykalo-Fesenko[4], Julio Camarero[1, 5]*

[1] Division of Permanent Magnets and Applications, IMDEA Nanoscience, Campus Universidad Autónoma de Madrid, 28049 Madrid, Spain

[2] IFW Dresden, Institute for Metallic Materials, P.O. Box 270116, D-01171 Dresden, Germany

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Exchange-bias (EB) is frequently used in magnetic random access memories and magnetoresitive read heads to pin the magnetization of a reference layer. Setting EB is usually achieved by cooling a ferromagnetic-antiferromagnetic bilayer under an applied field through the blocking temperature [1]. By comparison with conventional EB systems, the possibility of inducing EB-like effects has been demonstrated in systems consisting of two coupled ferromagnets with orthogonal anisotropies and with no need of any post-depositional treatment. Experimental results and micromagnetic simulations showed that the loop shift magnitude in an orthogonally coupled [Pt/Co]/NiFe structure is strongly dependent on the strength of the out-of-plane anisotropy of the [Pt/Co] multilayer [2]. On this basis, perpendicular epitaxial hexagonal $SmCo_5$ might be an excellent candidate to control the EB phenomenon in a similarly engineered structure, as it exhibits the largest uniaxial magnetocrystalline anisotropy of K_u=14 MJ/m^3 at room temperature as a bulk phase [3].

Following these considerations, we have designed a system consisting of a hard magnet epitaxial $SmCo_5$ film with perpendicular anisotropy in interaction with a soft magnetic amorphous $Co_{62}Fe_{26}B_{12}$ film (in-plane anisotropy) through a spacer. The angular evolution of the coercivity has been studied by applying an in-plane magnetic field to the system while rotating in a full 0-360° angular range [Figs. 1(a)-(b)]. Sputtering of the CoFeB was done with oblique incidence of the atomic flux in order to induce an in-plane uniaxial anisotropy [see Fig. 1(a) for a reference CoFeB single layer] [4].

This work presents the first experimental evidence of the possibility of controlling isothermally not only the magnitude but, remarkably, also the sign of the bias field in two orthogonally coupled ferromagnetic layers. This has been accomplished in an unprecedented manner by pinning exclusively one of the branches of the hysteresis loop while displacing the other one along the field axis when varying the orientation of an applied in-plane magnetic field [Fig. 1(c)]. Choice of the spacer thickness has allowed tuning the strength of the magnetostatic coupling between the soft and the hard magnetic layers.

By proper design of key reference samples (variation of the initial magnetization states of $SmCo_5$ and CoFeB), we have proven that the observed effect is due to the interplay between the uniaxial anisotropy of the soft magnetic layer and the bias field imprinted by the magnetostatic field provided by the hard layer. Moreover, it is demonstrated that the orientation of the magnetization (up/down) in the $SmCo_5$ film determines the initial sign of the bias field in the $SmCo_5$/spacer/CoFeB system. The observed effect is of interest for applications in spintronics and magnetic sensors as it allows modulation of the bias field strength and sign by proper choice of the orientation of an externally applied magnetic field.

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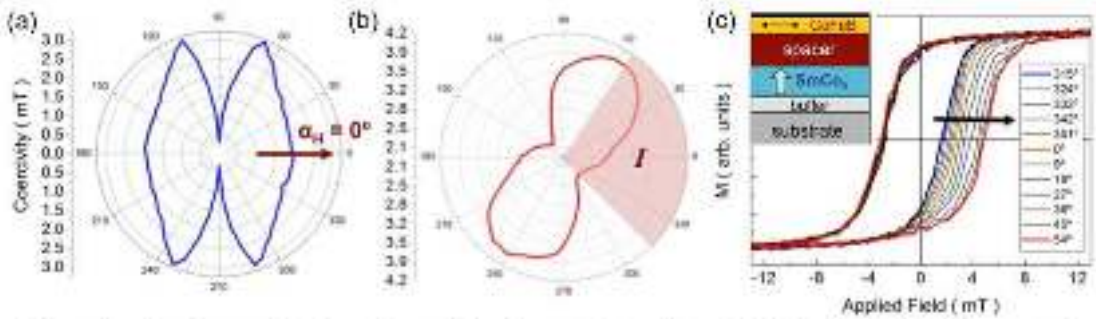

Figure 1. Angular evolution (polar plot) of coercivity for: (a) Si/SiO_2/CoFeB reference; and (b) $SmCo_5$(30nm)/spacer(12.8nm)/CoFeB(3nm). (c) In-plane hysteresis loops recorded with the magnetic field applied at different in-plane angles, α_H, from Region *I* (see (b)). $\alpha_H = 0°$ corresponds to application of the field along easy axis direction of CoFeB reference (see (a)).

P96 - Exchange biased Hard/ Frustrated ferromagnetic bilayers analysis using static MH loops and FORCs

6. Magnetic thin films, multilayers, surface and interfaces

Vishal Bhardwaj[1] , *Md. Shadab Anwar*[1], *Satyendra Prakash Pal*[1], *Babita Ingale*[1], *Vladimir V. Khovaylo*[2], *Ratnamala Chatterjee*[1]

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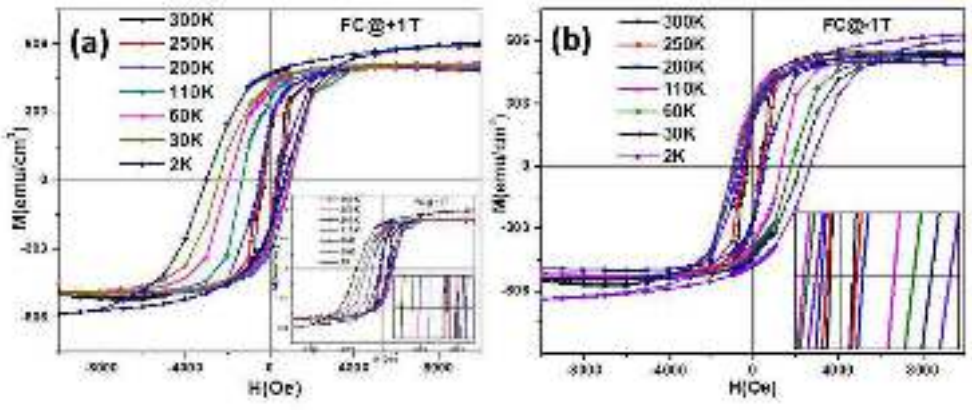
We report the phenomenon of tunable exchange bias (TEB) in the bilayer system consisting of hard ferromagnetic (FM) $ZrCo_5$ (CZ) and off-stoichiometric full Heusler alloy $Ni_{50}Mn_{30}Ga_{20}$ (NMG) which is a frustrated ferromagnet (FRM).We have performed experimental studies on this bilayer system using different characterization techniques such as XRD, XRR, AFM, and magnetic measurements using SQUID magnetometer. Magnetic virgin curve recorded at room temperature (RT) shows vertical shift, indicating the presence of remanent magnetization (RM) in the system. This RM value results in exchange bias (EB) effect in this bilayer system. At RT, oscillatory protocol was used to bring RM value to approximate zero value. Then the system was field cooled (FC) in the presence of the optimized magnetic fields of ±1T to measurement temperature, then the cooling field was set to zero and RM value was recorded before each MH measurement. In field cooling of +1T the M-H data showed a shifted loop along the negative field axis and shows maximum EB of -1166Oe at 2K [Fig. 1a] and in field cooling of -1T the MH loops shifted along the positive field axis and s hows maximum EB of +1005Oe at 2K [Fig. 1b]. The exchange bias effect in this CZ/NMG bilayer system is studied by magnetic hysteresis (M-H) loops measurements at various temperatures after field cooling (FC) the sample in the presence of the optimized magnetic fields of ±1T. This EB effect in CZ/NMG bilayer system can be tuned by changing magnitude/direction of applied magnetic field. Magnetic history of FM CZ layer results in considerable remanent magnetization (RM) present in this bilayer structure, which influences resulting coercivity and exchange bias fields. This work explains that after field cooling CZ/NMG bilayer system to temperature range between 2K-300K, measured coercivity is directly proportional to RM, whereas effective exchange bias field varies exponentially with RM. This measured exchange bias effect from M-H loops exist up to ~250K temperature, which is well explained using M-T measurements, as vanishing of short range interactions above this temperature. Distribution of local interaction/coercive field at the interface of CZ/NMG bilayer heterostructure was further explained by using first order reversal curves (FORCs) analysis.



P97 - Ferromagnetic Resonance and Inverse Spin Hall Effect in Permalloy/Pt bilayers

6. Magnetic thin films, multilayers, surface and interfaces

Sergi Martin Rio[1] , *Lluis Balcells[1]*, ***Alberto Pomar[1]***, *Carlos Frontera[1]*, *Benjamin Martinez[1]*
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The temperature dependence of magnetodynamical physical effects such as Spin Pumping and Inverse Spin Hall effect (ISHE) has been measured in a set of Py/Pt bilayers as a function of the Pt thickness. Additionally, important physical parameters such as Gilbert damping, saturation magnetization and anisotropy field has been determined as well. It is found that the Gilbert damping follows a non-monotonic behaviour with temperature, as reported in other systems [1]. Previous measurements on the temperature dependence of Spin Pumping and ISHE [2] in this system have the serious drawback of requiring the use of complex fabrication process to prepare the samples. In this work we present an easy-to-implement FMR setup for measuring all of those effects and parameters straightforwardly. It is found that the amplitude of the FMR absorption curves is constant from room temperature to approximately 100K and then it starts to decrease. Because of this reduction, it is of major relevance to normalise the measured ISHE voltage with the FMR absorption amplitude in order to obtain physically coherent results. We will discuss the obtained temperature dependence of ISHE.

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P98 - Ferromagnetic Resonance of FeSiB amorphous thin films

6. Magnetic thin films, multilayers, surface and interfaces

Gabriel Soares[1] , *Federica Celegato[1], Felipe Garcia-Sanchez[2], Gabriele Barrera[1], Marco Coïsson[1], Massimo Pasquale[1], Paola Tiberto[1]*

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The periodic structure of weak stripe domains in Fe based thin films has recently received renewed attention due to the possibility of propagation of spin waves for magnonics applications [1]. Fe based films with stripe domains have extensively been studied in the past decades [2,3]. Due to a weak out of plane (OOP) anisotropy associated to magnetostriction, these domains have a magnetization slightly tilted out-of-plane. Ferromagnetic resonance measurements were performed on selected amorphous FeSiB thin films having thickness of up to 230 nm as a function of their stress relieving annealing temperatures. The absorption spectra obtained with an in-plane external field show a double FMR peak structure that becomes a single uniaxial Kittel mode near saturation. Due to the in-plane stress-relief, the anisotropy field increases with increasing annealing temperatures, consistently with hysteresys loops measurements obtained by a Vibrating Sample Magnetometer [4]. The FMR linewidth analysis yielded an extremely low magnetic damping of 10^{-3}, which is of great interest for the propagation of spin waves. Micromagnetic simulations were then performed in order to verify the double peak structure and demonstrate the possibility of using these samples as magnonic devices.

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P99 - First-order metamagnetic transition in sub-10-nm-thick FeRh films: Microstructure role.

6. Magnetic thin films, multilayers, surface and interfaces

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First-order magneto-structural phase transitions[1] (MPT) typically entail abrupt changes in a material's properties[2], which open up new opportunities for engineering materials with novel functionalities. FeRh alloys gathered a great deal of attention in spintronics since the first-order antiferromagnetic (AF)-ferromagnetic (F) metamagnetic transition[3] is accompanied by a giant resistivity change. Heat assisted magnetic recording (HAMR) technology is a likely candidate for achieving higher areal densities in future magnetic recording technologies[4]. Moreover, research focused on FePt/FeRh/Fe exchange spring structures[5] seems to be quite promising, where the intermediate FeRh layer will be acting as a heat sensitive material, which will allow the thermal assisted switching, whilst significantly reducing the total thermal load needed. However, in order the HAMR concept to become a viable technology, much thinner and smoother FeRh layers, typically 2-10 nm-thick and atomically flat, must be needed. Such conditions will only be met, if we gain a deeper understanding of the underlying mechanisms that govern the MPT at the sub-10-nm scale.

We report on the correlation between magnetic and microstructural properties in single-crystal sputter-grown FeRh films deposited on MgO, where film thickness, t, ranges from 11.6 nm down to 1.5 nm. In sharp contrast to previous studies[6], our ultrathin FeRh films show a very smooth surface morphology (see Fig. 1(a)-1(b)). RMS roughness, R_{rms}, scales linearly with the rocking curve integral-breadth of the (002) Bragg peak, which suggests that R_{rms} is determined by the layer microstructure. We do assign the stabilization of the MPT even in the 1.5-nm-thick film to a large tetragonal distortion[7] of 1.5%. However, the observed decrease of the MPT temperature with t can only be accounted for if the effect of the microstructure is taken into consideration. Thus, the microstrain, ε, and grain size, d, are determined by analysing the integral-breadths of the (001) and (002) FeRh Bragg peaks by means of Williamson-Hall plots[8]; we find ε scales down as d^{-1} in good agreement with theory[9] (see Fig. 1(c)). We also observe the MPT temperature decays linearly as ε increases in the FeRh ultrathin films (see Fig. 1(d)). Therefore, building on the intense coupling between crystallographic and magnetic order in FeRh alloys[10], our results indicate that the dispersion in the lattice parameter, due to the strain-gradient introduced by the volume expansion around grain boundaries, modifies the exchange coupling landscape among neighbouring Fe sites, which shifts the MPT.

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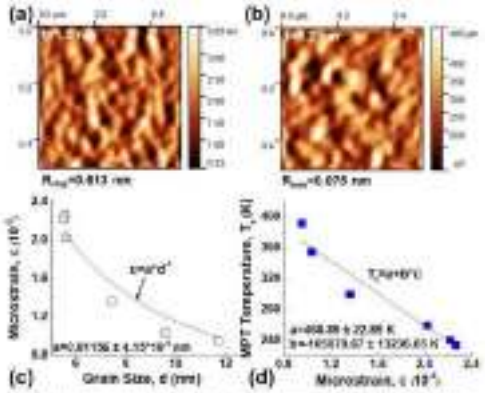
(a)
(b)
(c)
(d)
Grain Size, d (nm)
Microstrain, ε (10⁻³)
MIT Temperature, T_c (K)
Microstrain, ε (10⁻³)

P100 - First-principles study of magnetic structures in Fe/Rh bilayers on Re(0001)

6. Magnetic thin films, multilayers, surface and interfaces

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Transition-metal-superconductor hybrid systems are good candidates for realizing Majorana bound states which can be used to build topologically protected q-bits for quantum computation [1,2]. The prerequisite is a magnetic spiral structure within the transition-metal layer. It has been shown that Rh/Fe bilayers on Ir(111) can exhibit interesting magnetic structures due to the competition of Dzyaloshinskii-Moriya interaction (DMI) and higher-order exchange interactions (HOEI) [3]. The aforesaid facts indicate that Fe/Rh bilayers on Re(0001), a 5d transition-metal substrate with large spin-orbit coupling (SOC) strength which becomes superconducting at T = 2.4 K, can be an interesting system to investigate from theoretical and experimental point-of-view. Using density functional theory (DFT), we calculate spin-spiral (SS) energy dispersion with and without SOC and we also compute multi-Q states for Fe/Rh and Rh/Fe bilayers on Re(0001). Our results show that the magnetic ground state of Fe/Rh/Re(0001) can easily be tuned by changing the stacking sequences of Fe/Rh bilayers. We find that exchange and DMI favor FM, RW-AFM and SS as ground states in Fe/Rh/Re(0001), whereas, in Fe/Rh/Ir(111), HOEI are very strong and can stabilize multi-Q states. Finally, we mapped our DFT total energy onto an atomistic spin Hamiltonian to investigate the stability and lifetime of magnetic skyrmion in Fe/Rh/Re(0001) using spin dynamics simulations.

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P101 - Free-standing magnetic membranes for spin polarimetry

6. Magnetic thin films, multilayers, surface and interfaces

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This work deals with the fabrication of free-standing magnetic membranes and with the study of the spin-filtering process of a spin-polarized beam of low energy electrons impinging on them by controlling their magnetization and the transmitted beam polarization [1]. The working principle of the devices is to selectively transmit electrons with spin parallel or anti-parallel with respect to a quantization axis defined by the direction of the magnetization of the ferromagnetic layer [2].

A proper fabrication process is needed in order to obtain the free-standing spin-filtering membranes. The device is developed starting from a thermal silicon dioxide layer grown on a silicon substrate. Then, a Deep Reactive Ion Etching (DRIE) process is performed on the back side of the substrate in order to get free-standing oxide membranes (Fig. 1(a)). The spin-filtering active material is grown on the free-standing membranes through magnetron sputtering. The stack is composed by a layer which increases the mechanical resistance of the membranes, a layer of gold which acts as a capping, the active magnetic layer and a final gold layer to prevent the film from oxidation (Fig. 1(b)). According to the magnetization direction desired (in-plane or out-of-plane), different materials would be chosen, e.g. Co or CoFeB for the in-plane configuration and heterostructures as Co/Pt or CoFeB/Ta for the out-of-plane one. The whole structure cannot exceed the thickness of ten nanometers in order to guarantee a reasonable transmission of the device. As a final step a wet etching process is performed to remove the silicon dioxide and leave the free-standing magnetic membranes.

The magnetic characterization of the membranes is performed exploiting the Magneto-Optical Kerr Effect (MOKE) through a Kerr microscope which allows to locally probe (at the micrometric scale) the magnetic properties of the devices: the ferromagnetic remanence and the presence of magnetic domain structure.

The measurement of the spin-filtering efficiency is performed exploiting a spin polarized electron beam at low energy (0-30 eV) produced by a GaAs photocathode with negative electron affinity and recording the transmission of the membranes for different orientations of the beam polarization [3]. In this way it is possible to probe the Figure of Merit (FOM) of the device, which is $FOM = S^2 \times I/I_0$, where S is the Sherman function, i.e. the measure of the asymmetry produced by the filter given a certain polarization of the beam, I is the transmitted intensity and I_0 the incident one.

The objective of this work is the realization of self-sustained magnetic membranes with a thickness down to the nanometric scale which are mechanical robust, with efficient transmission (larger than 3×10^{-2}) and asymmetry ($S \cong 0.5$) [2] and a tunable filtering process according to the magnetization direction (in-plane or out-of-plane).

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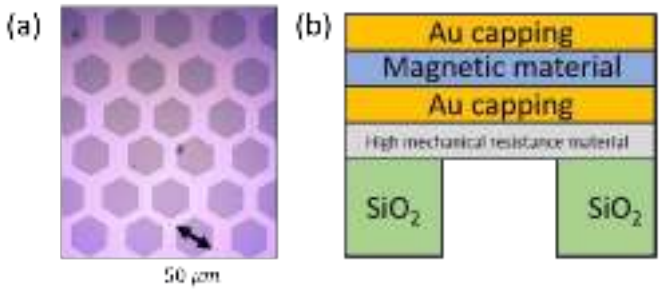

Figure 1. (a) Pattern of several membranes defined through optical lithography and reactive ion etching process. (b) Stack composing the active filtering membranes.

P102 - High coercive ultra-thin films of L10-MnAl

6. Magnetic thin films, multilayers, surface and interfaces

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Thin films with perpendicular magnetic anisotropy are attracting a lot of interest in spintronic devices, in particular in STT-MRAM (Spin Transfer-Torque Magnetoresistive Random Access Memory) and p-MTJs (perpendicular Magnetic Tunnel Junctions). For that purpose, the ordered binary Mn-based alloys with equiatomic ratio are considered good candidates and in particular, the ferromagnetic $L1_0$-MnAl [1,2]. In addition, the $L1_0$-MnAl is free of rare earths so it has been proposed for rare earth free permanent magnets applications as well, due to its high magnetic anisotropy constant.

In this study, ultra-thin films of MnAl have been grown on GaAs (001) by MBE (Molecular Beam Epitaxy) with thickness varying from 1 to 5 nm and without any buffer layer. XPS (X ray Photoelectron Spectroscopy) and LEED (Low Energy Electron Diffraction) were performed *in situ* in order to characterize the chemical states and the arrangement of the surface atoms. In order to prevent from ambient oxidation, a protective capping layer of Ta was deposited before the sample was withdrawn from ultra high vacuum. Magnetic and structural characterization was done *ex situ* by SQUID magnetometry and XRD, respectively. The growth of $L1_0$-MnAl on semiconductor surfaces enhances the potential applications on the fields of spintronics, ultra high-density recording media and non-volatile magnetoresistive random access memory [2, 3, 4].

In this work, well-oriented ultra-thin films of $L1_0$-MnAl with coercivities over 8 kOe have been obtained. The X Ray Diffraction measurements show the main reflections of the $L1_0$-MnAl phase in register with the substrate orientation, as it was expected for the epitaxial growth. This result is correlated with the magnetic properties, where it is found that there is a strong magnetic anisotropy with all the magnetization pointing out of the film surface. The use of a GaAs (001) substrate has allowed the simultaneous formation of a ferromagnetic interphase of Mn-Al-Ga-As which contribution competes with the MnAl one and can be tuned by the experimental growth conditions. Thanks to the surface analysis techniques available *in situ* at the MBE chamber, it was possible to discriminate the signal coming from the interphase compound [5].

Acknowledgments

Research supported by MINECO-M-era.Net Programme: NEXMAG (PCIN-2015-126), MINECO through ENMA project (MAT2014-56955-R); and Comunidad de Madrid: NANOFRONTMAG (S2013/MIT-2850). E.C. acknowledges MINECO for the Formación Posdoctoral (JdC) program (FPDI-2013).

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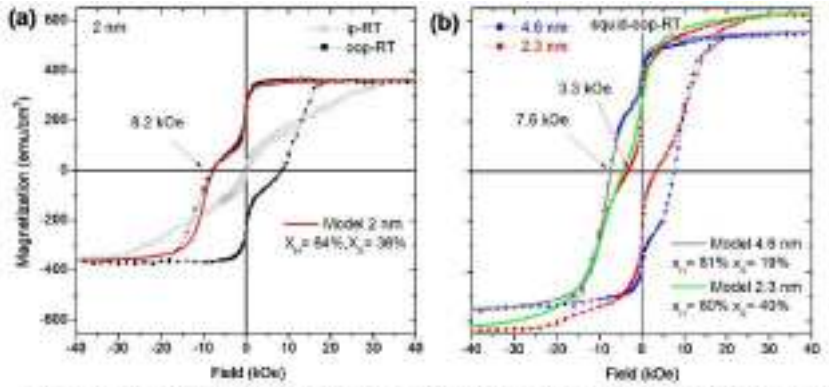

FIG. 1. SQUID measurements of (a) 2nm of MnAl grown on GaAs (001) at 300 °C with a post growth annealing process of 400°C, with the out of plane (oop) component in full black dots and the in plane (ip) one in open white dots. On panel (b) the oop SQUID measurements for a 2.3 and 4.6 nm of MnAl grown on GaAs (001) at 250 °C. Modeling of the hysteresis demagnetization curves with different hard and soft phase ratios (x_{h} and x_{s}, respectively) are shown as continuous lines.

P103 - Improving the Fe/Sb2Te3 interface quality with thermal annealing

6. Magnetic thin films, multilayers, surface and interfaces

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The interest in heterostructures based on ferromagnets (FM) and topological insulators (TI) is constantly increasing for their inclusion in the next generation of spintronic devices.[1,2] Ideally, the spin-polarized current flowing at the surface of TIs can be used to manipulate the FMs magnetization super-efficiently.[3] Therefore, to obtain high quality FM/TI interface is required. In this contribution, we present the chemical, structural and magnetic characterization of the Fe/Sb_2Te_3 interface as a function of rapid and mild (up to 200 °C for 10 sec) thermal annealing (RTA). The Sb_2Te_3 granular-TIs are deposited at room temperature on a 4'' wafer by Metal Organic Chemical Vapor deposition (MOCVD),[4] and subjected to RTA up to 200 °C. Then, the ^{54}Fe(10 nm)/^{57}Fe(1 nm) FM-bilayer is deposited by Pulsed Laser Deposition (PLD) on top of Sb_2Te_3, to allow interface-sensitive ^{57}Fe Conversion Electron Mössbauer Spectroscopy (CEMS). In our previous study, we detected a large intermix at the Fe/Sb_2Te_3 interface, with Fe coordinating both ferromagnetically, and paramagnetically in FeTe and FeOx – type of bonding.[5] Contrary to what has been observed at the interface between Fe with binary oxides,[6] the post Fe-deposition RTA was shown to be inefficient in reducing the intermix at the Fe/Sb_2Te_3 interface, but actually it increases the paramagnetic contribution (Fig.1(a)). In this work, by combining information from X-Ray Diffraction (XRD), X-Ray Reflectivity (XRR), Time-of-Flight Secondary Ions Mass Spectrometry (ToF-SIMS), Vibrating Sample Magnetometry (VSM) and CEMS, we show that an appropriate pre-Fe deposition RTA process can markedly improve the Fe/Sb_2Te_3 interface quality by simultaneously enhancing the crystallinity of the Sb_2Te_3 TI and drastically lowering the presence of unwanted FeO_x (Fig.1(b)). Remarkably, the fraction of FeTe seems unaltered with the RTA, further confirming that the preferential bonding between Fe and the chalcogen element of TI could be a general phenomenon.[5,7] In order to test the potential influence of the deposition method on the interface quality, we will also present a comparison with equivalent Fe/Sb_2Te_3 systems, where Fe is grown by e-beam evaporation.

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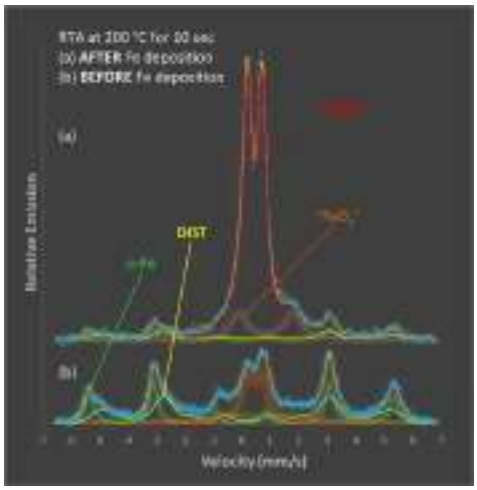
RTA at 200 °C for 30 sec
(a) AFTER Fe deposition
(b) BEFORE Fe deposition
(a)
DIST
(b)
Relative Emission
Velocity (mm/s)

P105 - In-situ differential phase contrast imaging of the AF/FM phase boundary in FeRh-based thin films

6. Magnetic thin films, multilayers, surface and interfaces

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Introduction

Equi-atomic iron-rhodium ($Fe_{48}Rh_{52}$ to $Fe_{56}Rh_{44}$), an ordered α' alloy, undergoes a magneto-structural transition from an antiferromagnetic (AF) to a ferromagnetic (FM) state upon heating (at ~ 350 to 380 K) [1]. The temperature at which this transition occurs can be raised (by doping with Iridium) or lowered (by doping with Palladium) [2]. These effects can be combined with use of subtle doping gradients, to enable manipulation of the AF/FM phase boundary.

To study the dynamics of this phase boundary in a thin film setting, a transmission electron microscopy (TEM) specimen was prepared and mounted on a DENSsolution *in-situ* heating holder, for imaging in an aberration-corrected JEOL ARM 200cF microscope. This instrument allows nanometre scale imaging of the physical, compositional and magnetic structure of materials. Using this capability, the dynamics of these technologically important phase boundaries[3], can be studied directly in thin films rather than in bulk specimens.

Results and Discussion

Uniform and Ir / Pd gradient-doped thin films of ordered α'-FeRh alloy were grown epitaxially on (001) MgO substrates by conventional DC magnetron sputter co-deposition (as described in Ref [4]).

The FeRh films were prepared for TEM study by focused ion beam (FIB) methods and transferred to *insitu* heating (DENSsolution WildfireTM) TEM electronic (e-) chips. The specimens were annealed *in situ* in the TEM at 650°C for 1 hour using the DENSsolution e-chips, in order to recover the ordered α' FeRh structure after FIB preparation. High-resolution scanning TEM and spectroscopic imaging confirmed the epitaxial structure, and that the desired Ir/Pd doping was achieved.

Differential phase contrast (DPC)-scanning TEM imaging of the annealed sample was performed synchronously with *in-situ* heating (presented in Fig. 1). This enabled direct observation of domain nucleation and phase boundary propagation within cross-sectional FeRh thin films. The phase boundary was observed to nucleate close to the Iridium-poor face of the FeRh film, and propagated through the film thickness as the sample was heated from room temperature to 200°C.

Acknowledgements

We acknowledge support from UKRI (grant numbers EP/M0190020/1 and EP/M019020/1).

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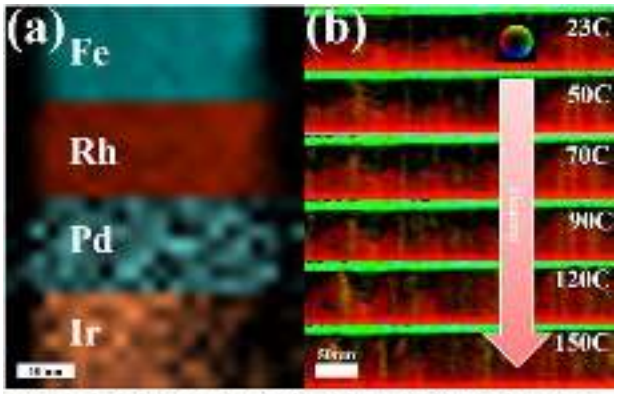

Figure (a) EDX maps showing elemental distribution within specimen. (b) DPC maps, at 23, 50, 70, 90, 120, 150°C. Red (ferromagnetic) region increases in thickness with temperature.

P106 - Influence of adsorbed hydrogen on magnetic properties of ultrathin Cobalt films in electrolyte

6. Magnetic thin films, multilayers, surface and interfaces

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Controlled manipulation of magnetic properties of a given ferromagnetic material is crucial for a wide range of applications ranging from sensors to storage devices. Here we study changes in coercivity and domain wall morphology in ultrathin cobalt films exposed to hydrogen in an aqueous electrolyte solution. Previous studies revealed a reversible tilt of the magnetic anisotropy axis upon hydrogen adsorption on the Co surface [1] or even in buried layers [2] without modifying the domain structure [1]. Thin Co layers (thickness 0.5nm-1nm) are sputter deposited on Pt and capped by AlO_x to prevent surface oxidation. This protection layer is removed *in-situ* in electrolyte solution under potential control. Perpendicular magnetic anisotropy is established by carbon monoxide adsorption at the film electrolyte interface. Application of a sufficiently high negative potential (< -1.25V against mercury-mercurous sulphate reference electrode (MSE)) across the film electrolyte interface leads to hydrogen evolution reaction (HER) exposing the film to hydrogen. With magneto optical Kerr effect (MOKE) measurements in polar geometry we monitor changes in coercive field and magnetization of the Co layer. We observe a strong and irreversible reduction of the coercive field after applying potentials in the HER range. However, in contrast to literature, we do not observe a reorientation of the magnetic anisotropy axis [1] or complete suppression of the magnetic moment [2]. With MOKE microscopy we observe changes in domain dynamics in the HER range, notably an increase in domain wall velocity and a reduction in the domain nucleation density (see Figure, domain nucleation images taken at $-0.8V_{MSE}$, white scale bars correspond to 100 µm) pointing at a modification of the pinning site density and strength.

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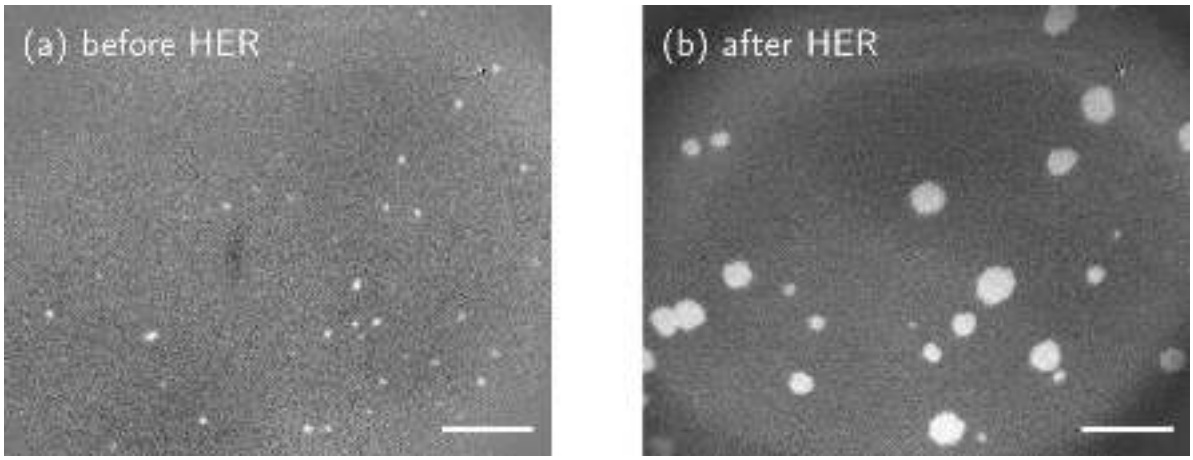

P108 - INFLUENCE OF EPITAXIAL STRAIN ON ELECTRONIC TRANSITIONS IN LA2/3SR1/3MNO3 ULTRATHIN FILMS

6. Magnetic thin films, multilayers, surface and interfaces

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Ultrathin films of $La_{2/3}Sr_{1/3}MnO_3$ (LSMO) show promise for applications in spintronics due to their unique physical properties (colossal magnetoresistance, metallic conductivity, high Curie temperature, high degree of spin polarization). Their ferromagnetic properties were first explained by a double-exchange (DE) interaction [1], which is strongly influenced by Mn-O-Mn geometry. Therefore, one of the main factors responsible for change of their magnetic properties is epitaxial strain.

Using pulsed laser deposition, we prepared LSMO films on four different substrate materials, providing a substantial variety of strains. The exact strain states of the films were determined by X-ray diffraction. Spectroscopic ellipsometry and magneto-optical (MO) spectroscopy was used to characterize the optical and MO properties. Spectra of the off-diagonal permittivity tensor elements reveal presence of previously reported electronic transitions around 2.5 eV [2] and 3.5 eV [3]. Another transition around 4.3 eV is observed only in spectra of films deposited under compressive strain. We show that this transition is likely to originate from lowering of the crystal symmetry because of the epitaxial strain. It serves as a manifestation of the key role strain plays in controlling the magnetic properties of ultrathin perovskite layers.

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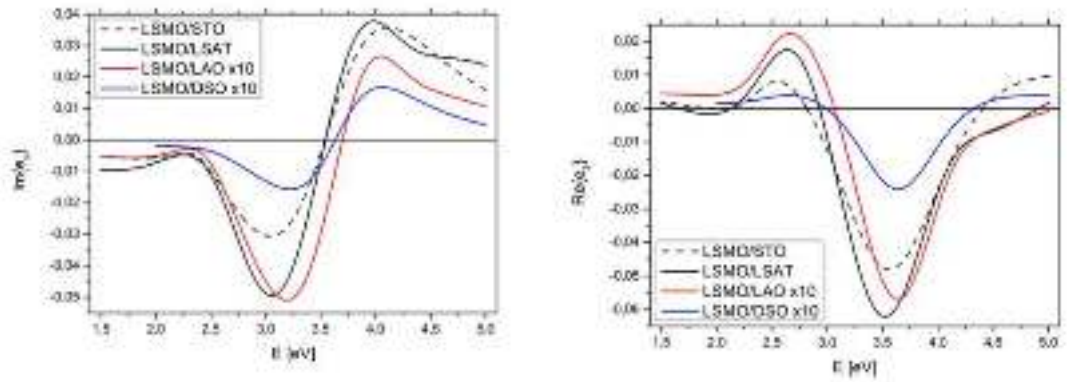

Fig. 1 Off-diagonal permittivity tensor elements

P109 - Investigation of Magnetic anisotropies and Exchange Bias in ultrathin IrMn/Co/Si(100) thin films

6. Magnetic thin films, multilayers, surface and interfaces

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From both the technological and fundamental viewpoints, the magnetic anisotropy is one of the most important properties of magnetic materials. The exchange bias (EB) anisotropy is currently exploited to pin the magnetically hard reference layer in spin-valve read-back heads and MRAM memory circuits, as well as to increase the thermal stability of fine magnetic particles in advanced disk media. In this work, we have investigated the contribution of different types of magnetic anisotropies including the exchange bias coupling as a function of different thickness of the ferromagnetic Co layer coupled with antiferromagnetic IrMn of constant thickness 10 nm. The series of Co(t_{Co}=6-20nm)/IrMn(10nm) bilayer thin films were deposited by magnetron sputtering on 10 × 15 mm^2 on SiO_2/Si substrates using 99.99 % pure Co and IrMn targets. All the samples are grown at room temperature and no magnetic field is applied during deposition. The samples were rotated during the deposition (4.2 rpm). After evacuating the chamber to a base pressure of 1 × 10^{-6} Torr, each layer was sequentially grown at working pressure of 2 ×10^{-3} Torr. The XRD patterns of the films revealed that the grain size is almost independent of thickness of Co film for these polycrystalline EB bilayer samples. The study revealed that the anisotropy of IrMn layer and its coupling to different cobalt grains are responsible for such significant high value of EB field (H_E) at room temperature. The thickness of individual layers and associated interfacial roughness were accurately determined from X-ray Reflectivity (XRR) measurements. We have done in plane angular variation measurement by longitudinal magneto optic Kerr effect (MOKE) M-H system which confirmed the unidirectional nature of Exchange bias coupling. Variation of H_E and enhancement in corecivity (H_C) with the FM layer thickness in these thin films is studied by MOKE. The EB response in these bilayers has also been investigated at low temperature (T=50 K) under positive as well as negative field cooling by using VSM option of Physical property measurement system (Model Evercool Ⅱ). From these M-H loops, it is confirmed that sample has negative exchange bias. Angle dependent Ferromagnetic resonance (FMR) measurement were preformed to quantitatively evaluate the different contributions of the magnetic anisotropy present in these bilayers.

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P110 - Investigation of magnetic domains in (YSmLuCa)_3(FeGe)_5O_12 films using MFM and other techniques

6. Magnetic thin films, multilayers, surface and interfaces

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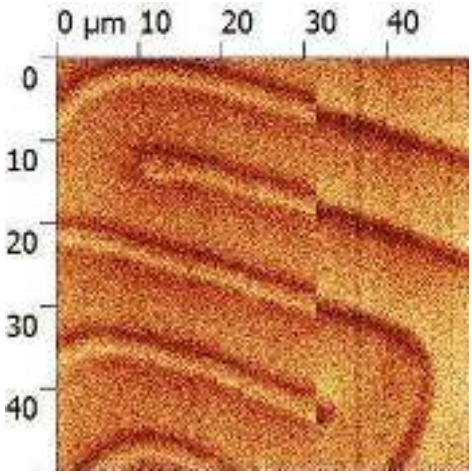
The work is devoted to the detailed analysis of the behavior of magnetic domains by magnetic force microscopy (MFM) technique in transparent ferrite–garnet films prepared on gallium-gadolinium substrate. 3-6 μm thick layers of $(YSmLuCa)_3(FeGe)_5O_{12}$ were grown on 450 μm $Gd_3Ga_5O_{12}$ substrate by liquid-phase epitaxy. Structural and phase composition of the samples were checked by X-ray diffraction and scanning electron microscope with energy dispersive X-ray detector.

The magnetic domain structure was studied by MFM in external magnetic fields up to ±500 gauss out-of-plane and ±1000 gauss in-plane. The results were compared with the domain patterns obtained by magneto-optical Kerr microscopy. It was confirmed that the transformation of the domains depends on the thickness of the film and the domain structure is much more sensitive to out-of-plane field. Bulk magnetic properties of the samples were also measured by vibrating sample magnetometer and local hysteresis loops analyzed by tracer placed directly inside the Kerr microscope.

As the domain structure of the films was very clear and homogeneous over the surface, they also provide suitable reference samples to test the optimization of the MFM parameters. We focused our attention mainly (i) to the effect of external fields on the tip and thus on the contrast of MFM image and (ii) to the undesirable influence of the magnetic field of the tip on the sample as we tested different types of probes. Figure shows the domain patterns of garnet film measured by MFM10 tip in magnetic field -350 gauss. During the measurements, pre-magnetization of the tip was observed.



P111 - Investigation of magnetic MAX phases and i-MAX phases

6. Magnetic thin films, multilayers, surface and interfaces

Einar Baldur Thorsteinsson[1] , *Arni Sigurdur Ingason*[2], *Fridrik Magnus*[1]

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[2] Grein Research

MAX phases are nanolaminated films, with ordered atomic layers in the format M-A-M-X-M-A-M-X-M. Where M is a transitional metal, A is a A-group metal (Si, Ge, Ga, Al etc.) and X is either carbon or nitrogen. MAX phases exhibit both properties of metals and ceramics making them interesting materials. Using magnetic elements in the structure expands the possibilities of potential applications. A variation on the MAX phase structure is the i-MAX phase, where the M element is alloyed, resulting in a Kagomé-like structure with in-plane chemical ordering [1].

We have grown epitaxial thin films of the MAX phase Mn_2GaC and i-MAX phase $(Mn_{2/3}Sc_{1/3})_2GaC$ by DC magnetron sputtering. We use elemental Ga for the sputtering of the MAX phases, which enables us to have excellent control over the composition of the films. The growth parameters for the Mn_2GaC phase were optimized and thicker samples were made for improved signal compared to previous studies [2]. This allows us to determine the magnetic signal of the thin film more reliably, Figure 1. Structural parameters were investigated with x-ray diffraction (XRD), while magnetic properties were measured using a vibrating sample magnetometer (VSM) in the range from 2-300 K.

The effects of alloying with Sc to produce the $(Mn_{2/3}Sc_{1/3})_2GaC$ phase were then investigated. This phase has been synthesized using bulk methods before, however, this is the first time it is made as an epitaxial thin film. Simulations indicate that the magnetic ground state is anti-ferromagnetic (AFM), although close to degenerate with ferromagnetic (FM) ordering [3]. The structural and magnetic properties were investigated with XRD and VSM measurements and compared to the pure Mn_2GaC phase.

[1] M. Dahlqvist, J. Lu, R. Meshkian, Q. Tao, L. Hultman, and J. Rosen, Prediction and synthesis of a family of atomic laminate phases with Kagomé-like and in-plane chemical ordering, Sci. Adv. 3, e1700642

[2] M. Dahlqvist, A. S. Ingason, B. Alling, F. Magnus, A. Thore, A. Petruhins, A. Mockute, U. B. Arnalds, M. Sahlberg, B. Hjörvarsson, I. A. Abrikosov, and J. Rosen, Magnetically driven anisotropic structural changes in the atomic laminate Mn_2GaC. Phys. Rev. B 93, 014410

[3] A. Petruhins, M. Dahlqvist, J. Lu, L. Hultman, and J. Rosen, Theoretical prediction and experimental verification of chemically ordered atomic laminates $(Cr_{2/3}Sc_{1/3})_2GaC$ and $(Mn_{2/3}Sc_{1/3})_2GaC$ (i-MAX phases), *In manuscript*

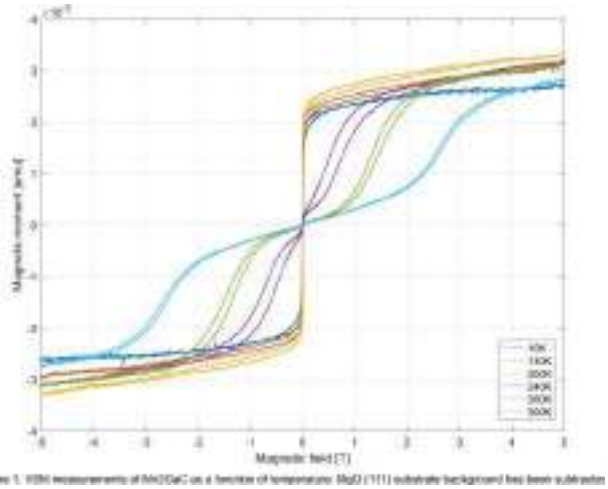

Figure 1. VSM measurements of Mn_2GaC as a function of temperature. MgO (111) substrate background has been subtracted.

P112 - Large variation of the g-factor in exchange spring [CoFeB/Pd]/Co multilayer

6. Magnetic thin films, multilayers, surface and interfaces

Carlos Garcia[1] , *Claudio Gonzalez-Fuentes[1], Johan Akerman[2]*

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We report on a large variation of the gyromagnetic factor in exchange spring system with tilted magnetic anisotropy in [CoFeB(0.4nm)/Pd(1nm)]x5/Co(t) with t= 0, 0.5, 0.7, 0.9, 1.1, 1.3, 2.0 and 2.5 nm multilayers fabricated by DC sputtering in an ultra-high vacuum chamber. By careful evaluation of the spectroscopic g-factor, we determine the orbital moment along the out-of-plane and in-plane directions and compare with X-ray magnetic circular dichroism measurements.

We also present a model describing the ferromagnetic resonance of multilayer structures, which was used to characterize the interface anisotropy constant and interlayer exchange coupling strength associated to individual components of [CoFeB/Pd]xn multilayers with perpendicular magnetic anisotropy and [CoFeB/Pd]5/Co exchange spring structures by comparing with ferromagnetic resonance behavior measurements. We find that the effective perpendicular anisotropy increases with the number of repetitions of the multilayer. Additionally, we show that effective magnetization, Meff, and uniaxial anisotropy, Ku, of the multilayers decrease within creasing the thickness of the Co layer.

P113 - Magnetic and structural ordering in Fe3O4-Metal interfaces

6. Magnetic thin films, multilayers, surface and interfaces

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The ability to transform heat currents into spin currents (Spin Seebeck Effect, SSE) has been intensely investigated in the last years with the driving force of both, the development of efficient thermoelectric power generators and, on the other hand, the achievement of a fundamental explanation of this phenomenon, which still presents controversies and an important lack of understanding. The SSE was previously reported in several ferromagnetic materials, including semiconductors, metals, and insulators. To detect the SSE, thin films of non-ferromagnetic metals with large spin orbit coupling are deposited on the ferromagnetic material (FM). The spin current generated by thermal gradient is pumped from the magnet into the metal, where a transverse charge current, that can be detected and measured, due to the inverse spin Hall Effect (ISHE). The understanding of the structural and magnetic coupling at the FM-Metal interface is crucial in order to clarify the involved mechanisms and to develop and optimize SSE effect based devices. In this work, using the framework of Density Functional Theory (DFT), we study the electronic, magnetic and structural ordering in magnetite (Fe_3O_4), which is one of the most promising materials together with YIG to exploit the SSE, and at the interfaces of Magnetite with different non magnetic metals.

We use DFT in the GGA+U approach, considering a Hubbard term for the electrons localized at d orbitals and taking into account the spin orbit coupling. The charge localization process in the Fe^{2+} polarons of magnetite is studied, showing that it can be achieved still in the cubic phase without previous structural deformations, and allowing the conduction by polaron hopping in such cubic phase. Reconstructions of the (001) surface termination of cubic magnetite, are simulated to compare their structural stability and to realize the surface effects on the electronic and magnetic properties. Finally, Fe_3O_4-Metal interfacial properties are analyzed considering thin films of non-magnetic metals with large spin orbit coupling (Pt, Au, Nb, Ta, and W) deposited on the (001) magnetite surface. We find that these metallic over-layers grow preferentially in the (001) direction, on top of the oxygen ions. The total magnetization density as a function of z (along the (001) direction) shows that, depending on each metal, the first or the first two atomic metallic layers on the magnetite surface present a moderate magnetization, and this magnetization vanishes within the next atomic layers. The Au over-layer exhibits the lowest magnetization, with 0.01 μ_B per atom versus magnetizations ranging from 0.1 to 0.2 μ_B in Pt, Nb, Ta and W. The metals with more than half of the d orbitals occupied (Pt and Au) couple ferromagnetically to the upper layer of magnetite, while the metals with less than five d electrons (Nb, Ta and W) show an antiferromagnetic coupling with the magnetite surface. We think these results can provide insight into the fundamentals and contribute to the development of efficient devices for spin caloritronics.

P114 - Magnetic and Structural Properties of CoZn Alloy Thin Films

6. Magnetic thin films, multilayers, surface and interfaces

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The author has chosen not to publicise the abstract.

Field 5

Field 6

P115 - Magnetic anisotropy in cobalt thin films modulated by organic semiconductors.

6. Magnetic thin films, multilayers, surface and interfaces

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Recent investigations in molecular spintronic devices highlighted the role of the interfacial interactions between the organic molecules and the ferromagnetic metals, defining the electronic and magnetic properties of both components [1-3]. For a molecule chemisorbed on a ferromagnetic surface, the rearrangement of the surface orbitals has a strong impact on the magnetic anisotropy of the magnetic inorganic layer, inducing various phenomena such as magnetization reorientation and others [2].

In this work we present the investigation of magnetic anisotropy of ultrathin polycrystalline cobalt films (5 nm) after deposition of two organic semiconductors (OSC) widely used on hybrid spintronic devices: C_{60} [2] and Gaq_3 [3]. The bare cobalt thin films were obtained by e-beam deposition on single crystal $Al_2O_3(0001)$ substrates.

AFM images show an atomically flat surface with RMS of 0.4 nm over which continuous organic layers have been grown by thermal evaporation at room temperature in UHV to preserve the interfacial quality.

The *in-plane* magnetic anisotropy of the bilayers has been studied by L-MOKE. The bare cobalt thin film (used as a reference) presents a weak uniaxial anisotropy. The deposition of the two OSC produces strong and opposite effects: coercive field values increase in case of C_{60}/Co and decrease for Gaq_3/Co. Moreover the magnetization in plane is described by a non coherent mechanism with different anisotropy in the two cases. These results are interpreted on the basis of different surface anisotropy terms due to the cobalt/OSC interface.

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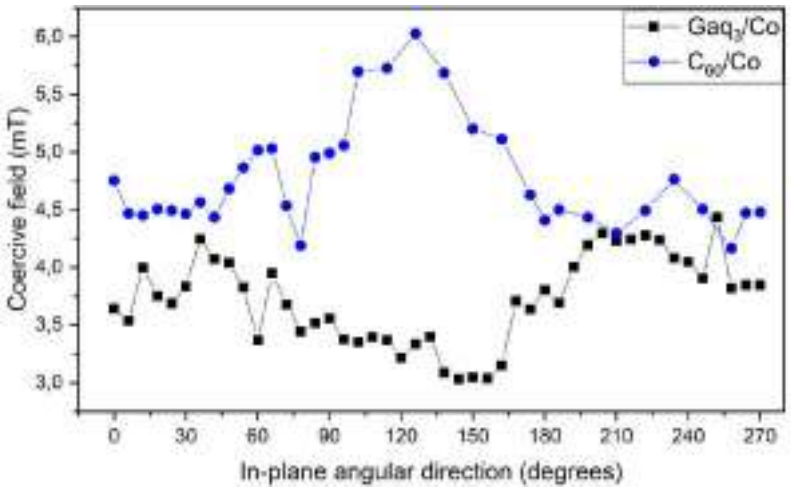

P116 - Magnetic phase transition of FeRh/MnRh superstructures

6. Magnetic thin films, multilayers, surface and interfaces

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Magnetic materials featuring first-order phase transitions between multiple order parameters are outstanding candidates for exploiting new functionalities and emergent phenomena on the nanoscale. A prime example is represented by a class of binary alloys such as MnRh and FeRh. Such compounds undergo the magnetic phase transition from a low temperature antiferromagnetic phase (AF) to a high temperature ferromagnetic phase (FM) at 275 K [1] and 360 K [2] upon heating, respectively. We focus on the epitaxially-ordered superstructure comprising thin film multilayers of FeRh and MnRh prepared by magnetron sputtering at high vacuum conditions. We study here the control of magnetic properties of the entire metamagnetic system based on variable thickness of individual layers. Combining of X-ray diffractometry (XRD) – [see Fig. 1], vibrating sample magnetometry (VSM) and electrical transport measurements we investigate a mutual interaction between individual layers. Then we detect changes of magnetic properties through the coupled order parameters: crystalline structure, magnetization and electrical resistivity.

We further demonstrate the underlying effects of substrate and order of individual layers on magnetic properties of FeRh/MnRh multilayers.

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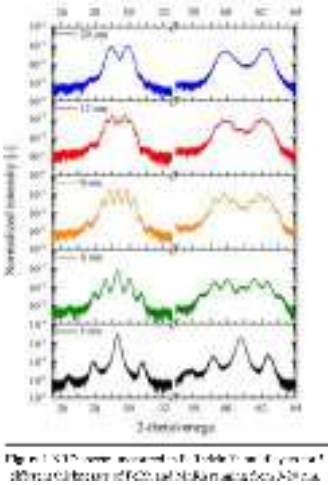

P117 - Magnetic properties of (Y1-xCex)Co5 and (Y1-xSmx)Co5 thin films grown by molecular beam epitaxy

6. Magnetic thin films, multilayers, surface and interfaces

Shalini Sharma[1] , *Philipp Komissinskiy[1], Iliya Radulov[1], Konstantin Skokov[1], Oliver Gutfleisch[1], Lambert Alff[1]*

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In quest of materials as sustainable magnets for emerging green energy technologies, we aim to investigate the role of rare-earth (*RE*) in *RE*Co_5 (*RE* = Y, Ce and Sm) systems. In this work, the evolution of magnetic properties in $(Y_{1-x}Ce_x)Co_5$ and $(Y_{1-x}Sm_x)Co_5$ thin films are studied where Y is gradually substituted by Ce and Sm. The synthesis of materials as thin films represent model systems as the composition and contamination can be controlled with atomic precision under ultra-high vacuum conditions. The films (30 nm) are grown by co-evaporation of *RE* and Co by electron beam onto (001) Al_2O_3 substrates by molecular beam epitaxy [1-2]. A gradual replacement of Y with Ce gives rise to non-linear behavior of anisotropy, K_1, and magnetization, M_S, with Ce content, *x*, in $(Y_{1-x}Ce_x)Co_5$ thin films as shown in the figure. However, for $(Y_{1-x}Sm_x)Co_5$ thin films, the magnetization and anisotropy show a linear dependence with Sm content. To explain this contrasting magnetic behavior, the effect of valence state of *RE* ion, chemical strain, crystal structure and micro structure of the films will be discussed. Furthermore, the films exhibit perpendicular anisotropy which make them interesting for ultra-high density magnetic storage and nano-scale spintronic applications. These results provide us guidelines to tune as well as design the magnetic parameters of the materials depending on their application as permanent magnets or in magnetic storage devices.

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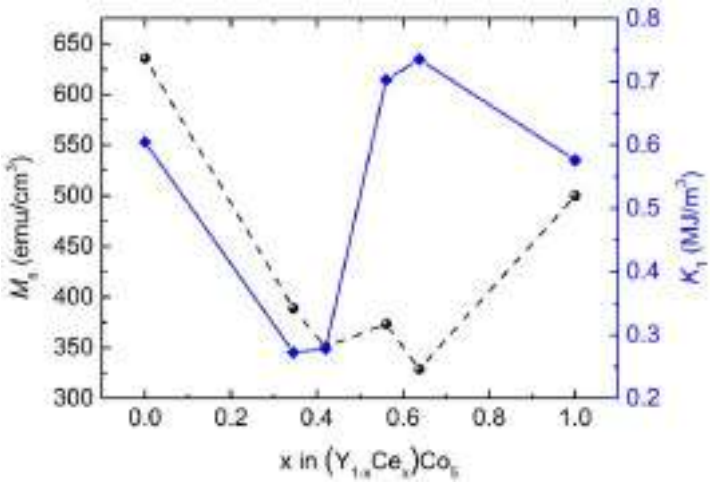

P118 - Magnetic proximity effects in magnetic heterostructures.

6. Magnetic thin films, multilayers, surface and interfaces

Kristbjorg Anna Thorarinsdottir[1] , *Heikki Palonen*[2], *Gunnar Karl Palsson*[2], *Björgvin Hjörvarsson*[2], *Fridrik Magnus*[1, 2]

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The magnetic proximity effect refers to an induced magnetic ordering in a non-magnetic material which is brought about by proximity to a magnetically ordered material. Typically, it is observed in composite or layered materials, where one layer is ferromagnetic (FM) or antiferromagnetic (AFM) and the other is paramagnetic (PM) or has a lower ordering temperature [1]. The influence of such a proximity effect can be diverse. In FM-PM systems magnetization can be induced in the PM above its intrinsic ordering temperature [2].

By changing the composition in amorphous $Co_x(AlZr)_{x-1}$, we can tune the T_c to be below room temperature so that the layer is at the verge of ferromagnetism. Here, we show that in $Co_{60}(AlZr)_{40}Co_{85}(AlZr)_{15}$ multilayers with alternating high- and low T_c (Fig.1) there is a magnetic proximity induced region in the PM layer. This magnetic state has a very large extension and survives up to three times the intrinsic ordering temperature of the low T_c layer. We find that the magnetization scales linearly with thickness and by using a simple model, can extract the induced magnetization in the low T_c layer, which shows that there is a non-zero magnetization in the PM layer above T_c [3].

We also investigate the influence of the proximity effect on the magnetic anisotropy. By layering \TbCo/$Co_{70}(AlZr)_{30}$/$Co_{85}(AlZr)_{15}$ we can observe how the TbCo, which is a ferrimagnet with a strong perpendicular magnetic anisotropy (PMA), affects the $Co_{85}(AlZr)_{15}$ which has in-plane magnetic anistropy (IMA). The $Co_{70}(AlZr)_{30}$ spacer layer has T_c below room temperature, so we can study the magnetization induced in this layer by proximity to the TbCo. The two layers will also be in a large magnetic field from the TbCo layer, and the effect this has on the magnetic anisotropy is unknown. By scaling the thickness of the spacer layer, we can observe how the PMA affects the IMA on different length scales.

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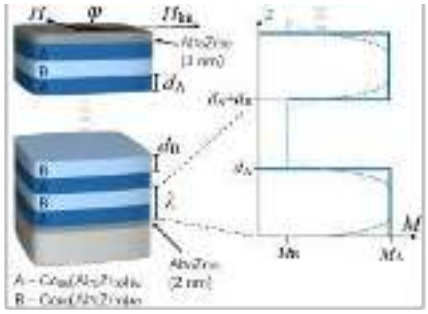

Figure 1: A schematic of the multilayer sample structure (left) and the magnetization profile of one bilayer, below T_c^b (right). The solid lines are a simple constant magnetization approximation whereas the dashed lines represent a smoothly varying magnetization across the interfaces.

P119 - Magnetic structure of monatomic Fe chains on Re(0001)

6. Magnetic thin films, multilayers, surface and interfaces

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Magnetic nanostructures on heavy-element superconducting surfaces are in the focus of recent research efforts, particularly because of the formation of noncollinear spin configurations, Yu-Shiba-Rusinov states and Majorana bound states. The signatures of these phenomena have been recently investigated in atomically fabricated Fe chains on the Re(0001) surface via scanning tunneling microscopy and spectroscopy measurements [1]. Here we investigate the magnetic ground state and interactions in this system using ab initio methods [2]. Spin model calculations based on a Hamiltonian containing only two-spin tensorial interactions agree with the fully ab initio energy minimization in predicting a spin spiral ground state for a 15-atom-long chain, but the chirality of the spiral is found to be different for the two methods. This discrepancy is resolved by taking into account four-spin chiral interactions in an extended spin model.

[1] H. Kim et al., Sci. Adv. 4, eaar5251 (2018)
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P120 - Magnetic structure study through polarized neutron reflectometry: FePt thin film with stripe domains

6. Magnetic thin films, multilayers, surface and interfaces

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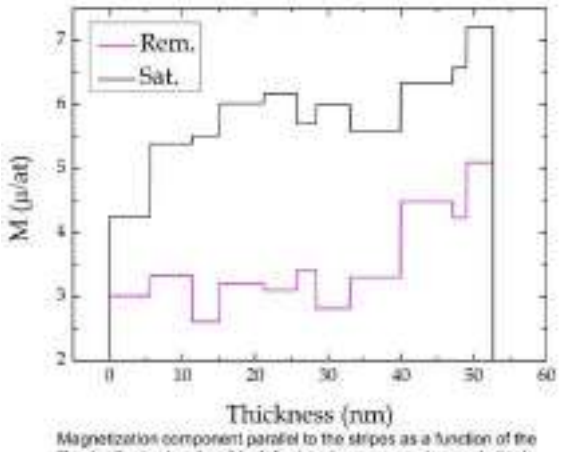
One of the most complex magnetic structures in thin films is observed when the perpendicular anisotropy (PMA) is not strong enough to overcome the demagnetizing field. Under this condition, a periodic structure of stripe domains is formed. When the stripe domains are set, the spatial components of the magnetic moments vary periodically along the three directions. But depending on the region of the sample, the magnetic domains present different preferential directions: i) The film presents out of plane domains localized at the center of the sample. ii) On the film surfaces domains are formed, which are mainly parallel to the film plane. They are called closure domains and they help to minimize the dipolar stray field. iii) Inside the film and adjacent to the out of plane domains, there exists other domains mainly oriented along the stripe direction.
In the literature, we find very few experimental studies focused on a quantitative measurement of such complex domain structure. This limitation is mainly due to the difficulty in quantifying their sizes that can be as small as few tens of nanometers. What is known so far, and well accepted within the community, is through analytical and micromagnetic calculations. However, the calculations have computational time limitations and memory, and refer to ideal systems. This does not allow, for example, to introduce pinnings centers, defects and local variation of anisotropies that have a very important effect on the properties of the stripe domains.
A useful technique to study the structure of domains that are even buried below the sample surface is the polarized neutron reflectometry (PNR). This technique, which is carried out in instruments of neutron beam laboratories generated by a spallation source or a nuclear reactor, is sensitive to changes in magnetization as a function of the depth of the thin film. The PNR is usually used to detect magnetization changes in surfaces and interfaces of heterostructures, generally due to magnetically dead layers and charge transfers in such interfaces. However, its ability to distinguish changes in magnetization as a function of depth makes it particularly useful in determining the change of the domain volume fraction along the growth.

With the aim of studying such magnetic behavior we have performed PNR experiments at PRISM beamline of the Leon Brillouin Laboratory. The measurements were carried out on sputtered FePt thin films of 60 nm thick that present stripe domains. The PNR spectra were taken at different applied fields, H, along the stripe direction in order to determine the changes of the magnetization profile as a function of H.
The results show that the component of the magnetization parallel to the stripes varies as a function of sample depth. Furthermore, it is reduced at the middle of the film with respect to the sample edges where the magnetization reaches the maximum value. This magnetization reduction is more pronounced when H is reduced (see figure).
Micromagnetic calculations were performed in order to simulate the magnetization profile and they are in agreement with the profile experimentally determined.



Magnetization component parallel to the stripes as a function of the film depth at saturation (black line) and remanence (magenta line).

P121 - Magnetization of Fe in epitaxial Fe\Cr\Fe tri-layers: effect of structure & stress on the magnetism

6. Magnetic thin films, multilayers, surface and interfaces

Gladice Magnifouet[1]

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Fe/Cr/Fe tri-layers and Fe\Cr multilayers were deposited on MgO(100) and STO(100) substrates using molecular beam epitaxy (MBE). Thanks to the excellent growth conditions of MBE technique (ultra-high vacuum , small atomic rate < 0.1), we have obtained a better epitaxial quality and smaller swelling compared to the previous results on sputtering samples. The structure of the tri-layers is as follows: MgO(100)\ MgO (20 nm @ 600°C)\ Fe (@ RT + annealed @ 600° C)\ Cr @ RT \ Fe @ RT\ Au (5 nm @ RT). A 20nm of MgO buffer layer was deposited to smooth the surface of the substrates before growth and a 5nm of gold layer was deposited to protect the tri-layers from oxidation.

Reflection high-energy electron diffraction (RHEED) was used to follow the surface crystalline structure of the substrates, the MgO buffer layer and each layer of Fe and Cr. Reflectometry results indicate flat interfaces between MgO and the first iron layer. Complementary analyses using Atomic force microscopy show a good topography of the substrate surface after the growth of the MgO buffer layer.

X-ray diffraction was used to study the structure of the Fe/Cr/Fe tri-layers. Both the specular scans and pole figure mappings indicate the epitaxy of the films along the [100] direction of MgO(100) and STO(100). High crystalline quality is also obtained for Cr and Fe layers. However, for Fe\Cr\Fe tri-layers with the thicknesses smaller than 10nm, the epitaxial quality is not good: we observe a roughness of the layers and the presence of different growth directions as shown by x ray reflectometry (XRR) and pole figure maps respectively.

The “$\sin^2(\Psi)$ method” is used to analyze the stress giving access to the in-plane and the out-of-plane lattice parameters. The values of the residual stresses obtained become smaller when the thickness of the tri-layers increases and are those expected for a coherent epitaxy of tri-layers. A negligible swelling of Fe and Cr layers indicates the absence of external factors such as oxygen (observed in the case of tri-layers prepared by sputtering).

SQUID measurements were used to determine the average magnetization of Fe as a function of the thickness of Fe. The average magnetization of Fe is close to the bulk value and is higher for the growth on STO(100) compared to the ones on MgO(100). For the thickness above 10nm, the values of the magneto-crystalline anisotropy energy are close to the bulk Fe value 5.5×10^5 erg/cm^3.

P122 - Magnetization reversal and ferromagnetic resonance of heavy metal/ferromagnetic heterostructures.

6. Magnetic thin films, multilayers, surface and interfaces

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In the investigated heavy metal / ferromagnetic (HM/FM) multilayers a labyrinthine-like domain structure with perpendicular magnetization is formed. In this work, we show that the chiral parallel stripe domains structure aligned by the treatment with magnetic filed can be considered as one-dimensional (1D) magnonic crystal (MCs) in which the spin waves may propagate. It is expected that spin waves can be applied in fast data storage technology, magnonic logic devices characterized by low power consumption and being faster than skyrmions and domain wall velocity [1]. In such metamaterials, with periodic modulation of their magnetic properties spin waves propagate in a controlled way.

Inspired by the theoretical calculation [2], a set of FM/HM heterostructures has been fabricated by molecular beam epitaxy (MBE) technique, where FM is Co and HM: Pt and W. Such system exhibits the high spin-orbit coupling (SOC). Moreover, large additive iDMI (interfacial Dzyaloshinskii Moriya interaction) strength and perpendicular magnetic anisotropy are observed. To enhance iDMI, the multilayers with Co asymmetrical surroundings $[W/Co/Pt]_N$ were prepared, where N= 10 or 20 is a trilayer repetition number. High quality of the layered structure has been confirmed by XRD (satellite peaks) and XRR (Bragg peaks and Kiessig fringes). Magnetic properties have been measured by SQUID magnetometer in the polar configuration. The multilayers are characterized by higher (by 20%) than bulk Co magnetization saturation and strong perpendicular magnetic anisotropy ($K_u \approx 2.3$ MJ/m^3) The shape of the hysteresis loops (zero coercivity) suggests a presence of the multidomain structure with magnetization oriented in the perpendicular direction to the film plane.

Domain structure of the multilayers has been investigated by magnetic force microscopy (MFM) The labyrinthine-like magnetic domains observed in as-deposited samples evolve into parallel stripe domain structure (parallel stripe domains in Fig. 1.a and 1.b) after saturation in the magnetic field applied in the sample plane, followed by an in-plane ac demagnetization with decreasing amplitude. The average periodicity of the labyrinth and the width of parallel stripe domains decrease with the repetition number of multilayers (Fig.1). To stabilize the parallel stripe domains, the relation $QK_u/2\prod M_s^2 \leq 1$ has to be obeyed. In our samples, the Q factor is lower than 0.3 for all analyzed systems. Additionally, FMR spectra reveal resonances lines originating from uniform ferromagnetic precesion (above saturation field) and stripe labyrinthine domain structure occurring below the saturation field. Obtained results give insight into dynamics properties of the samples which can be used as MCs.

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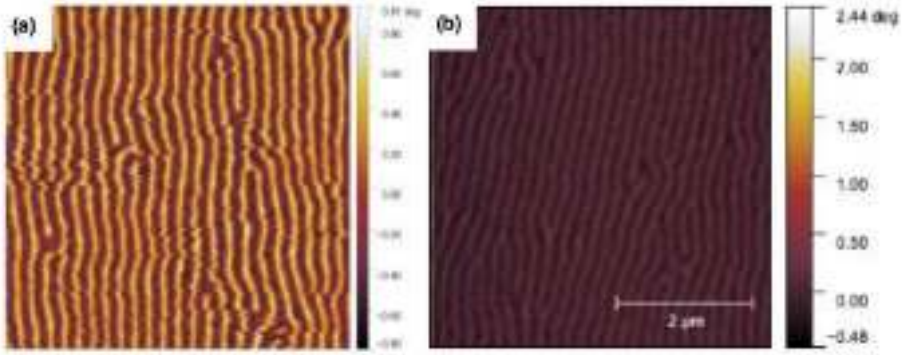

Fig.1(a) and (b) depicts the parallel domain structure for 10 and 20 repetitions for W/Co/Pt multilayers respectively.

P124 - Magnetization reversal of strongly exchange-coupled double layers of Co/Pt and TbFe

6. Magnetic thin films, multilayers, surface and interfaces

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Exchange-coupled systems with perpendicular magnetic anisotropy, consisting of a rare earth-based ferrimagnet (amorphous TbFe) and a transition metal-based ferromagnet (crystalline [Co/Pt] multilayers), are promising candidates for a variety of applications ranging from spin valves to heat-assisted magnetic recording. Due to the amorphous and ferrimagnetic nature of TbFe, which affects the magnetization reversal of the ferromagnet differently compared to an antiferromagnet-based system, surprisingly complex and strong coupling interactions at the interface can occur [1,2]. Macroscopic magnetization measurements alone cannot account for all the details behind these interactions, thus studying the reversal locally is crucial. In this work, the reversal mechanism of the soft [Co/Pt] is understood by high-resolution and quantitative magnetic force microscopy (MFM) combined with micromagnetic simulations. The $Tb_{25}Fe_{75}$(20nm)/[Co(0.4nm)/Pt(0.7nm)]$_{\times 5}$ films are prepared at room-temperature on Si substrates using DC magnetron sputtering. The magnetic imaging is performed in a home-built low temperature UHV MFM at 10.5K and in high fields of up to 7T. Using a novel tip-sample distance control method, which allows for the average tip-sample distance to be kept the same between different samples [3], a quantitative analysis of our images is also possible. Hysteresis loop simulations with varying magnetic parameters for the TbFe/[Co/Pt] system are performed using the finite element *magnum.fe* package [4]. Instead of the conventional lateral wall motion observed in the soft layer of a weakly exchange-coupled system, a nucleation-dominated three-stage magnetization process showing a significant spatial variation occurs (see Figure): **stage 1: rotation** (panels a, b, and c), where an increase in contrast with no pattern change can be observed in the MFM images for low fields; **stage 2: switching** (panels d, e, and f), appearing in intermediate fields and where a drastic increase in contrast together with a pattern change (see arrows) are visible; and **stage 3: rotation**, where a decrease in contrast with no further change in pattern can be seen for higher fields. We attribute the spatial variation of the magnetization reversal process to grain-to-grain variations in the magnetic properties of the [Co/Pt] film which may arise from the growth of [Co/Pt] on top of amorphous TbFe, or to an inhomogeneous interfacial exchange-coupling to the TbFe film. We further show that the interfacial coupling can be tuned to smaller values by inserting an interfacial Pt layer of increasing thickness in between TbFe and [Co/Pt]. For a sufficiently reduced interfacial exchange-coupling (i.e. for a thick enough Pt layer) a conventional domain-wall motion governed magnetization process re-occurs.

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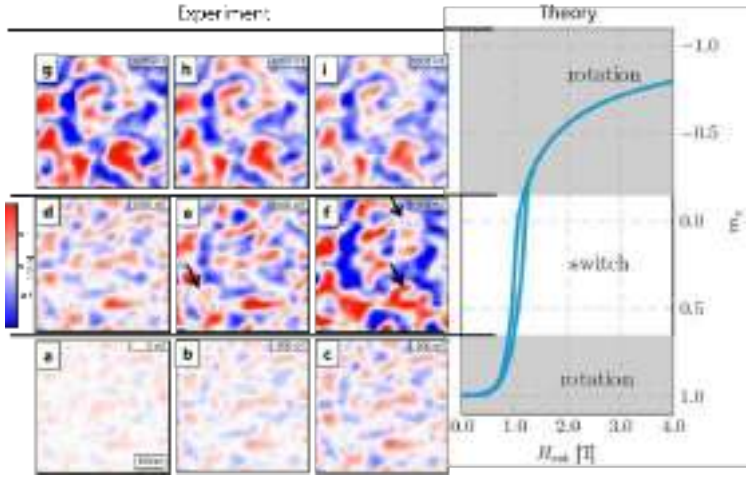
Experiment
Theory
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rotation
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−1.0
−0.5
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1.0
m_z
0.0
1.0
2.0
3.0
4.0
B_{ext} [T]

P125 - Magnon-mediated ferromagnetic coupling through antiferromagnetic spacers

6. Magnetic thin films, multilayers, surface and interfaces

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Inspired by the demonstration of the magnon-valve effect [Phys. Rev. Lett. **120**, 097205 (2018); Phys. Rev. B **98**, 134426 (2018)], we report an observation of a magnon-mediated coupling between two ferromagnetic (FM) layers in a FM1/AFM/FM2 structure with an antiferromagnetic (AFM) spacer. We demonstrate both experimentally and theoretically that the magnons propagating through the AFM layer establish correlations between the magnetization dynamics of FM1 and FM2, which can be seen as simultaneous switching of the two FM layers by an external magnetic field. These correlations substantially increase in the vicinity of the Néel point, $T \lesssim T_N$, and strongly depend on the thickness t of the AFM layer. Experimentally, we study field-induced switching in a set of Py/$Fe_{50}Mn_{50}$(t)/[Py/Fe] multilayers with different AF thicknesses (t = 4–12 nm) in a wide temperature range. Depending on temperature, the trilayer exhibits three distinct switching regimes, which are observed using MOKE magnetization measurements (see Figure). (i) The field-offset double-loop observed at low temperatures ($T << T_N$) indicates independent switching of the two FM layers as well as individual exchange biasing due to the coupling of FM1 and FM2 to the AFM spacer. (ii) The single loop at intermediate temperatures ($T \lesssim T_N$) indicates a strong ferromagnetic coupling between FM1 and FM2. (iii) The field-centered double-loop at high temperatures ($T > T_N$) shows that the FM layers are fully decoupled and fully de-pinned from the spacer. We interpret these results as originating from the exchange coupling at both AFM/FM interfaces and strong temperature dependence of the frequency of the AFM magnons at $T \lesssim T_N$. Indirect interaction between the FM layers is mediated by the AFM magnons, which can either propagate or tunnel through the AFM spacer. The tunneling process prevails at low temperatures, where the AFM magnon gap is much larger than the magnon frequencies in the FM layers. Therefore, the corresponding correlations are weak and exponentially decay with t; the FM layers are decoupled as a result. In contrast, at $T \lesssim T_N$, the main contribution into the magnon density comes from the propagating magnon modes due to the significant softening of the AFM spectrum, which substantially enhances the ferromagnetic correlations and induces a strong coupling between FM1 and FM2. Above T_N, the direct exchange coupling at the AFM/FM interfaces is suppressed, which decouples FM1 and FM2. To conclude, we demonstrate a way of thermally controlling the exchange interaction between two FM layers by using a suitably optimized AFM spacer, which should be of interest for designing new elements of future magnon-based logic as well as for tailoring the magnetization dynamics of FM/AFM-type nanostructures employed in today's spintronics applications.

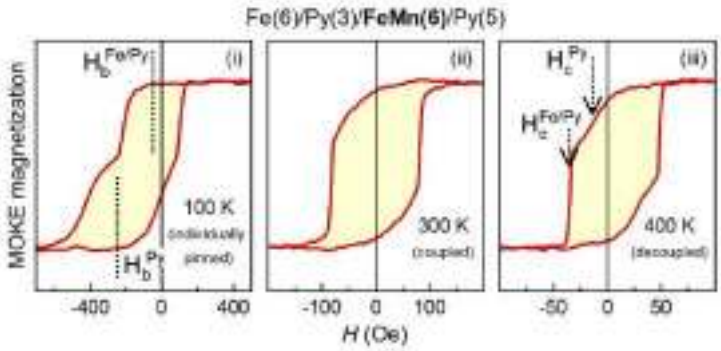

Figure. Selected MOKE magnetization loops indicating three switching regimes: (i) individual exchange biasing of the Py and Fe/Py layers (100 K), (ii) ferromagnetic interlayer coupling (300 K), and (iii) fully de-coupled and fully de-pinned state (400 K). The exchange field *Hb* and coercivity field *Hc* of the individual Py and Fe/Py layers are determined by comparing with the respective reference films and bilayers (not shown).

P126 - Managment of surface and magnetic structure of Ni-Fe nanocrystalline films

6. Magnetic thin films, multilayers, surface and interfaces

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Ni-Fe alloys have optimal balance of magnetic and functional properties. The particular interest in Ni-Fe quasi-2D structures near the percolation region for fundamental investigation and spintronic application is caused by the demonstration of unique magnetic phenomena like skyrmions and vortex-antivortex pairs. Arrays of magnetic nanoparticles (dipolar nanosized magnets) are considered to form the basis of novel magnetic data storage technology with ultrahigh density. Magnetic properties in nanocrystalline structures with single-domain Ni-Fe nanosized grains usually exhibit complex behavior a consequence of the superferromagnetic phase coexistence determined by self-arrangements of neighboring interacting particles. The abilities of nanostructured magnetic materials are essential but issues of controlled production of nanosized structure with desired properties are still relevant, which can be a brake on the industrialization of nanosized magnetic structures. We first showed the correlation between the technological parameters of Ni-Fe films production using pulsed electrolyte deposition with ultra-short pulse duration and their microstructure and magnetic structure features. The use of pulsed electrodeposition with ultra-short pause duration and variable interpulse relaxation time make it possible to formation Ni-Fe nanocrystalline films with controlled nanosized grain size and may have impact on the mechanism of their growth. Combining data obtained using scanning electron, atomic force and magnetic force microscopy made it possible to establish that the choice of films growth mechanism determines the surface and magnetic structure. So, we showed the principle possibility to controlled transformation of the films growth mechanism from the “layer-by-layer” through “layer-plus-island” to “island” formation by controlled conglomerations of nanosized grains with excess of surface energy which intensified with an increase in the time for system relaxation. In addition, the electrodeposited Ni-Fe films had a different magnetic structure. There are monolayer with single-domain Ni-Fe nanosized grains, nanocrystalline films including multi-domain conglomerates of nanosized grains surrounded single-domain individual grains and finally separate single-domain magnetic “island” on gold surface. The origin of the unexpected conglomeration and changing in growth mechanism and magnetic structure was found in the high surface energy of the nanosized grains. So, we first showed the ability to control the mechanism of the Ni-Fe films growth by controlled nanocrystallites conglomeration during pulsed electrodeposition process. The results of investigations of the correlation between the synthesis parameters and structure peculiarities are needed to improve the functional properties for a broad range of practical applications of the magnetic materials such as magnetic field sensors, high density magnetic storage, highly efficient electromagnetic shields and so on.

P127 - Metadynamics study of spin-reorientation phase transitions in ultrathin magnetic films

6. Magnetic thin films, multilayers, surface and interfaces

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The competition between different types of magnetic anisotropies often leads to a reorientation of the magnetization direction. The temperature driven spin-reorientation transition in thin films is usually explained by competing uniaxial on-site anisotropy and shape anisotropy. In this study we present the results of Monte Carlo simulations based on a classical Heisenberg model. The free energy landscape is sampled along a path relevant for the reorientation by means of well tempered metadynamics [1]. The simulation has been performed using both model parameters and parameters obtained from *ab-initio* calculations in case of an Fe bilayer on the W(110) surface. We demonstrate that the competing magnetic anisotropies can result in both first and second order spin-reorienation phase transitions.

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P130 - Microstructure Evolution and Magnetic Properties of Nanocrystalline Ni75Fe25 Thin Films

6. Magnetic thin films, multilayers, surface and interfaces

Kaibi Amel[1]
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Permalloy (Py) thin films were evaporated from nanocrystalline soft $Ni_{75}Fe_{25}$ powder onto glass and Al_2O_3 kapton substrates [1]. The thicknesses of these films range from 16 nm to 250 nm. The as deposited films were characterized by Grazing incidence X-ray diffraction (GIXRD), Scanning Electron Microscopy (SEM), Atomic Force Microscopy (AFM) and vibrating sample magnetometry (VSM). From GIXRD spectra, we have shown that the films are amorphous for the thinner films. However, for the thicker films, a polycrystalline fcc structure is present. For the intermediate thicknesses, the nature of substrate determines the texture of the films. The SEM micrographs indicate that the nature of substrate influences on the morphology and grains size of Py films. From AFM observations, the nanocrystalline nature of the grains is evidenced. Hysteresis loops reveals the ferromagnetic character of Py films. We have shown that the values of coercive field, Hc, generally, decrease with increasing thickness. Moreover, the Hc values are higher for films deposited onto kapton substrate than those on glass one. The nature of substrate and thickness seems to influence the magnetic properties of Py films. A correlation between these physical properties will be established and discussed.
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P131 - Modification of magnetic properties in thin films by substrate roughness

6. Magnetic thin films, multilayers, surface and interfaces

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Some of the most influential thin film technologies are based on magnetic films, which are indispensable in magnetic data storage, magnetic sensing or actuation devices. The ability to manipulate their magnetic and structural properties is therefore of great interest. One of the ways in which we can alter the behaviour of a film is through the preparation method. This is typically achieved by adjusting base pressure of the system, rate of deposition or angle of substrate with respect to the deposition source. More elaborative methods include growing films under influence of external magnetic field thus setting up preferred magnetisation or by using a seed layer in order to control nucleation process. In this work, we studied how substrate roughness affects the thin film properties. Three substrates of different average roughness were chosen, two of which are mechanically flexible. Films of varied thickness were plasma sputtered onto each substrate and their magnetic properties studied by Magneto Optic Kerr effect and atomic force microscopy.

We have found some unexpected results connecting film’s magnetic properties to the substrate roughness. When the film thickness values are similar to substrate roughness, the magnetic coercive field is at the highest value. We measured remarkable increases in coercive fields of 15 nm films of various magnetic materials coated on rough substrate compared to the same films coated on a smooth one. This effect was backed by an observed emergence of magnetic anisotropy, even for materials not normally possessing magnetocrystalline anisotropy, such as Permalloy.

To back our results we have assessed our finding by modified micromagnetics calculations that included surface roughness. Modelling confirmed that the observed anisotropy and coercive field increases result from spatial anisotropy of surface roughness leading to an effective in-plane magnetic anisotropy.

We believe that roughness effect is not only a scientifically interesting phenomenon but it also provides a simple and inexpensive way of modifying magnetic properties of thin films. We further remark that our best results were achieved with flexible substrates, which are the key players on electronic market today and they bring a new dimension to magnetic thin film technologies.

P132 - Modification of the phase transition of FeRh thin films induced by capping of heavy metals

6. Magnetic thin films, multilayers, surface and interfaces

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FeRh ordered alloy shows a phase transition from antiferromagnetic (AFM) to ferromagnetic (FM) state. This unique magnetic property has attracted much attention due to its potential to be integrated in AFM spintronic devices. Previous studies show that the magnetic state of FeRh is sensitive to the interface between FeRh films and the capping layers [1]. However, the origin has been still elusive. In this work, here we demonstrate the capping effect of heavy metals such as Pd, Ir and Pt on the phase transition of FeRh thin films. FeRh epitaxial films were grown on MgO(001) single crystal substrates at 620°C by co-evaporation of Fe and Rh in a molecular beam epitaxy chamber. After the growth, a mask was introduced *in situ* (without breaking the vacuum) to cap 20-nm-thick Ir, Pd and Pt layers on the half of the films. The samples were cut into two pieces, one of which is capped and the other is the pristine film. The capping layers were grown at room temperature to minimize possible intermixing at the interface between FeRh films and the capping layer. Epitaxial growth and the CsCl (B2) structure of the films were confirmed by the clear (001) and (002) peaks in the x-ray diffraction spectra. The temperature dependence of the magnetization was measured in an in-plane magnetic field of 1 kOe using a vibrating sample magnetometer. All the films show a clear phase transition from AFM to FM state in the range between 360 and 380K. We find that the transition temperature T_t of all the capped samples notably increases. In particular, the sample capped with Ir shows a diffusive phase transition with a narrower width of the thermal hysteresis. Note that the results rule out the possibility of inter-diffusion of heavy metals across the interface since mixing of Pd with FeRh is known to decrease T_t in contrast to our results [2]. A previous study shows that T_t can be tuned through the variation in the c/a ratio due to the strain induced by capping layers. A first-principles calculation study also points out that the magnetic order at the interface is driven by the tetragonal distortion and volume expansion [3]. On the other hand, large spin-orbit coupling also could contribute to the significant change in the characteristic AFM to FM phase transition due to the hybridization of 3d and 5d orbital states. Therefore, we consider that the enhancement in the phase transition temperature arises from a combined effect of strain induced by the capping of heavy metals and spin-orbit coupling that destabilizes the interface ferromagnetic state.

This work was supported in part by JSPS KAKENHI Grant Numbers JP17H03377, JP18F18353, JST CREST Grant Number JPMJCR18J1, and the Asahi Glass Foundation.

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P133 - Non Walker limit of domain wall speed in Pt/Co/Ir/Co/Pt spin valve with perpendicular anisotropy

6. Magnetic thin films, multilayers, surface and interfaces

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Ferrimagnets made of two ferromagnetic layer antiferromagneticaly coupled have shown interesting magnetization relaxation behaviors [1, 2]. We has investigated series of the Pt(3.2 nm)/Co(1 nm)/Ir(1.4 nm)/Co(t)/Pt(3.2 nm) samples with varied thickness of one of the Co layer (t = 0.6 - 1 nm). The synthetic ferrimagnet has four possible stable states, that correspond to all combinations of mutual orientations of magnetization of two nonequivalent ferromagnetic layers: two different parallel states (↑↑ – P^+, ↓↓ – P^-) and two antiparallel states (↓↑ – AP^+, ↑↓ – AP^-). The velocities of domain walls (DW) for different magnetic transition were investigated using MOKE technique. The sample was placed into the saturation field, after that magnetic field was turned down to the negative value close to the critical field switching between the stable states. Non monotonic dependence of domain wall speed v_{DW} on magnetic field H was observed. The velocity of the AP^-/ AP^+ domain border first increases with increasing of the magnetic field, but after a certain field value (H_C), the velocity decreased (Fig. 1, dependences 1 and 2 recorded for different nuclei). The DW velocity of AP^- nuclei v_{DW} correlates well with the average magnetization variation ΔM/τ(H)) of the full sample as a whole (Figure. 1, curve *3*). Estimated values of limit velocity and Walker field are much higher, than experimental values in our samples. Decrease of DW velocity of AP^- domain under increasing magnetic field is caused by interaction between AP^- and P^- domains. The P^- domains are appeared as a nonequilibrium state in the magnetic field used in our experiments. This phase rapidly generated near surface imperfections and suppressed by following expansion of the AP^- state.

This work was financially supported by Ministry of Education and Science of Russian Federation grant 3.1992.2017/4.6.

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P134 - Noncollinear spin density of an adatom on a magnetic surface

6. Magnetic thin films, multilayers, surface and interfaces

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Today, noncollinear spin structures at surfaces and interfaces receive great attention due to potential applications in spintronic devices. In such magnetic structures, the spin direction changes from atom to atom. Besides this inter-atomic noncollinear magnetism, there is also intra-atomic noncollinear magnetism in which the spin direction varies for different orbitals of an atom [1]. It can occur due to spin-orbit coupling or due to a noncollinear spin structure.

Here, we demonstrate that intra-atomic noncollinear magnetism can occur for adatoms on a magnetic surface with a noncollinear spin structure [2]. As an example, we study Co and Ir adatoms on Mn/W(110) using density functional theory. We find that the canted spin structure of the Mn surface layer is encoded into different orbitals of the adatoms. Our conclusions apply in general to adatoms on surfaces with a noncollinear magnetic structure e.g. spin spirals, skyrmions or domain walls and explain recent experimental results of spin-polarized scanning tunneling microscopy experiments [3].

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P137 - Processing effects on magnetic domains in amorphous soft magnetic films in integrated devices

6. Magnetic thin films, multilayers, surface and interfaces

Luke Guinane[1] , *Ehtsham Ul-Haq*[1], *Jan Kubik*[2], *James Hodgins*[2], *Bernard Stenson*[2], *Mike Morrissey*[2], *Shane Geary*[2], *Syed Tofail*[1]

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Recent advances in electronics have driven towards miniaturisation of components that has made possible the advent of many intelligent devices such as smart phones, portable electronics and Internet of Thing products. High frequency operation in power converters opens the door to integrated passive magnetic components, namely inductors and transformers, which will, in turn, allow for integration of much more transducers and communication systems (e.g. WLAN) within a given area [1]. However, these integrated components suffer from low power conversion efficiencies when compared to their discrete sized counterparts. Sources of inefficiency originate from power loss in conductive windings and the properties of magnetic material. Hysteresis and eddy currents are significant loss components in ferromagnetic cores that increase with the frequency of the driving current [2]. It is known that the structure and dynamics of magnetic domains as well as the magnetization behaviour affects hysteresis and eddy current loss in soft magnetic materials which are typically used in these power converters [3]. The order of the magnetic domains and magnetic properties are proportional to the material type, its thickness, area, substrate and processing methodology [4]. Here we report the domain formation, structure and properties of soft magnetic; thin films, bilayers, and multilayer samples representative of an integrated magnetic core. The layers under investigation are magnetron sputtered onto a wafer, 8 inches in diameter with an Al_2O_3 substrate. The sputter deposition takes place in a biasing magnetic field. We have varied the thickness of the films from 50 – 200 nm. The static magnetic properties of the samples are measured by a hysteresis loop tracer. The hysteresis loops of blanket (non-patterned) films are shown in Figure 1. The axes of magnetization and properties extracted from the hysteresis loop indicate a change in domain formation due to film thickness and flux closure in bilayers. We also emulate the post processing steps of integrated component manufacturing including thermal curing and patterning. The thickness and crystallization of the as deposited amorphous samples have been determined by cross-sectional transmission electron microscopy (x-TEM). The composition of the samples were measured by energy dispersive X-ray (EDX) analysis. We use scanning probe microscopy (SPM) including atomic force microscopy (AFM) and magnetic force microscopy (MFM). AFM was used to investigate the surface state and roughness of single films and bilayers. MFM was used to observe domain formation as well as their response to static and dynamic magnetization. X-ray reflectometry (XRR) is used to measure the interface roughness and film thickness in the multilayer sample. The suite of structural and surface metrology tools and analysis allows us to find the interrelation of topography, domain formation and magnetic properties for a desired film thickness and post processing to optimise multilayer magnetic cores for use in integrated components.

Acknowledgement: IRC EBPPG/2016/271

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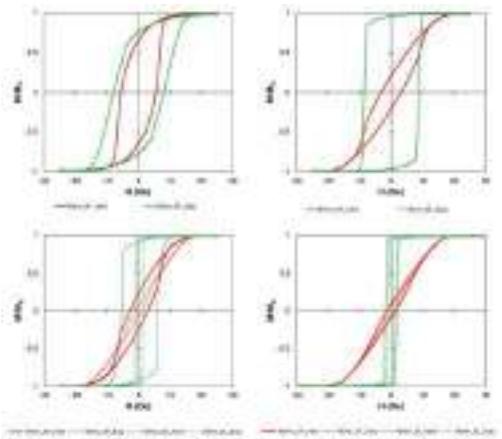

P138 - Pseudo soft phases in rare earth-transition metal alloys caused by sample mounting during sputtering

6. Magnetic thin films, multilayers, surface and interfaces

Andrada-Oana Mandru[1] , ***Oguz Yildirim***[1], *Miguel Marioni*[1], *Hartmut Rohrmann*[2], *Marcos Penedo*[1], *Xue Zhao*[1], *Michael Heigl*[3], *Oana Ciubotariu*[3], *Manfred Albrecht*[3], *Hans Hug*[1, 4]

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In the fast-advancing field of spintronics there is a renewed interest in rare earth-transition metal amorphous ferrimagnets. Examples include TbFe-based perpendicular systems, with compensation points covering a large temperature range and with very high coercive fields for certain compositions. Their useful properties make them attractive pinning layers as an alternative to conventional antiferromagnets such that when coupled with perpendicular ferri- or ferromagnetic layers, the possible applications extend into the exchange-bias and heat-assisted magnetic recording fields. The high magnetic tunability of these heterostructures allows for their properties to be tailored to specific applications only if their magnetic parameters are determined accurately. Magnetometry is the primary tool used to describe the magnetic properties and determine the magnetic parameters of such systems. Although well established, magnetometry measurements are not error free and care needs to be taken during measurements to ensure reliable and reproducible results. There have been reports of various issues that arise during magnetometry measurements, such as inadequate sample positioning and handling, sample holder off-centering, contaminations/impurities, etc., that already make an interpretation of the data not trivial [1,2]. For the specific case of Tb(Co)Fe, which is known to be very sensitive to the growth conditions, the appearance of soft phases mixed within a magnetically-hard matrix has been observed and mainly explained as the result of preferential oxidation of the rare-earth element and/or chemical inhomogeneities [3]. However, distinguishing between real and pseudo soft phases can be challenging and requires some caution. In this study, we reveal the existence of artificial soft phases and implicitly the misinterpretation of magnetometry data in sputtered TbFe alloys of various compositions. By implementing various sample configurations during DC magnetron sputter depositions (see accompanying Figure), we show that the soft phases are mainly due to sample mounting during growth, where contributions from the edges create a considerable ferromagnetic signal. We also observe that soft phases are occasionally induced by cutting from a larger sample after deposition; although a common practice in magnetometry, the cutting technique clearly lacks reproducibility. Carefully masking the samples during growth such that only the top is coated seems to give the most reliable results. We further show that the observed effects are also applicable to systems that do not contain rare-earth elements, such as [Co/Pt] multilayers. As numerous studies investigate exchange-coupling in TbFe/[Co/Pt] or similar systems [4,5], the issues that we describe here become exceedingly important when interpreting the coupling and magnetization reversal processes in such heterostructures. In fact, we argue that these observations hold true for any magnetic thin-film system prepared by methods other than magnetron sputtering.

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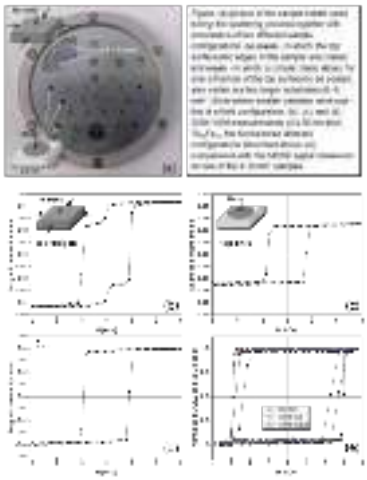

P139 - Resistive Switching of SrIrO3 thin films in the vicinity of a Metal Insulator Transition

6. Magnetic thin films, multilayers, surface and interfaces

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The relation between Metal Insulator Transitions (MIT) and Resistive Switching (RS) is important from the fundamental point of view, but also highly relevant because of the possible applications of RS based devices in non-volatile memories [1]. Transition metal oxides (TMO) offer an excellent playground to tune MIT due to the close interplay between characteristic energies as electron correlations or crystal field splitting. Furthermore, in the case of 5d TMO, the competing spin-orbit coupling rise new mechanisms and leads to unexpected electronic behaviors [2]. Here we studied the local electrical properties of semimetallic 5d $SrIrO_3$ thin films in the vicinity of a Anderson type MIT triggered by disorder and spatial localization due to film thickness reduction. RS was studied for two characteristic cases: 1. in a thick film which behaves like a semimetal, and 2. in a very thin film which has undergone the MIT and is in an insulating state (see Figure 1a). Local electrical properties were measured by means of Conductive Atomic Force Microscopy (C-AFM). In the case of very thin and initially insulating films, I/V curves presented an abrupt increase of the current intensity above a well-defined voltage threshold demostrating a sharp transition into low resistance state (LRS) associated with the opening of a gap due to thickness reduction. On the other hand, thicker samples exhibit a semimetallic character and I-V curves show progressive changes of the local resistance without a clearly defined threshold voltage, thus evidencing the absence of a real gap between the different resistance states (see Figure 1b). In both samples RS mechanism is related to the migration of oxygen vacancies trough the interface promoted by the applied electric field. Then, to maintain electrical neutrality, a valence change of the cations nearby takes place and therefore, a modification of the charge carriers' density and of the position of the Fermi level. The differences in the observed RS behavior are thus related to the the appearance of the MIT, with the concomitant aperture of a band gap. Current maps performed with voltage values above the threshold value and of different polarity allow demonstrating the writing/erasing processes making evident the feasibility of the system for the implementation of Re-RAMs.

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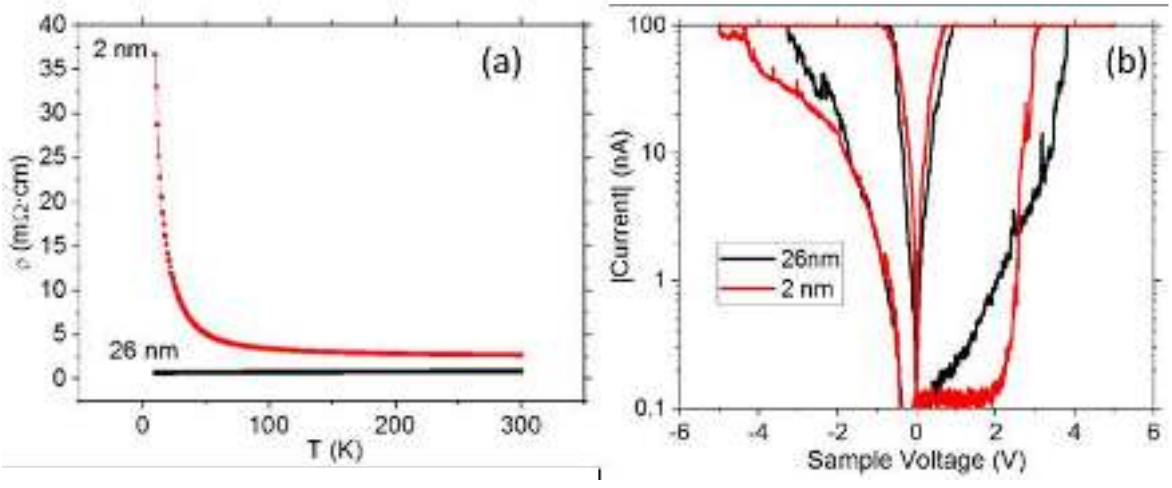

P140 - Role of varying Co layer thickness on the magnetic properties of Co/Si multilayers

6. Magnetic thin films, multilayers, surface and interfaces

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The magnetic multilayers and thin films exhibiting spin dependent transport phenomena such as AMR, GMR, TMR, AHE, became a major field of research since the discovery of GMR in 1988 [1]. Due to their complicated behaviour and potential applications, the ferromagnetic-semiconductor (FMS) multilayers have drawn attention ofthe scientific community. The properties of multilayers with metallic spacer layers are well understood. However, for FMS it is controversial. The Co/Si multilayers show interesting behaviour depending on the Co layer thickness. For higher Co layer thickness, the Co layers are ferromagnetic [2,3] and for low thickness they are superparamagnetic [3-5]. In this article, we studied the effect of the Co layer thickness on magnetic properties of Co/Si multilayers.

The multilayers are deposited on glass and Si (111) substrates using DC magnetron sputtering at 4×10^{-3} mbar Ar pressure. The multilayers are of the form $[Co(t_{Co})/Si(20Å)]_{20}$, where t_{Co} is the Co layer thickness varied from 10 Å to 100 Å. Magnetic properties are studied through M-H and ZFC-FC databy using VSM and SVSM.

From ZFC-FC and hysteresis data of the samples magnetic properties are investigated. The M-H studies in the range 4.2 K to 300 K show that the saturation magnetization (M_s) of the multilayers is low compared to the bulk Co (1452 emu/cc). This is due to superparamagnetism in Co layers. The ZFC-FC curves reveal the ferromagnetic signature with superparamagnetic contribution [6]. The magnetic dead layer (δ) of the multilayers are derived from the plot of $M_s\times t_{Co}$ as a function of t_{Co}. The deduced average magnetization (M_0) and δ are 950 emu/cc and 5 Å respectively. The obtained M_0 is smaller than that of bulk Co, which is similar to the reports by some authors [1,3].

The ZFC-FC curves at different applied fields show that the bifurcation temperature (T_{bif}) of the FC and ZFC curves lower with increase in applied field and the peak of ZFC curve broadens. Experimental data show that the T_{bif} is a non-linear function of applied field, which indicates the different strength of interactions ofthe multilayers. However, for t_{Co} = 30Å, the ZFC-FC curve does not behave in similar way. Initially at low temperature, FC has a constant trend, then it increases with increasing temperature up to 390 K. This isdue to presence of strong nanoparticle interactions [7.8].

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P141 - Skyrmionic bubble devices made from Pt/Co/HM multilayers - a feasibility study

6. Magnetic thin films, multilayers, surface and interfaces

Valentin Ahrens[1] , *Simon Mendisch[1], Martina Kiechle[1], Adam Papp[1], Markus Becherer[1]*
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In this work perpendicular magnetized Co/Pt/Ir and Co/Pt/W multilayers are investigated as a potential host for skyrmionic Bubble devices. These films are prepared using room temperature RF-magnetron sputtering on oxidized silicon substrates. To promote an improved understanding of the multilayers, experimental studies of a simple trilayer stack are executed. Especially the coercivity and effective anisotropy are investigated while varying the Co thickness. Anomalous Hall effect (AHE) measurements are performed where K_{eff} can be extracted, while the coercive field is assessed by means of laser magneto-optical Kerr effect (MOKE) measurements. In the following, the interlayer exchange coupling is investigated in a bi-repetition stack of these trilayers varying the thickness of the HM interlayer. Hereby the exchange coupling is quantified as the shift between minor and major loop hysteresis. Finally, multilayers (number of repetition $n > 2$) of the given material systems are evaluated for the condensation of zero field, room temperature stable skyrmionic bubbles. To be able to reach skyrmion bubble states the films are brought to a demagnetized lowest energy state using a damped oscillatory magnetic field. Afterward out of plane magnetic fields of different field strength B_{field} and pulse length t_{pulse} are applied leading to skyrmion bubble condensation. For visualization of these skyrmion bubbles, laser scanning and widefield MOKE microscopy as well as magnetic force microscopy (MFM) are utilized (see Fig. 1). In Pt/Co/W also skyrmion bubble nucleation from remanence is shown to occur at very low domain wall depinning fields (B_{dep}<10mT).

The most promising of the analyzed multilayer films are patterned into various test structures using FIB lithography. In a consecutive step, by means of local FIB irradiation (Ga^+), the anisotropy of the nanostructures is decreased at a well-defined spot to form so-called artificial nucleation centers (ANCs). Beyond that, this irradiation allows to explicitly tune the interlayer exchange coupling from FM to AF and back to FM by means of Ga^+ irradiation. This tunability appeared to be highly sensitive to the Ga^+ ion dose and enables artificial "splitting" of the stack into magnetically *softer* and *harder* layers. Above and beyond that, we investigate if by means of FIB irradiation, the energy landscape of these films can be engineered such that artificial skyrmion bubbles appear at well-defined sites.

Based on this tuning of the energy landscape artificial room temperature skyrmion bubble lattices that are independent of stochastical pinning sites i.e. grain boundaries, local variations of Keff, DMI, etc., are envisioned. Fully exploiting this technique even skyrmion generation sites, tracks and logic gates can potentially be realized.

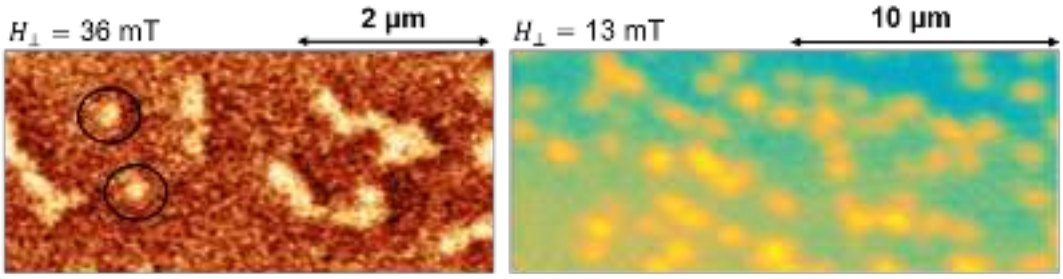

Fig. 1. Left: Skyrmionic bubble condensation from the demagnetized state in $[Pt_1/Co_{0.6}/Ir_1]_5$ with around 400 nm diameter (circles) imaged using magnetic force microscopy.
Right: Skyrmionic bubble nucleation (diameter<1 µm) in $[Pt_{1.1}/Co_{1.0}/W_1]_5$ from FM state visualized by an scanning LMOKE image.
Both domain images are taken at remanence after application of oop-fields (field magnitude in the upper left corner).

P142 - Sputtering of Soft Magnetic Thin Films on 300 CMOS for Integrated Voltage Regulators

6. Magnetic thin films, multilayers, surface and interfaces

Claudiu V. Falub[1] , *Xue Zhao[1], Martin Bless[1], Hartmut Rohrmann[1], Maurus Tschirky[1], Marco Padrun[1]*

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As semiconductor industry continues boosting the transistor density by electronic miniaturization (according to Moore's scaling law) to meet the demands of modern computing, power density becomes an ever more difficult challenge with each new generation of fin field-effect transistor (finFET). At 7 nm node and beyond increasing thermal constraints require not only that the central processing unit (CPU) needs to be throttled more frequently, but also that a significant fraction of the CPU cannot be powered on at all (dark silicon). Hence, to further enable "More Moore" scaling, dynamic and heterogeneous power/thermal management of the CPU by means of integrated voltage regulators (IVRs) is an absolute "must have" technology. Previous IVR applications have however been hold back by the unavailability of appropriate integrated power inductors, but several solutions based on integrated thin film soft magnetic cores with high permeability were recently proposed by several device manufacturers. Yet, integrating these magnetic films on the complementary metal-oxide-semiconductor (CMOS) platform is technologically and economically very challenging, since for a significant inductance enhancement, several micrometer-thick films with ultra-low losses need to be deposited. Based on our success story of manufacturing deposition equipment for high quality soft magnetic thin films with tunable properties on 200 mm wafers [1-5], we have recently made the transition from 200 mm to 300 mm, and we are currently ready to offer a cost-effective solution to manufacturers of CMOS IVRs.
In this work, we investigate the physical properties of CoTaZr/Ta_2O_5 soft magnetic multilayers fabricated by a physical vapor deposition (PVD) process on 300 mm Si and Si/500-nm-thermal-SiO_2 wafers in an industrial multi-chamber CLUSTERLINE® 300 BMD (Batch Module Drum) magnetron sputtering system. For high volume manufacturing, two BMD sputter units can be clustered around a standard 300 mm vacuum transfer module including an atmospheric front-end module (AFEM), each BMD unit being configurable with up to six sputter stations and capable to process nine 300 mm wafers at the same time. In this configuration, the throughput for depositing a 3-microns-thick CoTaZr/Ta_2O_5 multilayer consisting of 36 periods of alternating 80-nm-thick CoTaZr and 4-nm-thick Ta_2O_5 sublayers is at least 20 wafers/hour. We introduced the in-plane magnetic anisotropy in these films during sputtering by means of a linear magnetic field. The properties of our soft magnetic multilayers are setting a new benchmark of quality for cost-effective manufacturing of integrated power inductors on 300 mm CMOS. Thus, the alignment of the easy axis on the 300 mm wafers was < ±2.2º. The saturation field along the hard axis (H_k) for these films was 21.2 Oe, and the sputter process parameters were selected such that the coercivity (H_c) was kept extremely low at about 0.1 Oe.

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P143 - Static torques and low-frequency magnetisation dynamics in a zero-moment half-metal

6. Magnetic thin films, multilayers, surface and interfaces

Ajay Jha[1] , *Gwenal Atcheson[1], J.M.D. Coey[1], Karsten Rode[1], Plamen Stamenov[1]*
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Since the theoretical prediction [1] of the existence of zero-moment half-metals by Val Leuken et al., almost 30 year ago, the quest to realize an example of this material class experimentally has been futile. Only recently (2014) [2], with the discovery of Mn_2Ru_xGa (MRG) as the first prototype. The MRG samples provide unique combination of low saturation magnetisation, high spin-polarisation, low Gilbert damping and high magnetocrystalline anisotropy, which could be explored in detail.

The obvious appeal of this system is for exploitation as the active layer of spin-transfer or spin-orbit torque oscillators. Narrowband ferromagnetic resonance well above 0.2 THz [3], where the central frequency of radiation is determinedby the anisotropy field, has already been demonstrated in these class of samples. A tantalizing prospectemerges, for the generation of oscillations, well into THz region, by exploiting higher-order anisotropy effects and nonlinear excitation.

Here, we present an analysis of the monocrystalline anisotropy of MRG samples by means of spontaneous Hall effect (SHE). SHE is sensitive towards the out-of-plane component of the magnetisation of primarily one of the spin sub-lattice, which contributes most of the DOS at the Fermi level. It also allows for the determination of the torque acting on the same, which is rather useful in thin epitaxial films of low-moment materials, as the conventional magnetometry techniques run out of sensitivity.

SHE has been measured in different measurement geometries, revealing the details of the different anisotropy components. To determine the out-of-plane anisotropy, a sample has been uniformly rotated in the *yz*-plane with constant magnetic field along *z*-axis (see fig.1a). The magnetization has two-fold dynamics, first a continuous rotation of against the anisotropy field and second, switching of the magnetization. Our work clearly illustrates the existence of a large out-of-plane 2-fold anisotropy field of above 1.5 T. A smaller 4-fold in-plane anisotropy field of about 0.1 T becomes apparent, when the field is rotated within the sample plane (in the *xy*-plane), as shown on fig. 1b. The 2-fold asymmetry visible is due to small misalignment of the rotation plane and is easily fitted out. Large applied field along the *y*-axis allows for the observation of the transverse magnetic hysteresis (fig. 1c). We attribute the low-frequency magnetisation dynamics to a combination of discrete switching and rotation of the magnetisation and interpret it within a model based on a rather simple (normal, but corrected for finite linear viscosity) distribution of hysterons (within a Preisach picture) corrected for the continuous rotations before and after each elementary switching event. The excellent agreement between this 4-parameter model and the data is demonstrated on fig. 1c for field in the *xy*-plane and fig.1d for field out-of-plane. We trust that the same characterisation approach is applicable to a broad variety of highly polarised low-moment ferrimagnets.

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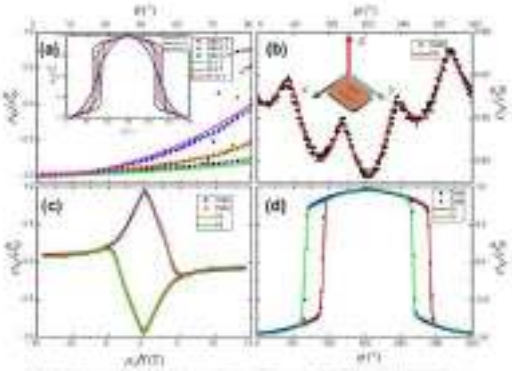
(a)
(b)
(c)
(d)

P144 - Structural and magnetic properties in low damping Fe/V(001) superlattices

6. Magnetic thin films, multilayers, surface and interfaces

J. Saha[1] , *G. K. Palsson[1], E. K. Delczeg-Czirjak[1], O. Eriksson[1], P. Svedhlindh[2], G. Andersson[1]*

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The author has chosen not to publicise the abstract.

Field 5

Field 6

P145 - Structural and magnetic properties of V2O3/Ni epitaxial hybrid magnetic heterostructures

6. Magnetic thin films, multilayers, surface and interfaces

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Recently, hybrid magnetic heterostructures based on transition metal oxides have come under interest. Among these transition metal oxides is V_2O_3 which undergoes a first order structural phase transition from a high temperature metallic state to a low temperature insulating state [1]. The structural transition occurring in oxides such as V_2O_3 has been shown to couple through interfacial strain to ferromagnetic materials in contact with the oxides. This coupling strongly affects the magnetization and coercivity of the magnetic material [2, 3]. This effect allows the manipulation of the magnetic properties additional to the conventional methods of using temperature and external fields to change the magnetic state. Previously we have shown that highly crystalline atomically flat films of V_2O_3 can be obtained by reactive dc-magnetron sputtering [1]. Here, we show how epitaxial hybrid heterostructures of V_2O_3 with overlying nickel magnetic layers can be fabricated by dc-magnetron sputtering (see Figure). The high quality of these heterostructures allows us to investigate the effects of interfacial coupling in these systems. We report on the structural properties of these films and their temperature dependent electrical and magnetic properties and how they are affected by the structural transition in the V_2O_3 layer and the epitaxial nature of the heterostructure.

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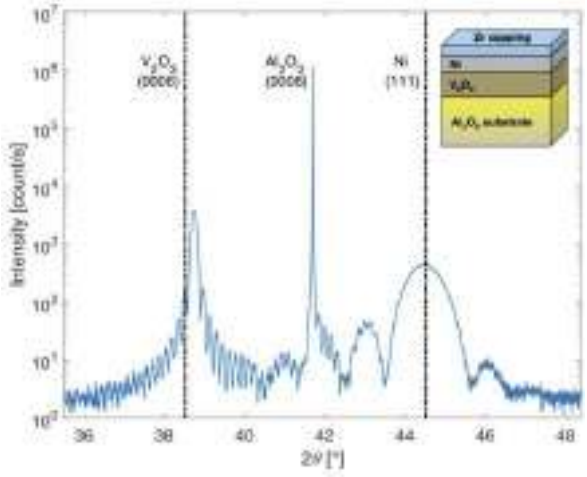
Figure. X-ray diffraction scan of a V_2O_3/Ni/Zr hybrid heterostructure grown by magnetron sputtering. Both the underlying 60 nm thick V_2O_3 and overlying 10 nm Ni layer reveal a highly epitaxial nature with both layers exhibiting clear, strong Laue fringes. The V_2O_3 was deposited using reactive sputtering at a substrate temperature of 485°C and the Ni layer and Zr(5 nm) capping layer were deposited at room temperature. The dashed lines indicate the peak positions for bulk V_2O_3 and Ni.



P146 - Study of damping in Ru/Co-based multilayer thin films with Dzyaloshinskii-Moriya interaction

6. Magnetic thin films, multilayers, surface and interfaces

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Recent development of the magnetic material engineering led to achievement of the systems with a high Dzyaloshinskii-Moriya interaction (DMI). As a result, the formation of noncolinear magnetic soliton states or nonreciprocal spin wave (SW) dynamics are achievable. Typical materials that are used are based on bi-layers Heavy Metal/Ferromagnet, e.g., Pt/Co. These layers are characterized not only with strong DMI, but also spin pumping effect and resulting large damping. In this work, we show that the significant DMI can be also present in multilayer films based on Ru/Co, characterized with low spin pumping effect and low magnetic damping. Therefore it is a good candidate for the dynamical studies and implementations of chiral DMI. The value of DMI can be strongly affected and controlled by the strain of the lattice. We show both theoretical and experimental comparison of magnetic parameters between Pt/Co and Ru/Co-based multilayer films.

P147 - The effect of various annealing treatments on Sr2FeMoO6 thin films

6. Magnetic thin films, multilayers, surface and interfaces

Minnamari Saloaro[1] , *Ilari Angervo*[1], *Hannu Huhtinen*[1], *Petriina Paturi*[1]

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The great spintronic application potential of complex magnetic oxides is widely recognized and it can be actualized by fabricating high quality thin films of these materials. One of the excellent candidates for such applications is Sr_2FeMoO_6 (SFMO), which possesses large magnetoresistance as an intrinsic property and Curie temperature higher than room temperature. However, the fabrication of SFMO thin films without the deterioration of the magnetic properties in comparison with the bulk material, is challenging. On the other hand, the spintronic applications are multilayer structures that have high demands on the surface of the individual layers. Therefore, we have investigated the effect of various post-annealing treatments on SFMO films focusing on the magnetic properties and surface properties.

Several series of pulsed laser deposited SFMO films were grown in 9 Pa pressure Ar atmosphere using polycrystalline target. SFMO films of one series were in situ annealed at different temperatures and pressures right after deposition. Other films were ex situ annealed either at around 650 °C in oxygen atmosphere and close to UHV conditions or at several lower temperatures in UHV chamber connected to the X-ray photoelectron spectroscopy setup. The experimental investigations of the films were carried out with magnetometers, X-ray diffraction, positron annihilation spectroscopy and X-ray photoelectron spectroscopy.

Our earlier investigations have identified the anti-site disorder and oxygen vacancies as the most important factors to improve the SFMO thin film properties. Our previous experimental and theoretical results are in good agreement and they show that the magnetic properties of SFMO could be affected by manipulating these nanoscale defects. Here, the experimental investigations confirmed that we have been able to affect the amount of nanoscale defects in SFMO films and that way modify the magnetic properties by annealing treatments. For example, we observed that the amount of oxygen vacancies is increased and the amount anti-site disorder is reduced after in situ annealing as summarized in the enclosed figure. In addition to magnetic properties, the ex situ annealing provides a significant cleansing for the film surface from the organic compounds. Hence, with annealing treatments, we have found a way to engineer nanoscale defects and clean the films surface, which will allow us to improve SFMO films towards spintronic and magnetiresistive applications.

P148 - The influence of composition on magnetic ordering in amorphous Fe1-x(Al0.80Zr0.20)x alloys

6. Magnetic thin films, multilayers, surface and interfaces

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The ordering temperature of $Fe_{1-x}Zr_x$ amorphous alloys is strongly suppressed as compared to Fe [1-2]. Furthermore, the ordering temperature (T_c) has unusual concentration dependence, with a maximum of T_c at around $Fe_{0.8}Zr_{0.2}$ [1-4]. Here we address the substitution of Zr by $Al_{0.8}Zr_{0.2}$ and we discuss the effect of the substitution on the structural and magnetic properties of the alloys. First of all, $Al_{0.8}Zr_{0.2}$ can be used to obtain Fe based amorphous materials in a wide concentration range, similar to that obtained by Zr. Furthermore, the maximum in the T_c of $Fe_{1-x}(Al_{0.8}Zr_{0.2})_x$ is about twice as high as obtained in $Fe_{0.7}(Al_{0.8}Zr_{0.2})_{0.3}$, 400 K as compared to 240 K in $Fe_{0.8}Zr_{0.2}$ as shown in Fig. 1. The ferromagnetic ordering was observed in a wider concentration range in $Fe_{1-x}(Al_{0.8}Zr_{0.2})_x$ as compared to $Fe_{1-x}Zr_x$ and the moment per Fe atom is also higher.

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P149 - Tunable Anisotropy and Coercivity in Amorphous Tb-Co/Sm-Co Bilayer Films

6. Magnetic thin films, multilayers, surface and interfaces

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Amorphous Tb-Co films have previously been shown to exhibit large out-of-plane anisotropies and high coercivity. This remains true for extremely thin films (~1 nm) and for films deposited in the presence of in-plane growth fields [1]. The magnetic domain structures show strong dependence on anisotropy, and can thus be tuned by both composition and applied growth fields. We demonstrate via magneto-optical methods that depositing amorphous Tb-Co films on top of Sm-Co films in the presence of an in-plane field results in a rotation of the Tb-Co anisotropy from perpendicular to in-plane easy axis below a critical thickness of 7-8 nm. Additionally, above the critical thickness, Tb-Co films deposited on top of Sm-Co exhibit greatly reduced coercivities compared to single films of corresponding thickness and composition. The figure shows out-of-plane hysteresis loops measured for amorphous $Tb_{16}Co_{84}(x\,\text{nm})/Sm_{15}Co_{85}(20\,\text{nm})$ bilayers. At around $x = 7$ nm, the loop closes and the easy axis shifts to in-plane.

Element-specific hysteresis measurements using XMCD suggest that the coupling between the Sm-Co and Tb-Co layers leads to rich, non-trivial switching behaviour. We have investigated individual behaviour for Sm, Co and Tb for bilayers with compositions on both sides of the Tb-Co compensation point. From these investigations we can model how the individual moments are correlated to each other. The results show great promise for applications which demand materials with both tunable anisotropy, in terms of direction and coercivity, and large magnetization.

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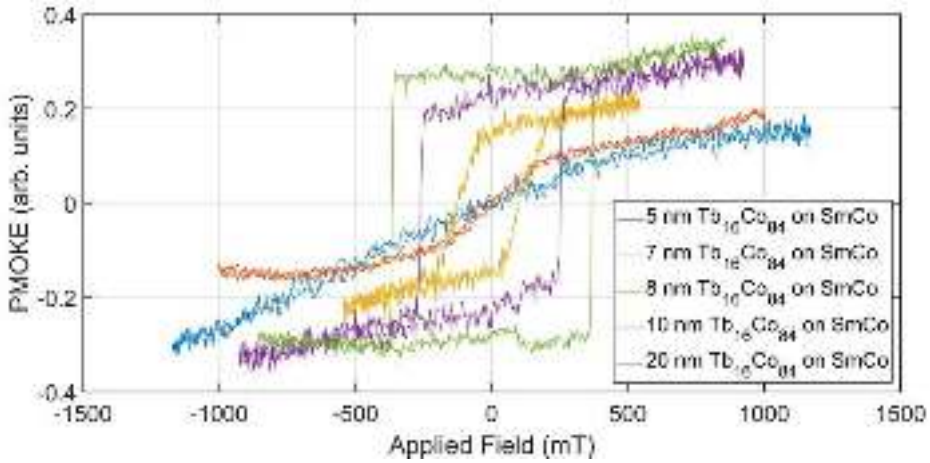

P150 - Tuning magnetic anisotropy in Co\Pt multilayers: crystalline texture vs. interface quality

6. Magnetic thin films, multilayers, surface and interfaces

Oguz Yildirim[1, 2] , *Miguel A. Marioni*[1], *Claudiu V. Falub*[2], *Dominik Jaeger*[2], *Marco Rechsteiner*[2], *Hartmut Rohrmann*[2], *Hans J. Hug*[1]

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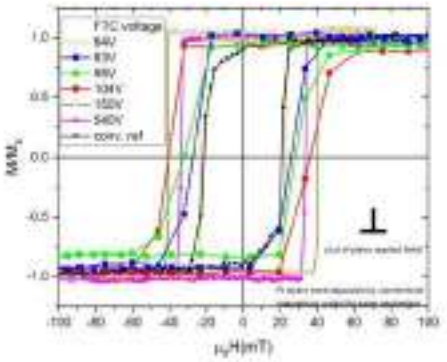
High speed data transfer and high density data storage can be achieved by faster, denser and more efficient spintronic devices. Such spintronic devices require magnetic multilayers with strong out-of-plane magnetization. Stabilization of room temperature skyrmions by means of interfacial Dzyaloshinskii-Moriya interactions (DMI) in asymmetric Pt\Co\Ir multilayers [1] and achieving higher frequencies in spin-torque oscillators [2] have further fueled the interest in such materials. In these multilayered systems there are two major contributors to the perpendicular magnetic anisotropy (PMA): (i) interface between the magnetic 3d element (Co) and the heavy non-magnetic element (Pt or Pd); (ii) crystalline texture. Thus, improving the crystalline quality and reducing the amount of defects at the interfaces is of utmost importance for improving the PMA required for high performance future devices.

In this work, we prepared "substrate\Pt(10nm)[Co(0.4nm)\Pt(0.7nm)]$_5$\Pt(2nm)" multilayers by magnetron sputtering from both conventional and facing-target cathode (FTC) magnetrons. The FTC configuration enabled us to control the impact of ion-induced damage on the interfaces. We sputtered the Co and Pt layers by varying the voltages in FTCs, and we combined these layers with those sputtered by conventional magnetron sputtering. Moreover, Si\SiO_2 (100) and Al_2O_3 (0001) substrates were used in order to further tune the crystalline texture of the multilayers. Influence of deposition parameters on the formation of PMA was investigated by means of structural and magnetic characterizations.

Compared to the Co/Pt multilayers where both Co and Pt sublayers were deposited with conventional magnetrons, the films grown with the FTCs exhibit considerably larger coercivities (Fig. 1). Moreover, we found a strong dependency of PMA on the FTC voltage, i.e., from the lowest up to 150V, coercive field increases. Above 150V, coercive field drops. This indicates that we can tune the energy of the particles impacting the growing film to a point where we can achieve a peak for the coercivity. Above that energy, decrease of the coercive field is attributed to the excess energy of the particles originated from the sputtering process.

This work was supported by "Swiss Federal Commission for Technology and Innovation" under grant no. 18940.2 PFNM-NM.


FTC voltage
64V
83V
88V
93V
102V
140V
conv. ref
1.0
0.5
0.0
-0.5
-1.0
-100
-80
-60
-40
-20
0
20
40
60
80
100
$\mu_0 H$(mT)

P151 - Tuning of magnetic anisotropy in amorphous SmCo/CoAlZr thin films

6. Magnetic thin films, multilayers, surface and interfaces

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The author has chosen not to publicise the abstract.

Field 5

Field 6

P152 - Velocity Enhancement by Synchronization of Magnetic Domain Walls

6. Magnetic thin films, multilayers, surface and interfaces

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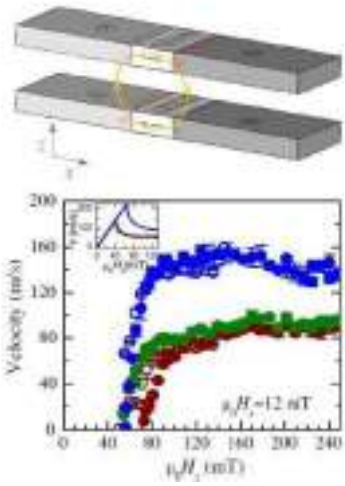
Magnetic domain walls are objects whose dynamics is inseparably connected to their internal structure. We have investigated domain wall dynamics in Pt/Co/Au/Co/Pt multilayers with perpendicular magnetization, which are engineered such that a coupled pair of domain walls, one in each layer, is stabilized by a cooperation of the Dzyaloshinskii-Moriya interaction (DMI) and a flux-closing mechanism. The dipolar field mediating the interaction between the two domain walls (Fig. 1(top)) links not only their positions but also their structures. The aim of our study is to show that this link has a direct impact on their magnetic-field-induced dynamics.

Domain wall velocities vs. magnetic field were measured using Kerr microscopy. For this purpose we used specially developed microcoils and pulsed current generators allowing the application of nanosecond field pulses up to 450 mT. The different Kerr contrast arising from the top and the bottom Co layers allowed distinguishing the dynamics of domain walls in either Co layer separately and the dynamics of coupled domain walls. Our measurements show that the velocity of a pair of coupled domain walls (Fig. 1, blue symbols) is larger than the velocity of a single domain wall in either of the two layers (Fig. 1, green and brown symbols). A comparison of our experimental data with micromagnetic simulations using MuMax3 revealed that for the field range where the dynamic coupling is observed, the domain walls propagate in the precessional regime. The dynamics involves the synchronization between the two walls to preserve the flux closure during motion. Properties of these coupled oscillating walls can be tuned by an additional in-plane magnetic field enabling a rich variety of states, from perfect synchronization to complete detuning [1].

[1] Ales Hrabec, Viola Krizakova, Stefania Pizzini, João Sampaio, André Thiaville, Stanislas Rohart, and Jan Vogel, **Phys. Rev. Lett. 120, 227204 (2018)**.



7. Magnetism in alloys and intermetallics

P153 - (R,R')2Fe14B: Intrinsic properties and best compositions for practical use

7. Magnetism in alloys and intermetallics

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Nd-Fe-B-based intermetallics are of potential interest for electronic devices, motors, and wind turbines due to their preeminent magnetic properties such as high remanence and large magnetic energy product [1-4]. In this work, we investigate both experimentally and theoretically rare-earth intermetallics $(R,R')_2Fe_{14}B$, where R=Dy,Nd,Ho. The high-field magnetic behavior (up to the forced-ferromagnetic state) along the main crystallographic directions has been studied over a wide magnetic field and temperature range. To explain the observed properties peculiarities we applied a theoretical approach previously used successfully for rare-earth intermetallics [5,6]. From the comparison of the experimental data and theoretical results we evaluate the crystal-field and the exchange parameters. All magnetic properties of the rare-earth intermetallics $(R,R')_2Fe_{14}B$ can be successfully explained by the suggested model. Despite the fact that we also could not observe experimentally the full ferromagnetic state in the system experimentally in fields up to 60 T, the crystal-electric field and exchange parameters obtained allowed us to calculate the full magnetization process of rare-earth intermetallics $(R,R')_2Fe_{14}B$.

Strong magnets are demanded not only for the development of technologies but also for the energy saving. One of the important characteristic of the rare-earth permanent magnets quality is the maximum energy product $(BH)_{max}$. The obtained crystal-field and exchange parameters for Dy^{3+} and Nd^{3+} provide description of the $(BH)_{max}$ dependency on the external magnetic field and temperature in the series $(Nd_xDy_{1-x})_2Fe_{14}B$ compounds. It was revealed that the greater the percentage of dysprosium in $(Nd_xDy_{1-x})_2Fe_{14}B$, the better the magnetic properties are preserved with increasing temperature. At the same time, the replacement of neodymium by disprosium leads to a decrease of (BH)max. So to optimize contemporaneously the magnetic and thermal properties of the intermetallics, it is necessary to follow the desired concentration of Dy^{3+} very carefully.

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Pelevin, A.K. Zvezdin, M. Paukov, L. Havela, H. Drulis. $ThMn_{12}$-type phases for magnets with low rare-earth content: Crystal-field analysis of the full magnetization process. Scientific Reports, 8:3595 (2018).
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P154 - Ab initio inspection on the metallicity trends among rare-earth permanent magnet compounds

7. Magnetism in alloys and intermetallics

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Rare-earth permanent magnets (REPM's) are one of the critically important materials in the upcoming decades for a sustainable solution of the energy problem with the industrial applications in traction motors of electric vehicles and power generators, and for robotics to be further developed in conjunction with the progress of artificial intelligence. The Curie temperature of the main-phase ferromagnet in REPM controls the practical applicability in a given operation temperature range. For the champion REPM compound $Nd_2Fe_{14}B$, the relatively low Curie temperature at 585K, only half of the Curie temperature of elemental bcc-Fe at 1043K, had been posing a problem especially in the applications for traction motors which requires good magnetic properties up to 450K. Curie temperature originates mostly in magnetic exchange couplings among localized magnetic moments on Fe, while the exact nature of the effective localization in the metallic state needs to be properly understood in order to put Curie temperature under good control in a possible machinery for computational materials design of REPM. To make a crucial building block for this, Curie temperature is calculated for $Nd_2Fe_{14}B$ and for related ferromagnets on the basis of an effective spin model constructed on top of ab initio electronic structure. Trends with respect to the species of rare-earth elements in calculated Curie temperatures for $R_2Fe_{14}B$ [R=rare earth] are in agreement with experimental trends. Quantitative difference between Fe-based compounds and Co-based compounds is observed. Comparison with the results obtained on the basis of local moment disorder points to the robustness or fragility of localized magnetic moments at elevated temperatures among the target compounds. Effective range in the calculated exchange couplings among localized magnetic moments as an indicator of metallicity provides a validity condition for the spin model description of metallic ferromagnetism.

P155 - Ab initio study of magnetic and structural properties of the Fe1-xMnxRh alloys (x = 0.5 -1)

7. Magnetism in alloys and intermetallics

Oksana Pavlukhina[1] , *Vladimir Sokolovskiy*[1], *Vasiliy Buchelnikov*[1], *Mikhail Zagrebin*[1]
[1] Chelyabinsk State University

Fe-Rh alloys currently attract more and more attention owing to the possibility of their application in magnetic cooling, magnetic recording, and spintronic devices [1-2]. It well known, that the magnetic order in FeRh compounds depends strongly on the concentration. Theoretical research helps to describe and understand the phenomena occurring in the material. Therefore, in our previous work, $Fe_{1-x}Mn_xRh$ (x = x=0.125, 0.25, 0.375) alloys were investigated using first-principles methods [3]. In this work, we present theoretical investigations of the structural and magnetic properties $Fe_{1-x}Mn_xRh$ (x = 0.5, 0.625, 0.75, 0,875, 1) alloys.

The structural and magnetic properties of Mn-doped Fe-Rh alloys are investigated by using the density functional theory calculations as implemented in the VASP package. The ab initio calculations have been carried out by using the 16-atom supercell approach with different initial spin configurations. The energy calculations were performed for the supercell. Calculations were carried out for ferromagnetic, paramagnetic and three kinds of antiferromagnetic states as functions of the lattice parameter. The equilibrium lattice parameters a = 3.009 for $Fe_{1-x}Mn_xRh$ (x = 0.5) up to 3.031 for $Fe_{1-x}Mn_xRh$ (x = 1). It can be concluded that the addition of Mn atoms leads to an increase in the lattice equilibrium parameter.

The total and partial DOS curves for $Fe_{1-x}Mn_xRh$ alloy was calculated. The calculation of the total energy for the tetragonal distortion of the cubic structure along the z axis is performed also. To accomplish this, we fixed the volume of a supercell as $V_0 = a_0^3 \approx a^2c$. Our calculations have shown that the substitution of Mn for Fe results in an appearance of stable body-centered tetragonal state. We also calculated the lattice constants, volume cell, partial and total magnetic moments.

This work was supported by RSF-Russian Science Foundation No. 17-72-20022.

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P156 - Abnormal coercivity behavior and magnetostic coupling in SmCoCuFeZr Magnets

7. Magnetism in alloys and intermetallics

Sergio Romero[1] , *Fernando Landgraf*[1], ***Marcos De Campos***[2]

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It is investigated the behavior of the coercivity as function of the temperature in SmCo 2:17 type magnets.
These magnets are a 5 element alloy with Sm, Co, Fe, Cu and Zr.
The magnets have a peculiar nanostructure, where the nanocrystalline grains
of the main ferromagnetic phase - rhomobohedral Sm2(CoFe)17 - are enveloped by a cell boundary Sm(CoCu)5 phase.
It is found that the experimental hysteresis curves can be theoretically described by a modified Stoner-Wohlfarth model if a mean field is taking into account.
This mean field represents the magnetostatic interaction between the the 2:17 nanograins and the 1:5 cell boundary phase.
This 1:5 cell boundary phase has copper, which decreases the Curie temperature of the cell boundary phase Sm(CoCu)5.
When the temperature increases, making the cell boundary Sm(CoCu)5 be paramagnetic, the magnetostatic coupling no longer exist.
Thus, the abnormal behavior of coercivity is explained.

P157 - Crystallization kinetics of Fe80-xCoxP14B6 metallic glasses

7. Magnetism in alloys and intermetallics

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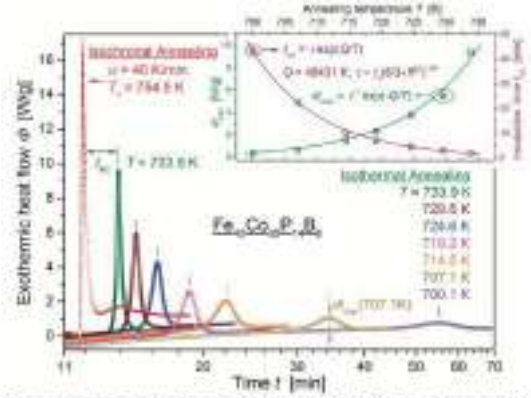
Crystallization kinetics and transformation of crystalline structure were studied in the series of novel rapidly solidified metallic glasses $Fe_{80-x}Co_xP_{14}B_6$ with x = 25, 32, 35 and 40 at.%. XRD patterns of as-quenched melt-spun ribbons revealed a superposition of two *bcc* α-FeCo and *bct* $(Fe,Co)_3(P,B)$ phases' signs. Size of regions coherently scattering X-rays is about 1.6 nm, which is typical for amorphous metallic alloys.

Finbak-Warren method was employed to examine experimentally obtained atomic pair distribution function, to compare it with a theoretical one, to ascertain α-FeCo and $(Fe,Co)_3(P,B)$ phases' fraction, and to identify this type of atomic arrangements as nuclei of existing parent phases in amorphous matrix. At continuous heating above 700 K, Rietveld analysis of XRD scans detects a predominant formation of nanosized *bcc* α-FeCo phase in initially amorphous alloys. As for $(Fe,Co)_3(P,B)$ phase, its percentage increases in Fe-rich metallic glasses at the expense of α-FeCo phase.

We made use of differential scanning calorimetry to determine crystallization temperature T_x and to demonstrate the incubation phenomenon occured at isothermal annealing. A modified Kolmogorov-Johnson-Mehl-Avrami (KJMA) approach appeared to be a powerful tool to model the transition of metallic glasses into crystalline state at different heating rates α ranged from 2.5 to 40 K/min. Also, it nicely fits calorimetric traces recorded in isochronal and isothermal regimes. Two basic material characteristics: activation energy of atomic transfer across crystal/amorphous interface Q and crystal/glass interfacial energy density (surface tension) σ were determined for metallic glasses with a different Co content.

Fabricated $Fe_{80-x}Co_xP_{14}B_6$ metallic glasses demonstrate much higher thermal stability compared to $Fe_{40}Ni_{40}P_{14}B_6$ metallic glass (Metglas® 2826) widespread in the commercial market. They possess increased by 60 K crystallization temperature T_x = 724 K against 662 K in amorphous Fe-Co and Fe-Ni ribbons, correspondingly. The highest T_x = 759 K @ α=40 K/min was found in $Fe_{55}Co_{25}P_{14}B_6$ specimen. Incubation effect was observed at temperatures below T_x (at first, as-cast ribbons were quickly at α = 40 K/min warmed up and then kept for a long time at the predetermined constant temperature). Crystallization, manifested in attached Figure by a peak of exothermic heat release $\Phi_{max}(t)$, is delayed by a certain time t_{inc} compared with a non-stopped continuous isochronal heating case.

The same parameters Q and σ calculated from isochronally annealing experiments explain exponential temperature dependencies of incubation time and a peak value of exothermic heat release $\Phi_{max}(T)$ obtained in isothermal crystallization process. Higher surface tension σ and diffusion barrier on crystal/amorphous interface Q lead to enhanced thermal stability of Fe-rich $Fe_{80-x}Co_xP_{14}B_6$ glasses that crystalize at higher temperatures. Thermal shocks dramatically enhance crystallization process thus degrade FeCo-glasses properties to a much greater extent than isothermal aging effects. Comparing isochronal and isothermal regimes of heating, we arrived to another rather unexpected conclusion. Isothermal annealing always results in the formation of nanosized nuclei within the amorphous metallic matrix, whereas rapid heating to high temperatures leads to the formation of crystallites much bigger in size. This conclusion holds even more since isothermally annealed specimens remain in the cooling oven for much longer than incubation time.



Comparison of differential isothermal calorimetric scans of $Fe_{36}Co_{36}P_{12}B_6$ ribbons annealed at seven different temperatures T with the isochronal heating recorded at the scanning rate α = 40 K/min. At temperatures below T_x = 754.5 K, crystallization process occurs after the incubation time delay t_{inc}. Inset shows dependencies of t_{inc} and exothermic heat release peak value Φ_{max} upon the annealing temperature T.

P158 - Emergence of room-temperature ferromagnetism in boron-added Mn compounds

7. Magnetism in alloys and intermetallics

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[3] Physonit Inc.

Mn-based ferromagnets attract considerable attention because the Mn atom exhibits the highest ordered moment value. Although Mn itself is the antiferromagnet, it is generally accepted that a ferromagnetic coupling tends to occur with increasing Mn-Mn distance. It is interesting to conduct materials research on Mn-based compounds, offering a platform enabling control of the Mn-Mn distance. In this paper we report the emergence of room-temperature ferromagnetism in boron-added Mn-based compounds of cubic $Pd_{0.75}Mn_{0.25}$ alloy[1] and $Sm_2Mn_8Al_9$ with the Th_2Zn_{17}-type structure.

Polycrystalline samples were prepared by arc melting the constituent elements under an Ar atmosphere, and annealed in an evacuated quartz tube at 800 °C for 4 days. The samples were evaluated using a powder X-ray diffractometer. The atomic compositions of the samples were verified by using an energy-dispersive X-ray spectrometer that was equipped in a field emission scanning electron microscope. The isothermal magnetization curve was measured by a vibrating sample magnetometer. The temperature dependence of ac magnetic susceptibility χ_{ac} (T) and that of electrical resistivity between 4 K and 300 K were measured using a closed-cycle He gas cryostat.

The χ_{ac} measurement has confirmed that the parent $Pd_{0.75}Mn_{0.25}$ alloy exhibits a spinglass transition at approximately 45 K, as reported earlier. The lattice parameter of $Pd_{0.75}Mn_{0.25}B_x$ increases as x increases from 0 to 0.155, which means that the Mn-Mn distance systematically increased. Figure 1 shows the isothermal magnetization curves of $Pd_{0.75}Mn_{0.25}B_x$ at room temperature. Room-temperature ferromagnetism is induced in x larger than 0.015. The saturation moment at room temperature systematically increases as x is increased from 0.015 and reaches $2.68\mu_B$/Mn at x=0.125, above which the saturation moment decreases. The Curie temperature T_C increases as x increases from 0.015 to 0.125, and reaches the maximum T_C of 390 K at x=0.125. Further increasing x to greater than 0.125 suppresses T_C. The rather good linearity between T_C and the Mn-Mn distance at x between 0.015 and 0.125 indicates that the B addition with increased Mn-Mn distance enhances the ferromagnetic exchange coupling according to the concept of the Bethe-Slater curve. Meanwhile, the further increase in Mn-Mn distance with x above 0.125 reduces T_C, which means a weakened ferromagnetic interaction. Therefore, the degree of ferromagnetic exchange coupling would not be determined only by the Mn-Mn distance, and additional factors should be considered.

$Sm_2Mn_8Al_9$ shows a paramagnetic behavior at room temperature, and seems to undergo an antiferromagnetic state below approximately 80 K. A slightly boron-added $Sm_2Mn_8Al_9B_{0.1}$ exhibits a room-temperature soft ferromagnetism. The saturated magnetic moment is systematically enhanced with the boron concentration. However, the saturated moment is $1.3\mu_B$/f.u. at x=1.0, and seems to be much smaller than that observed in $Pd_{0.75}Mn_{0.25}B_x$.

We will compare the boron concentration dependences of ferromagnetism between two compounds. Furthermore, a detailed magnetic phase diagram for each system is also presented.

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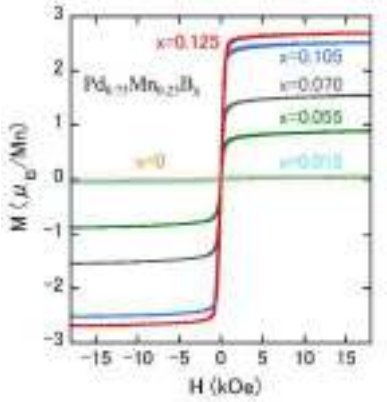

Fig. 1: Isothermal magnetization curves of $Pd_{0.75}Mn_{0.25}B_x$ at room temperature.

P159 - Exchange interactions and Gilbert damping in (Mn,Fe,Co)Ge B20 alloys

7. Magnetism in alloys and intermetallics

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First-principles investigations of the magnetic properties of various materials with B20 crystal structure have been performed for different composition and structure parameters. The calculations are based on the fully relativistic multiple scattering Korringa-Kohn-Rostoker (KKR) formalism. We focus here on the Gilbert damping (GD) parameter. For this value a rather strong difference was found in experiments dealing with FeGe compound [1]. Motivated by these findings, detailed investigations on the temperature and composition dependence of the GD have been performed for pure FeGe and MnGe compounds as well as for (Mn,Fe,Co)Ge alloys. These calculations show in particular a strong increase of the GD when going from MnGe to FeGe. The impact of the structure parameters and different types of defects (e.g. vacancies and antisite defects) was investigated to understand the dependence of the GD on sample preparation conditions. In addition, the exchange parameters, both isotropic and Dzyaloshinskii-Moriya interactions (DMI), have been calculated accounting simultaneously for thermal lattice vibrations and spin fluctuations, vacancies and antisite defects. The results show a strong dependence of the interatomic exchange parameters J_{ij} on temperature. We found also a significant increase of the diagonal elements of the DMI tensor, in the pure MnGe limit. All results are compared with available experimental data as far as possible.

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P160 - Growth and magnetodynamics characteristics of pulse laser deposited Co2MnAl Heusler alloy thin films

7. Magnetism in alloys and intermetallics

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We study the structural and magnetodynamics properties of Co_2MnAl (CMA) full Heusler alloy films grown on GaAs substrates by pulsed laser deposition technique as a function of the deposition temperature. X-ray diffraction patterns show crystalline films with Co_2MnAl phase. Broadband ferromagnetic resonance (FMR) measurements have been used to measure the magnetodynamics of the films, i.e. the effective magnetization (M_S) and the Gilbert damping constant (α). We observe an increase of M_S and α as deposition temperature is increased from 450°C to 750°C. We measured the lowest damping constant to be 0.0045 ± 0.0005 measured for the film grown at high deposition temperature (T = 750°C). We attribute the improvement in the characteristics of films due to the increase in the atomic ordering at high temperature.

P161 - Influence of annealing on structure and magnetic properties in cold-drawn nanocrystalline microwires

7. Magnetism in alloys and intermetallics

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In the last years, the high frequency magnetic properties of the conventional nanocrystalline microwires are intensively studied in order to obtain a new type of microwave absorber elements in electromagnetic shielding domain [1-4].
In this paper, the effect of the annealing conditions on the microstructure evolution and high frequency magnetic properties of FeSiB-based cold-drawn nanocrystalline microwires was studied in order to obtain tunable high frequency magnetic properties for electromagnetic shielding applications.
$Fe_{77.5}Si_{7.5}B_{15}$ and $Fe_{73.5}Si_{13.5}B_9Cu_1Nb_3$ (FINEMET) conventional amorphous wires with the metallic diameter, Φ, of about 120 μm have been prepared by the conventional in-rotating-water spinning technique in amorphous state. Wires with diameters down up to 10 μm were obtained by subsequent cold drawing. The cold drawn microwires (CDMWs) were annealed in vacuum for 1 h at temperatures between 100 °C and 600 °C to achieve the optimum nanocrystalline structure. The coercive field and relative magnetic permeability, μ_r, were measured using a modified a.c. fluxmetric method in magnetic fields up to 30 kA/m at 50 Hz. The high frequency magnetic properties of microwires have been investigated by “free-space” method in the frequency range 1-18 GHz. The microstructural investigations were performed by high-resolution transmission electron microscopy (S-TEM/HR-TEM) at 200 kV.
The microstructure of the annealed microwires evolves from an amorphous one into a nanocrystalline one with the nanograins dimensions increasing from an average size of 5 nm at 300 ^oC annealing temperature, to about 18 nm at 600 ^oC annealing temperature. The nanocrystals are homogeneously dispersed within the Fe-B rich amorphous residual matrix, as shown in a typical S-TEM image of CDMWs from Fig. 1 (a). The preponderant nanocrystalline phase in the microstructure of CDMWs are belong to α-Fe phase, while the Fe_3Si phase are found for larger diameters of microwires. The magnetic measurements indicated that cold drawn microwires annealed at temperatures below 300 ^oC shows an approximately constant values of the relative magnetically permeability, $\mu_r \sim 2\times10^3$. The highest value $\mu_r \sim 1{,}3\times10^5$, is obtained for FINEMET-CDWs with Φ=15 μm annealed at 500 ^oC while the FeSiB–CDMWs have the lowest magnetically permeability, $\mu_r \sim 10^3$, at the same annealing temperature and metallic diameter, as indicated in Fig 1(b).
FINEMET-CDMWs were found more suitable as microwave absorber elements for electromagnetic shielding comparing with FeSiB-CDMWs. The strongly effect of the nanocrystalline structure, aspect ratio, and composition on their microwave absorption properties will be presented and discussed in the paper. Their electromagnetic response can be conveniently tailored through designing of the microstructures and the geometrical factors such as wire diameter and composition.

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Work supported by the Romanian Ministry of Research and Innovation (MCI) under NUCLEU Program – contract no. 33N/2019, project PN 19 28 01 01 and Contract No.11PFE/16.10.2018.

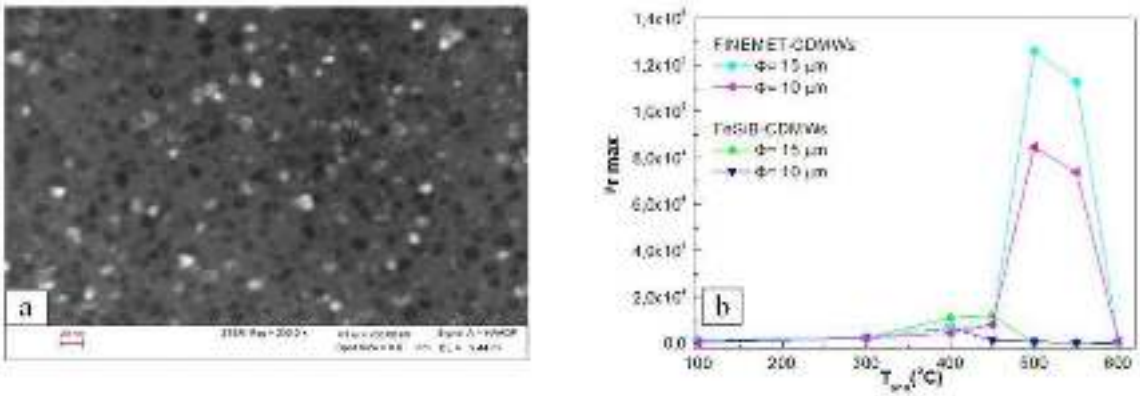

Fig.1. Typical S-TEM image of the microstructure of 15 μm FINEMET-CDMWs annealed at 500°C (a). Variation of μ_r with the annealing temperature of CDMWs for different metallic diameters (b).

P162 - Interaction field in nanocrystalline Sm-Fe-Ti alloys

7. Magnetism in alloys and intermetallics

José Luis Hidalgo González[1, 2] , *Jorge García-Rocha[1], José de Jesús Cruz-Rivera[1], Salvador Palomares Sánchez[3], Armando Encinas-Oropesa[3, 4], José Luis Sánchez-Llamazares[4], José Andres Matutes-Aquino[2]*

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Alloys of Sm-Fe-Ti were synthesized by mechanical milling for five hours, the hysteresis loop for nanocrystalline Sm-Fe-Ti alloys shows a bistable behavior partly repressed resulting from the presence of an effective field. The magnetic properties of remanence for nanocrystalline Sm-Fe-Ti alloys were measured to study the interactions between nanograins. By another hand, the plots of Henkel confirm the structural disorder of the nanocrystalline Sm-Fe-Ti alloys obtained by mechanical milling for five hours of milling, while for nanocrystalline Sm-Fe-Ti alloys obtained by mechanical milling for five hours of milling and annealing the effects dominate was due the mean field. For the study of magnetic interactions in the nanocrystalline Sm-Fe-Ti alloys also, Mössbauer Spectroscopy was used.

P163 - Laws of volume elasticity in deformational and energetic effect on structural transformations

7. Magnetism in alloys and intermetallics

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In paper [1], the effect of conductivity in the crystals of $YBa_2Cu_3O_{7-x}$ doped by LCMO was reported. Structural transformations in the vicinity of Curie temperature are substantially dependent on temperature, pressure and magnetic resistance. A similar effect was reported in [2,3] where a part of lanthanum was substituted with yttrium. In [4], aluminum doping resulted in a drop in the Curie temperature, despite the elements were of the same valence. With these data taken into account, the authors of [5] tested lanthanum-based polycrystals $La_{0.67-x}Sr_{0.33}MnO_3$ (further LaSr), $La_{0.60}Gd_{0.07}Sr_{0.33}MnO_3$ (LaGdSr) and $La_{0.60}Ey_{0.07}Sr_{0.33}MnO_3$ (LaEuSr). Dependence of ρ(T) in LaEuSr demonstrates a sharp maximum of the resistivity in the vicinity of the temperature of 300 K. At the same time, the authors stated that doping by europium or gadolinium resulted in a reduction of the resistivity in the ferromagnetic area. This behavior was determined by an increase in the contribution of grain boundaries at reduced crystal size that was in concordance with the hypothesis and experiments reported in [6].

When considering the effect of structural modifications on superconducting properties of polycrystals [1], a superconductor MgB was tested that was characterized by a relatively high critical temperature T_c = 39 K. The doping element was lanthanum-calcium LCMO. The scheme of the experiment was of SNS-type (superconductor – normal area – superconductor). When the transport current passed Ag-junction, electron-phonon spectrum in the vicinity of the potential barrier had a gap related to an increase in the resistance of the contact zone. To compare, a tunnel transition of electrons through Fermi zone is illustrated that is accompanied by a rising conductivity at the moment of the superconducting phase transition.

Grain boundaries affect this process, being substantially deformed both at T_c and under pressure P. The volume is reduced, the strain of the binding energy and the density are increased. The plot of the transport current is considered where the pressure effect on the conductivity band is seen. An analogous phenomenon was registered when studying the CoFeGe polycrystal contacting with Nb. The width of the conductivity band is more pronounced because of a larger amount of non-compensated carriers. Grained structure of the superconductor is a reason of reduced resistivity of grain boundaries due to increased conductivity at the moment of T_c.

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P165 - Magnetic behavior of CoCrFeMnNi and derived high entropy alloys

7. Magnetism in alloys and intermetallics

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The high entropy alloys represents the multi-principal element alloys with a nearly equimolar composition. Generally they are formed from at least five different elements. It differs them from common alloys, where a few element dominates. Thanks to the high number of constituents one obtains a significant entropy contribution to the Gibbs free energy, which ensure the stabilization in high temperatures. Besides, such number of constituents brings huge variability of their physical properties as well. Specific mechanical or electrical properties etc. can be mentioned. It makes HEAs highly promising for application in the industry. One of the primary models of HEAs is well known CoCrFeMnNi, so-called ‘Cantor alloys’, which exhibits unique mechanical properties. On the contrary the magnetism is highly suppressed there, despite of 3d magnetic elements. Therefore in our work we focus on their possible enhancement by varying chemical composition (substitution by Mo). Also the influence of a particular element on the magnetic behavior is studied in details.
The work is based on the ab-initio calculation, employing the TB-LMTO-ASA method. Thanks to the used Green’s function formalism we are able to treat the chemical disorder within the coherent potential approach. Moreover the Heisenberg magnetic exchange coupling were calculated by the Liechtenstein’s formula.
Based on band structure calculation and obtained exchange interactions we will discuss the contribution of a particular elements to magnetic behavior same as the energetic stability (enthalpy of formation) of modified alloys. We will try to suggest the way, how the magnetism makes stronger. Finally the magnetic ordering temperatures obtained by Monte-Carlo simulations are determined.

P166 - Magnetic interactions in nanocrystalline Sm-Y-Co alloys

7. Magnetism in alloys and intermetallics

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Magnetization curves were measured with the methods of isothermal remanent magnetization (IRM) and by the method of direct current demagnetization (DCD) for nanocrystalline $Sm_{0.5}Y_{0.5}Co_5$ alloys. Performed was the study of the magnetic properties for nanocrystalline $Sm_{0.5}Y_{0.5}Co_5$ alloys with the Physical Property Measurement System (PPMS), the alloys exhibit a high remanent coercivity of 2.1 MA/m. For nanocrystalline $Sm_{0.5}Y_{0.5}Co_5$ alloys, the remanence susceptibilities proportion was $\chi_{DCD}/\chi_{irr}=4.6$ that characterize the alloys with the presence of magnetic interactions. For the nanocrystalline $Sm_{0.5}Y_{0.5}Co_5$ alloys were studied magnetic interactions by measuring curves ΔM vs. the magnetic field, showing magnetic interactions.

P167 - Magnetic properties of Mn2XAl (X= Fe, Cr) Heusler compounds

7. Magnetism in alloys and intermetallics

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The author has chosen not to publicise the abstract.

Field 5

Field 6

P168 - Magnetic properties of OL52 and OL52/4 stainless steels under some sea water corrosive action.

7. Magnetism in alloys and intermetallics

Olga Demidenko[1] , *Aliona Zhyvulka[1], Kazimir Yanushkevich[1], Virgil Constantin[2], Ana Maria Popescu[2], Elena Ionela Neacsu[2], Cristina Donath[2]*

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Corrosive action of Mediterranean, Black and Aegean Sea waters on surface morphology and magnetic properties of OL52 and OL52/4 stainless steels is studied. X-ray studies of investigated stainless steels before and after corrosive action were carried out in CuK_{α}–radiation at room temperatures. Micrographic images of the samples before and after corrosion process were obtained using a metallographic microscope equipped with an acquisition digital camera. Corrosion behavior at the immersion of samples of OL52 and OL 52/4 in various sea waters were studied on alloy samples by gravimetric integral method. Sample mass loss tests were performed in aerated solutions at ~ 25° C and without thermostats. Samples in the study were weighed before the start of the test. As mass loss is not necessarily constant with the exposure time, the corrosion test was performed by successive increments of exposure time. It has been noted that mass loss increases with exposure time for all study cases, and the corrosion rate becomes approximately constant after > 1500 hours of immersion in all three sea waters types. These results are supported by the micrographs. Temperature dependences of the specific magnetization before and after corrosion action were obtained by ponderomotive method in 0.86 T magnetic field in the temperature range of 77 – 1000 K. Comparative analysis of temperature dependences of specific magnetization before and after sea waters exposure confirms a high corrosion resistance of magnetic characteristics of the OL52 and OL52/4 stainless steels under such kind of corrosion.

P169 - Magnetic properties of the skutterudite-related stannides of Sm3Co4Sn13 and Tb3Co4Sn13

7. Magnetism in alloys and intermetallics

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Single crystals of $Sm_3Co_4Sn_{13}$ and $Tb_3Co_4Sn_{13}$ were synthesized using tin flux method. Both $Sm_3Co_4Sn_{13}$ and $Tb_3Co_4Sn_{13}$ crystallize in a cubic $Yb_3Rh_4Sn_{13}$-type structure with lattice parameters $a \sim 9.515$ Å and 9.464 Å, respectively. confirmed by powder X-ray diffraction (XRD). The magnetic susceptibility measurements reveal that $Sm_3Co_4Sn_{13}$ and $Tb_3Co_4Sn_{13}$ exhibit previously unreported paramagnetic (PM) to antiferromagnetic (AFM) ordering below $T_N \sim 7.8$ and 11.4 K, respectively. The effective moment of the Sm and Tb analogues were determined to be 0.72 μ_B and 9.54 μ_B which are close to the corresponding effective moment of trivalent ions. For each compound, the observed specific heat anomaly at T_N confirms a bulk nature of the phase transition. The extracted Sommerfeld coefficient and Debye temperature are $\gamma = 680$ mJ/mol-K^2 and $\Theta_D = 180$ K for $Sm_3Co_4Sn_{13}$, and $\gamma = 680$ mJ/mol-K^2 and $\Theta_D = 224$ K for $Tb_3Co_4Sn_{13}$. The high values of the Sommerfeld coefficient indicate the enhanced effective electron mass in both $Sm_3Co_4Sn_{13}$ and $Tb_3Co_4Sn_{13}$.

P171 - On the magnetic hyperfine interaction at a Cd impurity in RCd: a functional integral approach

7. Magnetism in alloys and intermetallics

Alexandre Lopes de Oliveira[1] , *Marcus Vinicius Tovar Costa*[2], *Nilson Antunes de Oliveira*[3], *Carlos Maurício Chaves*[4], *Amos Troper*[4]

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In a previous work we performed a theoretical study in the systematic of the local magnetic moment formation and the related magnetic hyperfine fields at noble, s-p, and nd impurities diluted in GdZn and GdCd compounds at zero temperature [1]. A quite well agreement with experimental data was obtained. In this work we present a theoretical study of the local moment formation and the magnetic hyperfine field at a non-magnetic s-p impurity, namely Cd, embedded in *R*Cd (*R* = Gd, Tb, and Dy) compounds. The functional integral approach in the static approximation is adopted to calculate the temperature dependence of the local magnetic moments and hyperfine magnetic interactions, which is an extension of conventional mean field calculations [2]. The temperature range from 0 K up to the critical temperatures T_C of each compound, when they become paramagnetic is considered. We calculate the perturbed densities of states and the local magnetic moments at a Cd impurity site, as a function of the temperature. The results of our self-consistent calculations are in very good agreement with recent experimental reports [3]. In addition, in $T = 0$ K we can compare our results with those obtained from first principle calculations [3].

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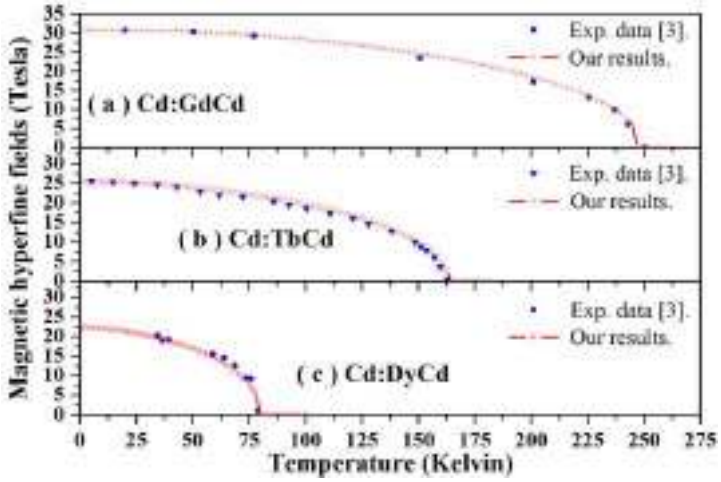

P172 - Pressure dependence of the Griffiths phase in R5(SixGe1-x)4 intermetallics

7. Magnetism in alloys and intermetallics

N. Marcano[1, 2] , ***P. A. Algarabel***[2, 3], *J. Rodríguez Fernández*[4], *J.P. Araujo*[5], *A. M. Pereira*[5], *J. H. Belo*[5, 6], *C. Magén*[2, 3], *L. Morellón*[2, 3, 7], *M.R. Ibarra*[2, 3, 7]

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The discovery of the giant magnetocaloric effect in $Gd_5Si_2Ge_2$has attracted a strong interest in the study of other $R_5(SiGe)_4$-type (R= rare earth) compounds in order to understand the relationship between their structural and magnetic properties. The extraordinary sensitivity of the electronic and crystal structures to external parameters such as the application of hydrostatic pressure have led to a systematic investigation over the last years [1] in order to comprehend the microscopic processes taking place in the 5:4 materials. Experimental observations of a Griffiths-like phase (GP) in the paramagnetic (PM) phase at a characteristic temperature $T_G$above the long-range order temperature (either T_C or T_N) were reported later in these compounds. The appearance of this regime has pointed to arise from the strong interplay between structure and magnetism present in these materials. According to a recent work, this behavior has been found to be restricted to 5:4 compounds which present the monoclinic $Gd_5Si_2Ge_2$-type (M) or the orthorhombic Sm_5Ge_4-type (O(II)) of crystal structure at room temperature [2]. The short-range magnetic correlations observed in the M-PM and O(II)-PM phases, an essential ingredient for the existence of Griffiths-like singularities, indicated that the system retains memory of the O(I) phase (pure state) signaled by an anomaly at T_G [2, 3].

In this work we report on a detailed study of the pressure effect on the Griffiths-like phase in several compounds of the $R_5(Si_{1-x}Ge_x)_4$(R = Tb, Gd and Dy) system stable in the M - PM and *O*(II) – PM phases at room temperature. The selected compounds for this study are representative of O(II)-AFM (R = Gd), O(I)-FM (R = Tb) and O(I)- FM (R = Dy) ground states, respectively presenting GP in both AFM and FM states. For all the analyzed cases, low field - dc susceptibility measurements show that the GP persists at pressures up to 10 kbar. The value of $T_{G,}$ associated with the onset of short-range ferromagnetic correlations, increases linearly with pressure. However, large differences in the rate of change dT_G/dP have been observed among them: The rate of the Tb - based compound is an order of magnitude greater than that of the Dy-based compound [4]. Such a different pressure dependence of the Griffiths phase in these compounds could arise from the particular character of the clusters and the competition between the different structural and magnetic phases.

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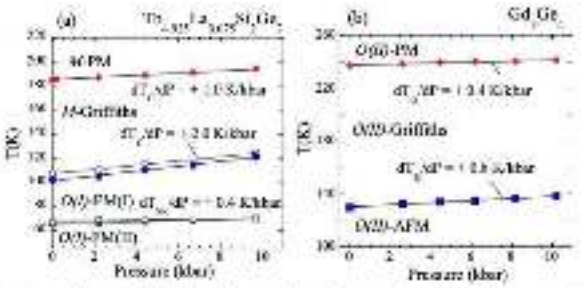

Temperature Pressure (T-P) phase diagram, shown T_N as determined from magnetization measurements for (a) $Tb_5Si_2Ge_2$ and (b) Gd_5Ge_2. Diamonds represent the onset of the GP phase (T_G), squares are used for the AFM transition (T_N), circles represent the onset of the FM order (T_C). Open symbols are used in the cooling curves (FC) and solid symbols in the heating runs (CW). The dashed line depicts the magnetic and/or crystallographic phase boundaries.

P173 - Soft Magnetic Co-Cu Alloys by High-Pressure Torsion Deformation

7. Magnetism in alloys and intermetallics

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High-pressure torsion, a method of severe plastic deformation, is a top-down technique to obtain nanostructured bulk materials at high homogeneity[1]. This technique can be also used to prepare samples from powders, whereas the resulting sample is in bulk form and therefore ready for further investigations. In this study, the binary Co-Cu system is investigated over a wide compositional range. This system is immiscible in the thermodynamic equilibrium, but intermixing can be induced by high-pressure torsion. Results from SQUID-magnetometry revealed soft magnetic properties of as-deformed samples, which might be explained by random anisotropy[2]. The magnetic properties are further tuned by subsequent annealing treatments. Particular emphasis in this study is placed on the correlation of magnetic data with microstructural characterization with techniques of electron microscopy, synchrotron X-ray diffraction and atom probe tomography.

This project has received funding from the European Research Council (ERC) under the European Union’s Horizon 2020 research and innovation programme (grant agreement No 757333).

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P174 - SPIN FLUCTUATIONS IN (Ce0.5Yb0.5)Ni5 INTERMETALLIC SYSTEM

7. Magnetism in alloys and intermetallics

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Several decades rare earth intermetallic compounds are systematically investigated already. One of the main reasons for this interest is the competition between Kondo effect and RKKY interaction. The first effect screens the local f- moments to produce a non-magnetically ordered state, which is characterized by the Kondo singlet state known as heavy quasiparticles, whereas the second effect correlates the same f- moments, via conduction electrons, bounding for long-range magnetically ordered state. This $4f$-magnetic competition could lead to attractive behaviour connected with quantum criticality.

$CeNi_5$ is a well-known spin fluctuations compound without magnetic ordering down to the lowest temperatures [1], whereas $YbNi_5$ orders magnetically at 0.55 K [2]. Due to the different character of rare earth magnetism in selected $RENi_5$ (RE = Ce, Yb) compounds, we decided to study the substitution $(Yb/Ce)Ni_5$.

In this work, we present the synthesis, the results of the structural and SEM/EDX analyses and physical properties measurements of $(Yb_{0.5}Ce_{0.5})Ni_5$.

The structural characterization shows the hexagonal $CaCu_5$-type crystal structure with P6*/mmm* space group. The chemical composition of the phase was checked by SEM/EDX and it is in a good agreement with the synthesis composition. An effective paramagnetic moment was determined by fitting the susceptibility with a Curie-Weiss law above 100 K. From the field dependence of the magnetization the tendency to saturation has not been found. The effect of spin fluctuations (SF) has been observed in M(T) at ~ 40 K. Heat capacity supports the results obtained from magnetic measurements. Collected experimental data show, that Yb/Ce substitution seems to favor the shift of the spin fluctuations to lower temperature, than those observed in pure $CeNi_5$, where the maximum of SF is ~ 100 K [3].

Acknowledgments:

This work was supported by the projects APVV-16-0079, VEGA 1/0956/17, VEGA 1/0611/18 and the grant from Slovak Academic Information Agency (SAIA) under National Scholarship program.

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P175 - SPIN FLUCTUATIONS, METAMAGNETISM AND MAGNETOCALORIC EFFECT IN Gd10Co20Si70 AND Dy6.5Co2Si2.5 ALLOYS

7. Magnetism in alloys and intermetallics

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We present the results of magnetic, thermodynamic, transport and magnetocaloric effect (MCE) studies of newly synthesized $Gd_{10}Co_{20}Si_{70}$ and $Dy_{6.5}Co_2Si_{2.5}$ alloys. Above measurements reveal that $Gd_{10}Co_{20}Si_{70}$ alloy exhibits antiferromagnetic transition at T_N = 9 K. Both MCE and magnetoresistance (MR) show quadratic dependence on the applied magnetic field, indicating the presence of spin fluctuations in the alloy. The maximum values of the magnetic entropy change determined from the isothermal magnetization data for magnetic field change of 7 and 9 T are found to be 10.5 and 15.6 J/kg.K, respectively. As a consequence of the spin fluctuations effect, the MCE peaks are pulled towards high temperature side as asymmetrically broadened peak. The MR attains a large positive value of 73% at 2 K in 8 T [1].

In case of $Dy_{6.5}Co_2Si_{2.5}$ alloy, it is found to crystallize in three phases, Dy_5Si_3, $Dy_3Co_{2.2}Si_{1.8}$, and Dy_3Co with four successive magnetic transitions at 43, 74.7, 90.5, and 132.4 K, resp. The magnetic measurements displayed competing ferromagnetic and antiferromagnetic interactions. At 2.5 K, the alloy exhibits hard ferromagnetic properties with a coercive field of 0.8 T. Metamagnetism is also evidenced in the isothermal magnetization measurements. The Arrott plot shows that this material undergoes first-order magnetic transitions below 47 K, and above which, magnetic transitions are of second order. The four successive magnetic transitions together with competing magnetic interactions give rise to a broadened magnetocaloric effect (MCE) peak with temperature width of ΔT = 83.8 and 93.2 K and consequently a large RC value of 474 and 739 J/kg, for a magnetic field change of 0–5 and 0–7 T, resp. Additionally, it was found that the alloy exhibits negative magnetoresistance and attains a value of − 11 and − 7% at 2.5 and 50 K, resp., in an applied magnetic field of 9 T [2]. Thus, the peculiar magnetic and magnetocaloric properties of $Dy_{6.5}Co_2Si_{2.5}$ and $Gd_{10}Co_{20}Si_{70}$ alloys make them promising not only for low-temperature magnetic refrigeration and as the attractive multifunctional magnetic materials but also for fundamental study perspectives [2].

This work was supported by the projects APVV-16-0079, VEGA 1/0956/17, VEGA 1/0611/18 and the grant from Slovak Academic Information Agency (SAIA) under National Scholarship program.

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P176 - Structure and Physical Properties of CeGe2–x (x ≈ 1/4)

7. Magnetism in alloys and intermetallics

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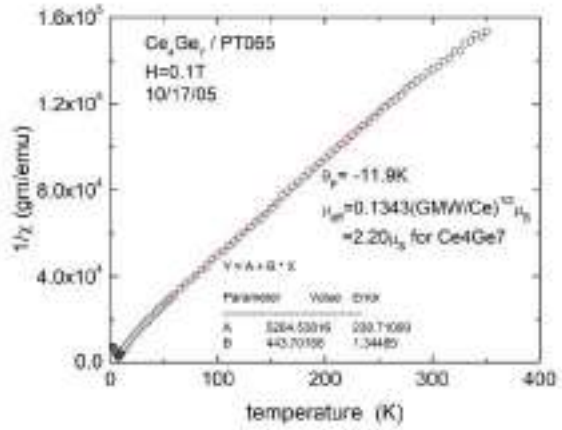
Rare-earth Cerium germanide with the general formula Ce_4Ge_7 has been synthesized using the In-flux technique. The structure established from X-ray diffraction (XRD) has been aided by electron diffraction, representing superstructures of the α-$ThSi_2$ structure type through the long- and/or short-range vacancy ordering. The coexistence of commensurate and incommensurate modulation is revealed in the Ce_4Ge_7 . The magnetic susceptibilities of Cerium germanide show antiferromagnetic, and even spin-glass-like behaviors. Mean-field theory in combination with ab initio calculation is used to evaluate the correlations between structural and magnetic property. Measurements on the electrical resistivities and the heat capacities are also presented to shed light on the structural evolution of the $REGe_{2-x}$ phases as nature of the rare-earth metal germanide.



P177 - Temperature dependence of the magnetic hyperfine field at a Ce impurity diluted in RZn

7. Magnetism in alloys and intermetallics

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In this work we present a theoretical study of the local moment formation and the magnetic hyperfine field at a Ce impurity diluted in *R*Zn (*R* = Gd, Tb, Dy), the impurity occupying a *R* site. We use an intermediate valence model, focusing on the temperature dependence of the magnetic hyperfine fields, thereby extracting the 4f Ce valence at the range of temperature $T \leq T_C$. The temperature dependence of the local magnetic moments and related hyperfine magnetic interaction are calculated adopting a functional integral approach in the static approximation. Our self-consistent calculations are in very good agreement with recent experimental results [1], in particular exhibiting the two regimes of the magnetic hyperfine fields (and local magnetic moments) with temperature.

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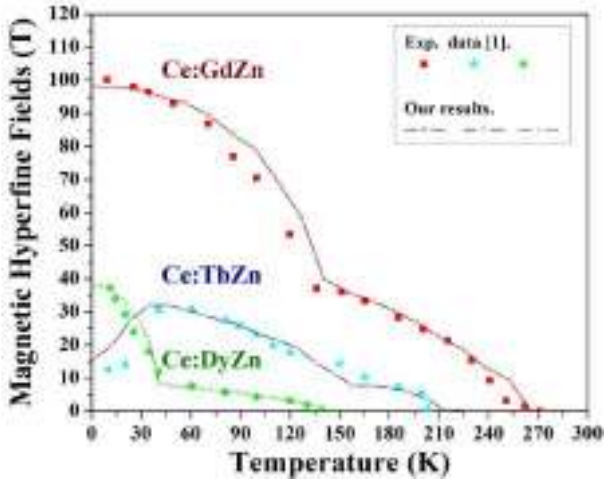

8. Novel magnetic techniques

P178 - 3D printing of polymer-bound anisotropic magnets under an external magnetic field

8. Novel magnetic techniques

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The possibility of producing polymer-bound magnets with the aid of additive processes such as 3D printing opens up a multitude of new areas of application. Almost any structures and prototypes can be produced cost-effectively in small quantities. Extending the manufacturing process allows the production of anisotropic magnetic material by aligning the easy axis of ferromagnetic particles inside a liquid compound material along the external field during the printing process. When the matrix is melted, the magnetic powder can orientate under the external field and form an anisotropic structure. A minimum magnetic flux density is necessary to orientate the particles inside the liquid plastic matrix. The field of a permanent magnet can be used to produce anisotropic structures by directly printing on its surface. With this procedure test-magnets are produced and their magnetic hysteresis is measured in a Vibrating Sample Magnetometer (VSM). This method offers a maximum flux density of approximately 550 mT for a cube shaped 40×40×40 mm^3 (L×W×H) NdFeB magnet in the centre and 150 mT for a plate cylinder with a diameter of 25 mm and a thickness of 3 mm. In order to print magnets under different external fields a spacer made of a nonmagnetic material is used during the printing process – the distance between magnet and probe is increased and the magnitude of the magnetic field lowered. It is necessary to print the magnets as close as possible to the centre of the permanent magnet otherwise it can lead to an unfavourable magnetisation of the sample.

Three different compound-materials provided by Magnetfabrik Bonn GmbH in Germany are compared to each other [1]:

1. SmFeN inside PA12,
2. Sprox® 10/20p (Hard ferrite inside PA6),
3. Sprox® 11/22p (Hard ferrite inside PA12).

The comparison of saturation- and remanent magnetisation of the hysteresis loop measured in the VSM reveals how good the particles in the matrix are aligned. Figure 1 shows the hysteresis loop of all three materials in hard and easy axis. For both Sprox® materials, it seems that an external flux density of 200 mT is sufficient for aligning the particles. However 150 mT is the highest external field where SmFeN can be printed, higher flux densities destroy the shape of the sample due to the higher remanence magnetisation of the material compared to Sprox®.

This approach allows the printing of samples with a higher maximum energy density $(BH)_{max}$ than usual. In addition, the results motivate the development of a customized 3D printer capable of aligning the particles arbitrarily during printing by applying a variable external magnetic field of approximately 200-300 mT in the desired direction for the alignment of the particle. After successfully implementing this design, complex structures with special magnetic capabilities should be printable. This would be a breakthrough in the development and manufacturing of magnets.

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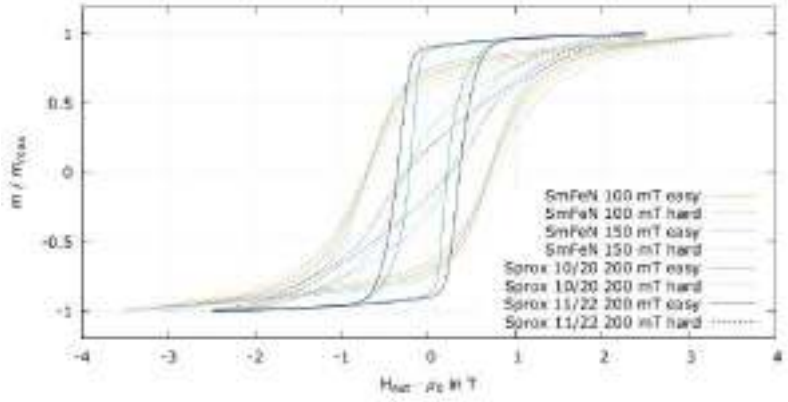
Figure 1: Hysteresis loops in hard- and easy axis of three different anisotropic samples with respect to the external magnetic field measured with a Vibrating Sample Magnetometer.



P179 - A new, fast and precise method for the determination of magnetic particles' core size distribution

8. Novel magnetic techniques

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Magnetic nanoparticles (MNPs) have been widely studied for use in biomedical and industrial applications. It is well known that the core size widely distributes in practical MNPs samples. The core diameter d_C and core size distribution are two key parameters [1]. The magnetic signal strength, Neel and Brownian relaxation time of MNPs are significantly dependent on the core diameter and core size distribution, which affect significantly the harmonic signal of MNPs magnetization. Currently, it takes a long time for a complete an estimation of core size distribution [2], and thus we proposed a novel and fast method for the estimation of MNPs’ core size distribution. In this study, considering the Brownian relaxation effects under ac excitation magnetic field, we presented a model for describing the harmonic amplitude and phase of MNPs' magnetization based on Fokker-Planck equation, and then constructed the mathematical model between the harmonic amplitude and core size distribution. The method employs the solution of the standard integral equation describing the magnetization of a non-interacting particle system in the given external ac magnetic field as a convolution of the harmonic amplitudes with the distribution of particle core size. The inversion problem was solved numerically by using a mathematical technique called nonlinear-non-negative least square method (NNLS). The reconstruction results were obtained both for the numerical simulation and for real experimental data, confirming the validity of the present method. Therefore, the present method can be useful to estimate the core size distribution of MNPs sample. It can be used as a fast and reliable way for a detailed characterization of MNPs, which is required in many advanced applications of these highly promising media.

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P180 - Advanced magnetic studies at the ALBA PhotoEmission Electron Microscope

8. Novel magnetic techniques

Michael Foerster[1] , ***Lucia Aballe***[1]
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The capabilities of the PhotoEmission Electron Microscope (PEEM) experimental station of the CIRCE soft X–ray beamline at the ALBA Synchrotron (Barcelona, Spain) for magnetic studies will be presented together with representative results from recent experiments.

Using electrons emitted from the sample upon illumination with the variable polarization tunable X-ray photons, surface imaging is performed with high chemical, structural, and magnetic sensitivity down to a lateral resolution of 20 nm [1].

PEEM microscopy with X-Ray Magnetic Circular Dichroism (XMCD) contrast is a versatile and powerful tool for the study of magnetic materials and micro/nanomagnetic systems. It provides non-invasive element-specific magnetic imaging with high spatial resolution and sensitivity (low moment). Thanks to the azimuthal sample rotation and the near grazing X-ray incidence, full 3D magnetization information can be obtained, as well as depth information of elevated objects such as cylindrical nanowires. Using X-Ray Magnetic Linear Dichroism (XMLD) contrast, also antiferromagnetic domains can be imaged.

The imaging column includes an energy analyser, so that spectromicroscopy is available both in X-ray absorption (XAS) and Photoemission (XPS) modes.

The station comprises in-situ surface and thin film preparation techniques such as variable temperature, metal evaporation, gas exposure, ion sputtering, and complementary characterization techniques including Low Energy Electron Microscopy, micro-spot Low Energy Electron Diffraction, and micro-spot Angle Resolved PhotoElectron Spectroscopy, making it also ideal for the multi-technique tackling of complex problems in 2D materials, nanostructures and surfaces.

A suite of state of the art sample holders and electronics provides a functional sample environment for applying electric and small magnetic fields as well as electrical signals (current pulses) [2]. Dedicated instrumentation has also been developed for time resolved measurements with sub 100 ps time resolution [3].

The ALBA PEEM is open to external users worldwide through a call for proposals procedure twice a year [4].

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P181 - Broadband magnetoimpedance in La0.7(Sr,Ca)0.3MnO3 from ferromagnetic to paramagnetic regime.

8. Novel magnetic techniques

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Although direct current magnetoresistance and low-frequency magnetic susceptibility (f < 1-10 kHz) of colossal magnetoresistive oxides have been extensively reported in the literature over the past two decades, magnetoresistance and magnetic properties of these oxides at high frequencies have been overlooked so far. Recently, we have shown that the archetypical double exchange ferromagnets such as $La_{0.7}Sr_{0.3}MnO_3$ and $La_{0.7}Ba_{0.3}MnO_3$ exhibit much larger magnetoresistance at low dc magnetic fields (= 40-60 % in H = 1 kOe) than dc magnetoresistance (< < 0.1%) if radio frequency current of frequency f = 1 MHz to 3 GHz is driven through the sample [1,2]. This puzzling effect was attributed to the magnetic field-induced suppression of high frequency transverse magnetic permeability and occurrence of ferromagnetic resonance in the sample but detail understanding is still lacking. Here, I overview this topic and present new results on $La_{0.7}Sr_{0.3-x}Ca_xMnO_3$ series whose magnetic state at room temperature can be changed from ferromagnetic to paramagnetic with increasing Ca content. Using a strip-coil and an impedance analyzer, we show that we can detect not only ferromagnetic resonance but also paramagnetic resonance in this series of samples. Our simple, low-cost experimental technique could be used to probe and exploit magnetization dynamics in multiferroics and other exotic systems.

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P182 - Development and Applications of a New Soft X-ray Ptychography Microscope at the Swiss Light Source

8. Novel magnetic techniques

Manuel Langer[1] , *Pelin Üresin[1, 2], Sabina Chiriotti[1], David Bracher[1], Michal Odstrcil[1], Sebastian Wintz[1], Simone Finizio[1], Manuel Guizar-Sicairos[1], Anna Bergamaschi[1], Carlos A. F. Vaz[1], Armin Kleibert[1], Jörg Raabe[1]*

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Soft X-ray microscopy has proven to be a unique tool for the investigation of nanoparticles and nanostructures. However, imaging by scanning transmission x-ray microscopy (STXM) faces a natural resolution limitation given by the size of the focus generated by x-ray lenses. This constraint can be overcome with the help of coherent diffractive imaging techniques, such as ptychography, enabling a diffraction-limited imaging at an ultimate spatial resolution.

We are currently developing a new soft x-ray ptychography spectro-microscope [1] at the SIM beamline of the Swiss Light Source with the goal of providing wavelength-limited spatially resolved maps of the spectroscopic and magnetic response of a broad variety of materials. Here, we benefit from the PSI-developed *Mönch*-detector [2], a low-noise charge-integrating hybrid-pixel detector, which is incorporated in our setup.

In this contribution, we provide an overview of the magnetic systems, which were studied with this setup. The imaging and spectroscopy capabilities of this new ptychography microscope are demonstrated on ferrimagnetic domains of FeGd microstructures as well as with the imaging of CoO nanoparticles and of the magnetic vortex core of a $Ni_{80}Fe_{20}$ disk. As ptychography is a phase-sensitive imaging method, our microscope can access both, phase and amplitude (see Fig. 1) of an object. Using this property, we provide some preliminary results of our investigation of the x-ray magnetic circular dichroism (XMCD) phase and amplitude on the example of FeGd around the Fe L2/3 edges (Fig. 1). In addition, we will present first data of our recent efforts to realize ptychographic microscopy in reflection geometry.

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under Marie Skłodowska-Curie grant agreement No. 701647.

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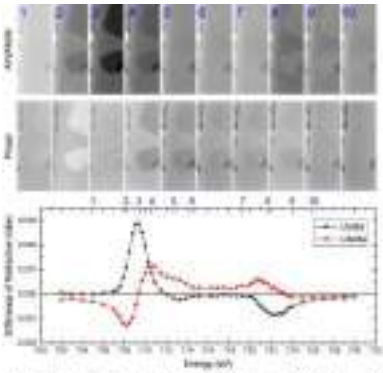

Fig. 1 *Reconstructions of amplitude and phase of bi-conjugate domains of a FeGd microstructure allowing for the calculation of the dichroic difference of the complex refractive index δ beta and δ delta due to the XMCD effect around the Fe L2/3 edges. The preliminary data shown in the plot were obtained from five different regions within oppositely magnetized domains.*

P183 - Investigating the local 3d spin with hard x-ray emission spectroscopy

8. Novel magnetic techniques

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K fluorescence X-ray emission spectroscopy (XES) has been extensively applied to the study of 3*d* transition metal compounds as it provides valuable information about the electronic structure (local charge- and spin-density) [1], [2] as well as the ligand environment [3]. In particular, Kβ (3*p*→1*s*) and Kα (2*p*→1*s*) emission lines are very powerful tools to extract spin state information. Their spin sensitivity stems from the intra-atomic exchange interaction between the 3*p* and 2*p* core-hole, respectively, and the net 3*d* shell spin of the transition metal ion. This gives the possibility of studying the local spin independently of long-range magnetic order. Another interesting feature of Kβ and Kα XES is that the hard x-rays probe the local spin with bulk sensitivity. XES is recently experiencing a growing interest because of the availability of commercial laboratory spectrometers and its attractiveness for ultrafast time resolved experiments at X-ray free electron lasers.
The sensitivity of K-emission spectroscopy mainly arises from intra-atomic electron-electron interactions that provide information on the local spin sate. They can be modelled in crystal field multiplet calculations. However, mixing between metal and ligand orbitals, many-electron transitions and the final state lifetime broadening are difficult to simulate precisely and thus render a full theoretical treatment very complex. We have carried out a systematic investigation by measuring Kβ and Kα XES on a wide range of Fe compounds with the aim to get further insight into the spectral sensitivity beyond an ionic model. More than 30 samples with different oxidation state (+2, +3, +4 and mixed-valence), spin (high spin, low spin and mixed-spin), ligands (fluorides, oxides, sulfides, etc.) or local coordination (octahedral, tetrahedral) were measured at beamline ID26 of the ESRF synchrotron (Grenoble, France). Intriguing variations of the Kβ and Kα spectral features appear for compounds with the same formal spin. We have quantitatively analysed the experimental data in terms of various parameters commonly used in Kβ and Kα XES studies to retrieve the spin evolution ($K\beta_{1,3}$-first moment, $K\alpha_1$-full width half maximum, and integrated absolute difference –IAD– [4]). The analysis reveals a significant spread of these parameters at fixed nominal spin values when data from all samples are considered. We interpret this result as a variation of the intra-atomic exchange interaction arising from delocalization of the 3*d* electrons.
Our findings presented for Fe compounds extend to the K-emission lines of all 3*d* transition metals and have important implications with respect to the determination of the relative changes in the local spin using XES. A reliable sensitivity to the spin evolution across a series of spectra is guaranteed only if there are no significant variations in physicochemical properties.

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P184 - Magnetic force sensing using a self-assembled nanowire

8. Novel magnetic techniques

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We present a scanning magnetic force sensor based on an individual magnet-tipped GaAs nanowire (NW) grown by molecular beam epitaxy [1]. Its magnetic tip consists of a final segment of single-crystal MnAs formed by sequential crystallization of the liquid Ga catalyst droplet [2]. We characterize the mechanical and magnetic properties of such NWs by measuring their flexural mechanical response in an applied magnetic field [3]. Comparison with numerical simulations allows the identification of their equilibrium magnetization configurations, which in some cases include magnetic vortices. We determine a NW's performance as a scanning probe [4], by measuring its dynamical response to the magnetic field of a micrometric current-carrying wire. The NWs' tiny tips and their high force sensitivity make them promising for imaging weak magnetic field patterns on the nanometer-scale, as required for mapping mesoscopic transport and spin textures or in nanometer-scale magnetic resonance.

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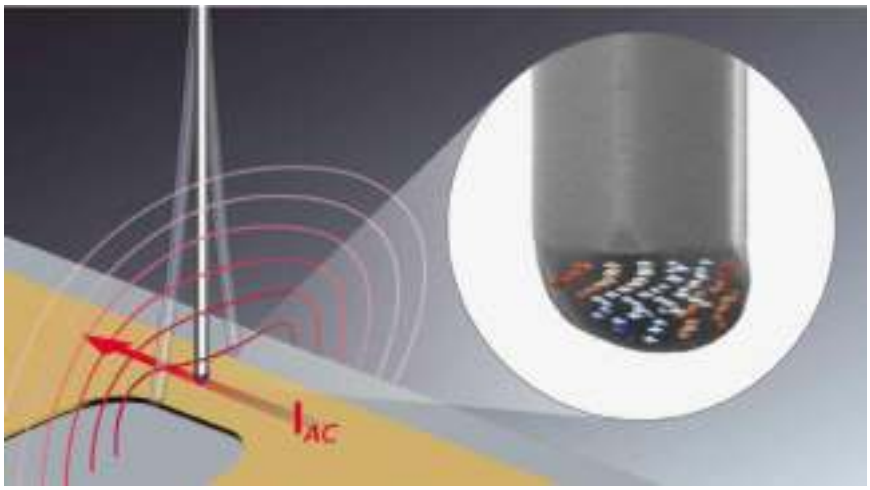

P185 - Phase of Higher Harmonic of magnetic nanoparticles' magnetization under low frequency magnetic field

8. Novel magnetic techniques

Zhongzhou Du[1, 2] , *Yi Sun*[1], *Oji Higashi*[2], *Yuya Fusayasu*[2], *Keiji Enpuku*[2], *Takashi Yoshida*[2]

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Magnetic nanoparticles (MNPs) have appealing properties for biomedical, biological and industrial applications, such as its high degree of heating efficiency, temperature sensitivity, and superparamagnetic properties. The magnetic particle imaging (MPI) [1,2] and magnetic nanoparticle thermometer (MNPT) [3] are the typical applications, which calculate the concentration and temperature utilizing the harmonics of magnetization based on the nonlinear property of MNPs' magnetization under external ac magnetic field. Both of applications assume that there are no relaxation effects under low-frequency excitation magnetic field, that is, there is no phase lag in each harmonic. However, in experiment, the harmonics of magnetization were still affected by Brownian relaxation, which there was phase lag of harmonics compared to the excitation magnetic field. Here, we investigated how the relaxation effects affect the amplitude and phase of higher harmonics of MNPs' magnetization under low frequency excitation magnetic field. The experiment results show that the effect of relaxation on the phase of higher harmonics is much more significant than first harmonic, and the phase lag of higher harmonics is gradually decreased with increased the intensity of the excitation magnetic field. Finally, we proposed a model for describing the amplitude and phase of higher harmonics based on Fokker-Planck equation, and the model was validated by comparison to experimental data. It is significant for improving the resolution of MPI and MNPT.

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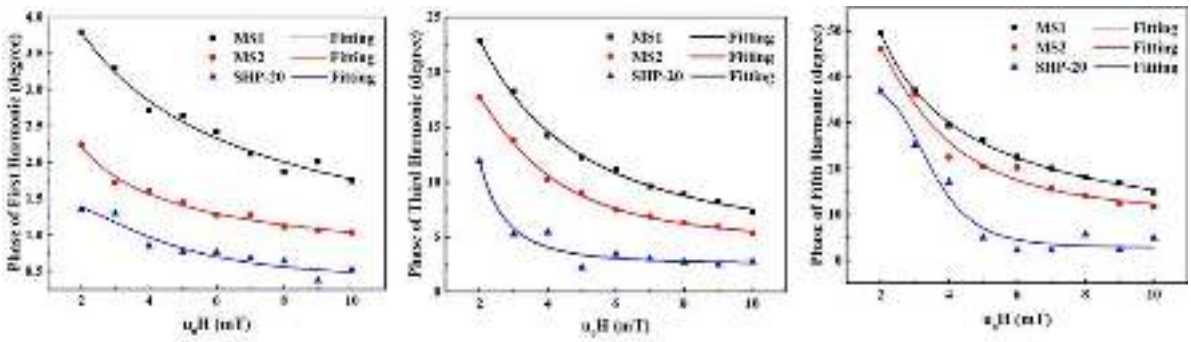

Figure. 1. Phase of harmonics under different excitation magnetic fields. (a) Phase of first harmonic. (b) Phase of third harmonic. (c) Phase of fifth harmonic

P186 - Quantum Motion of Muons and Muon Spin Relaxation (muSR)

8. Novel magnetic techniques

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Muons as used in the technique of muon spin relaxation and rotation (muSR) are powerful local probes of the magnetic state of materials boasting both exquisite sensitivity to minute internal fields at muon sites as well as a unique, broad frequency window over which the muons detect any dynamical fluctuations of these fields. Due to these characteristics muSR has become indispensable in characterizing a wide range of magnetic materials, both long-range ordered as well as classically or quantum disordered. However, despite its many advantages, the technique of muSR suffers from a basic limitation in that the crystallographic sites where muons stop inside a given material, and hence where they detect the internal magnetic fields, are *a priori* unknown, which often limits our ability to extract reliable quantitative data from muSR experiments without making assumptions about the muon sites. Further complicating the interpretation of experimental data are possible distortions of the local crystal structure (Fig. 1) that sometimes accompany an implanted muon.

Recently there has been a lot of work towards solving the muon-stopping-site and local-distortion problems in specific cases using *ab initio* methods, especially density functional theory (DFT), which resulted in substantial improvements in our ability to draw reliable conclusions from muSR data in some cases and enabling a quantitative comparison between experimental results and theoretical models of material magnetism. Though a significant step forward, the *ab initio* methods that are usually employed are not powerful enough to describe all materials of experimental interest, as they usually treat muons as classical, point particles and assume that they are completely at rest at their ultimate stopping sites during the experiment. Both of these assumptions are expected to fail in many real-world materials, especially those where muons are only weakly bound to a local potential minimum. This is due to the fact that muons are very light compared to ordinary nuclei (a muon is 1/9 the mass of a proton) and are thus expected to be potentially highly mobile. Furthermore, muons are expected to show pronounced quantum effect of zero-point motion, zero-point energy, and quantum tunnelling between nearby local potential minima.

We take the first steps towards incorporating these effects into an *ab initio* calculation by employing path-integral molecular dynamics (PIMD) DFT calculations. We further compare our results with the quantum motion of muons as described by – comparatively cheaper – harmonic-approximation phonon DFT calculations. Our work shows that quantum motion of muons can destabilize some putative muon stopping sites, change the energy ordering of stable muon stopping sites, as well as substantially shift the positions of resonances in quadrupolar level-crossing resonance (QLCR) muSR experiments, among other effects. We find that using this approach we can quantitatively explain experimental results that fall beyond the scope of classical-muon DFT methods, thus significantly expanding the range and accuracy of *ab initio* modelling of muSR data and reaffirming muSR as a uniquely-powerful method of probing subtle magnetic effects in materials.

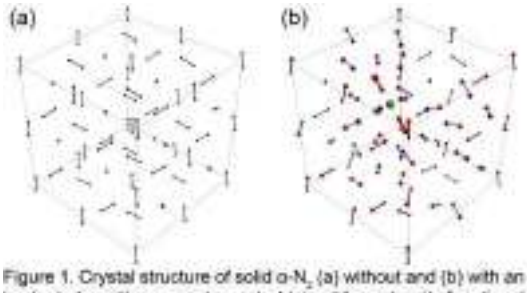

Figure 1. Crystal structure of solid α-N_2 (a) without and (b) with an implanted positive muon (green) obtained from density functional theory (DFT) calculations. The N_2 molecules (spheres connected by a stick) reorient and become electrically polarized around the muon in a N_2–μ^+–N_2 complex (blue denotes negative and red positive ion charge, while sphere size indicates absolute ion charge). The trapped muon experiences quantum zero-point motion, which is reflected in a shift of resonance fields in a quadrupolar-level-crossing-resonance (QLCR) muon spin relaxation (μSR) experiment.

P187 - Simulations of atomic resolution differential phase contrast imaging of magnetic materials

8. Novel magnetic techniques

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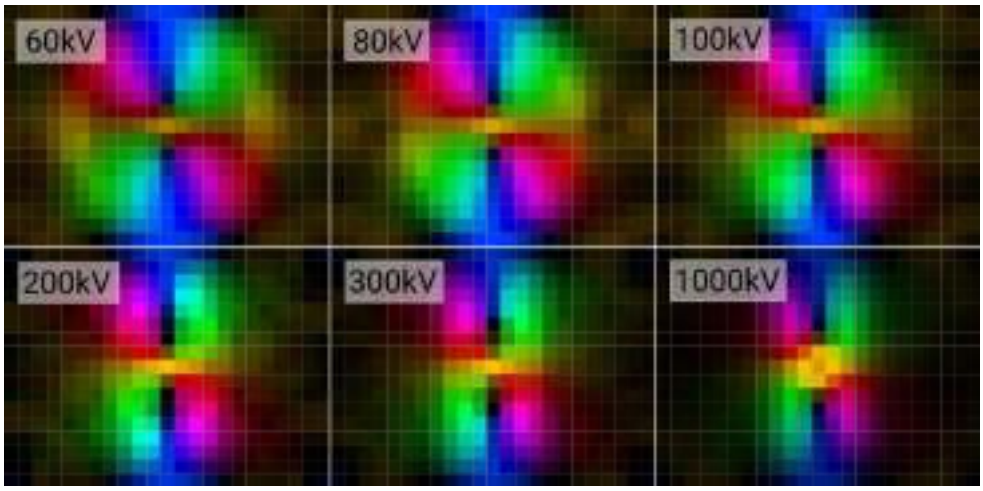
Utilizing the Pauli equation based multislice method, introduced in Phys. Rev. Lett. **116**, 127203 (2016), we study the atomic resolution differential phase contrast (DPC) imaging on an example of a hard magnet FePt with in-plane magnetization. Simulated center of mass pattern in a scanning transmission electron microscopy (STEM) experiment carries information about both electric and magnetic fields. The momentum transfer remains curl-free, which has consequences for interpretation of the integrated DPC technique. The extracted magnetic component of the pattern (see Figure) is compared to the expected projected microscopic magnetic field as obtained by density functional theory calculation. Qualitative agreement is obtained for low sample thicknesses and a suitable range of collection angles. [1]

[1] Alexander Edström, Axel Lubk, Ján Rusz, submitted, arXiv:1903.03083 [cond-mat.mtrl-sci].



P188 - Transport and optical measurements of HgTe/HgCdTe heterostructures under high magnetic fields

8. Novel magnetic techniques

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A high magnetic field is a powerful tool for investigations of electronic and magnetic structure of condensed matter. For instance, a clear observation of cyclotron resonances requires fulfillment of well-known condition $\omega_c\tau > 1$ where ω_c is the cyclotron frequency and τ is the mean free time. Since ω_c is propotional to the magnetic flux density B, a high magnetic field is necessary to study substances with low values of τ. The full magnetic phase diagram of room-temperature ferrimagnets lies in high-magnetic and even untrahigh magnetic field range (above 100 T) [1].

A nondestructive facility for generating pulsed magnetic fields of a millisecond range has been created at SarPTI NRNU MEPhI [2]. The maximum peak value of the magnetic field is 50 T. The solenoid (Fig.1) is made of a microcomposite Cu–Nb conductor and reinforced with a bandage with paraaramide fiber. A capacitor battery discharge to a solenoid is controlled by a solid-state switch based on a block of reverse-switched dinistors. The working hole diameter of the solenoid is 19.5 mm. It allows placing a cryostat in it with operating temperatures up to 4 K. Magnetization, complex conductivity, transport and optical characteristics of substances in the visible and infrared ranges can be measured.

The paper presents the technique and results of cyclotron resonance measurement in the temperature range 77–300 K in HgTe/$Hg_{1-x}Cd_xTe$ heterostructures with quantum wells [3]. The measurements were carried out in pulsed magnetic fields up to 50 T. The samples under the study differed in the width of the quantum wells, their number and the composition content. For these samples, cyclotron resonance lines were recorded (Fig.2) for the first time at temperatures above 77 K [4]. It is shown that it is possible to measure simultaneously cyclotron resonance and the quantum Hall effect in the pulsed magnetic field (Fig.2). The quantum Hall effect in several HgTe/$Hg_{1-x}Cd_xTe$ heterostructures was studied at a temperature of 4 K.

The paper also presents the methodology and results of the magneto-optical study of the magnetic phase diagram of a thin film $(LuBi)_3(FeAlGa)_5O_{12}$ on a $Gd_3Ga_5O_{12}$ substrate. The compensation temperature of sample was ~ 95 K. During the study of the films, an unusual precursor of the transition to the noncollinear phase (Fig.3) was found near the compensation temperature [4]. This precursor was observed both with increasing and decreasing magnetic field. The traditional theory for homogeneous almost compensated ferrimagnetics [1] does not yet allow describing this effect.

This work was partially supported by the Russian Foundation for Basic Research. (Project No.18-48-520006).

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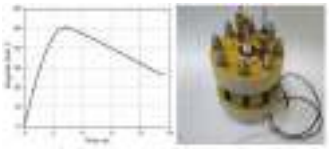

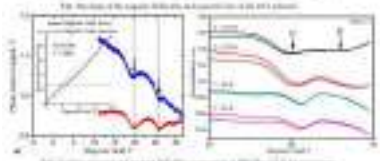

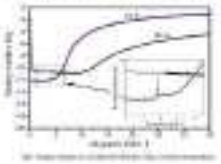

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

P189 - A simplified first-principles approach to entropy variations in magnetocaloric materials

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

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The increasing interest in the application of magnetocaloric materials for magnetic cooling devices has led to an intensive search for new materials with a more attractive performance to cost ratio. High-throughput studies based on first-principles calculations can play a crucial role to detect new magnetocaloric materials and help to estimate trends for material tuning. In order to identify systems of interest from a large body of data, screening parameters are necessary and must be carefully chosen since a balance between the accuracy and the cost of the calculations is needed.

One key quantity for the performance of magnetocaloric systems is the entropy change between two magnetic phases. To analyze this quantity in a cost-efficient but accurate way we try several approaches. A model for a first-principles estimation of the entropy variation which arises from the change of the magnetic phase is proposed, considering three distinct entropy contributions and being treated as independent: electronic, lattice, and magnetic. While the first terms are evaluated conventionally using the Sommerfeld expansion and the Debye Model, respectively, the later was initially estimated using a similar approach as reference [1], with the magnetic entropy variation derived from the definition of entropy, assuming an ideal first-order transition, as the variation of the exchange energy divided by the transition temperature. Two well-known systems have been chosen to test the approach: FeRh and Fe_2P. The results indicate that this approach is not adequate, and fluctuations on the magnetic moments must be included in the model. Estimated values are presented and the model applicability to compute the entropy variation as a screening parameter for magnetocaloric performance is discussed.

This work has been supported by the Swedish Foundation for Strategic Research, within the project *Magnetic materials for green energy technology* (ref. EM16-0039).

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P190 - ANHYSTERETIC MAGNETIZATION OF SUPERMALLOY COMPACTED POWDER

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

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Most remarkable permalloys are the alloys with composition close to $Ni_{80}Fe_{20}$, where both anisotropy and magnetostriction fall to zero at almost the same composition. A tendency towards unfavourable Ni3Fe-type L12 atomic ordering can be suppressed by Mo addition, i.e., in supermalloy NiFeMo [1].

The appropriate structure of NiFeMo having initial permeability much larger than that of pure iron arises after proper heat treatment. The form of a sheet is not suitable for some applications and therefore it is logical to attempt to prepare such material in another form, for example as a ring, which would be more convenient for construction of some type components for electronic devices. One of these methods is compaction of the powder prepared by mechanical milling or mechanical alloying.

We prepared the filings from the $Ni_{79}Fe_{16}Mo_5$ sheet by a rotary drill grinder mounted in a lathe, followed by milling in a planetary ball mill, Retsch PM 100 with hardened steel vials and balls for 6 hours with ball to powder ratio of 9:1. This powder was consequently compacted (in the shape of a ring) at a pressure of 700 MPa at the temperature of 410 °C stabilized for 5 min.

In this work various methods for the determination of anhysteretic magnetization are presented and compared. The anhysteretic curve was measured on modified DC hysteresisgraph [2]. Decreasing AC field was applied at every measurement point along the hysteresis loop by the third toroidal winding to obtain experimental points of anhysteretic curve. Demagnetization factor was determined by the linear part of anhysteretic curve ($H_{ext} \rightarrow 0$ A.m^{-1}) to quantify influence of non-magnetic part of compacted ring-shaped sample to inner demagnetizing fields inside the volume of the sample. Demagnetizing field in sample depends on numerous parameters such as shape and size of particle, porosity, clustering and distribution of ferromagnetic particles. The anhysteretic magnetization curve was used in the characterization of material.

Acknowledgement

This work was supported by the Slovak Research and Development Agency under contract No. APVV-15-0115 and by the Scientific Grant Agency of the Ministry of Education of the Slovak Republic and the Slovak Academy of Sciences KEGA 002TUKE-4/2019 and VEGA 1/0377/16.

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P191 - Characterization and Magnetic properties of Nd-Fe-B Nanoparticles Prepared by Cryo-milling

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

Marian Grigoras[1] , *Mihaela Lostun[1], Tiberiu Roman[1], George Stoian[1], Gabriel Ababei[1], Horia Chiriac[1], Nicoleta Lupu[1]*

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The development of technological devices in renewable energy, like wind turbine and electric or hybrid vehicles, is directly linked to the use of permanent magnets as essential constituents. Rare-earth hard magnetic nanoparticles have drawn great attention due to their potential applications in nanocomposite permanent magnets with high performance. The ball-milling technique, used for the preparation of nanoparticles, is a simple, inexpensive and efficient method for size reduction of nanocrystalline powders. The experimental parameters involved in ball-milling technique, such as milling time, milling energy, and ball size, are determinant in what concerns the magnetic properties of the nanoparticles. The milling temperature and milling medium are also known as critical factors impacting the morphology and performance of the nanoparticles.

Here, we report results on the morphology, structure, and magnetic properties of $Nd_{13}Fe_{81}B_6$ and $Nd_{14}Fe_{80}B_6$ nanoparticles prepared by two approaches: *(i)* surfactant-assisted high-energy ball milling at low temperature and *(ii)* high-energy ball milling in liquid nitrogen. For the samples prepared by surfactant-assisted milling, the heptane was chosen as milling medium, and the acid oleic was used as surfactant. The temperature of vial was keep below 0°C during the whole ball milling process by repeatedly introducing the milling vial in a liquid nitrogen bath. For the samples prepared by milling in liquid nitrogen, at 20 min. intervals additional liquid nitrogen was introduced into the vial to compensate the evaporation. According to EDX data, the second method allowed avoiding the critical contamination of material with O_2 or C additives. It was also revealed that milling of NdFeB alloy in liquid nitrogen did not change the initial composition of alloy. By comparing Nd-Fe-B nanoparticles produced by surfactant-assisted ball milling at low temperature and the ones produced in liquid nitrogen, we found that the former has: more homogeneous morphology and smaller size while the last one present better magnetic properties, especially markedly increased remanent magnetization (Mr). Specifically, after 7 hours of milling, nanaopowders obtained in the first approach *(i)* show an average dimensions of 110 nm, coercivity of about 5.2 kOe, and remanence of about 57.1 emu/g, while the nanaopowders obtained by second approach *(ii)* show an average dimension of 170 nm, but better magnetic properties, such as coercivity of about 7 kOe and remanence of about 64.5 emu/g. The $Nd_{14}Fe_{80}B_6$ nanoparticles obtained by ball milling in liquid nitrogen have great potential to be used for the production high performance nanocomposite permanent magnets.

Acknowledgements

This work was supported by the Romanian NUCLEU Programme (Project PN 19 28 01 01) and by a grant of the Romanian Ministry of Research and Innovation, CCCI-UEFISCDI, project number PN-III-P1-1.2-PCCDI-2017-0871/no.47PCCDI/2018 within PNCDI III.

P192 - Coercivity of (SmZr)1(FeCo)11-yTiy (y=1; 0.7) nanocomposite prepared by high energy ball milling

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

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The tetragonal $R_{1-x}Zr_x$ $(FeCo)_{11}Ti$, where R is a rare earth and T is a transition metal, are promising candidates for permanent magnet alloys due to their high magnetization, Curie temperature and magneto-crystalline anisotropy values [1, 2]. $Sm_{1-x}Zr_x(Fe_{0.8}Co_{0.2})_{11-y}Ti_y$ (x=0 and 0.25; y=1 and 0.7) alloys were prepared by arc melting in a high purity argon atmosphere and with different Sm excess content (20-30%). According to the Rietveld analysis, all as-cast samples were almost single-phase 1:12 with a small amount of a-Fe. Subsequently, all samples were milled using high-energy ball milling (HEBM) for different time (4 and 8 hours) in an argon atmosphere keeping a ratio weight of balls to that of powder 10:1. All samples after milling exhibit amorphous/disordered phase and a-Fe and were re-crystallized into a majority 1:12 phase after annealing at 700 ^{o}C-900 ^{o}C and different interval times (15-90 min). An overall view of the evolution of coercivity for $Sm_{1-x}Zr_x(Fe_{0.8}Co_{0.2})_{11-y}Ti_y$ (x=0 and 0.25; y=1 and 0.7 is shown in the Fig 1. The $SmFe_9Co_2Ti$ samples annealed at 900 ^{o}C exhibit a higher amount of a-Fe than when annealed at 800 ^{o}C, which can explain the moderate values of coercivity, reaching the maximum value of 4.04 kOe (annealing time 30 min). It seems that the annealed samples at 800 ^{o}C give higher values of Hc. Samples annealed at 700 ^{o}C for 15, 30 ad 60 min., exhibit a relatively low coercivity ~1.5 kOe. Correlation of grain size with the coercivity will be discussed.

Acknowledgements: This project was partially supported by the H2020 – MSCA-RISE-*2015 INAPEM: International Network on Advanced high energy Permanent Magnets* and H2020-NMP23-2015 NOVAMAG: Novel Materials by Design for substituting Critical Raw Materials.

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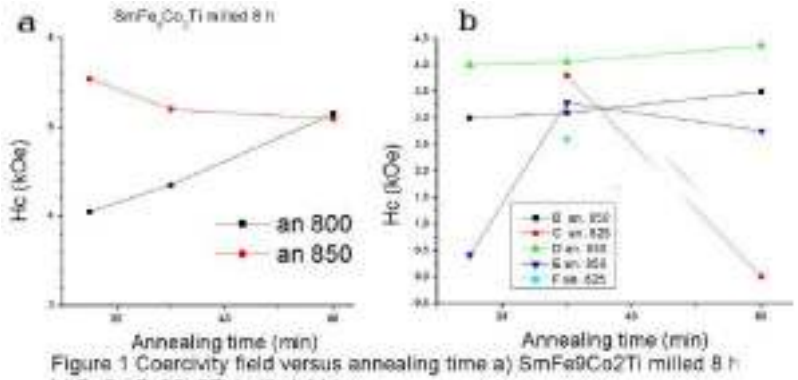

Figure 1 Coercivity field versus annealing time a) SmFe9Co2Ti milled 8 h b) B: SmFe9Co2Ti (milled 4 h), C and D: SmFe9.04Co2.26Ti0.7 (milled 8 h), an. 925 and 850 oC. E and F: Sm 0.75Zr0.25Fe9.04Co2.26Ti0.7 (milled 8 h) an. 850 and 925 oC.

P193 - Computational high-throughput screening of novel Rare-Earth free hard magnetic phases

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

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Nowadays, the great performance of Rare-Earth (RE) based permanent magnets (PMs) makes them essential in many technological applications (electric motors, generators, etc.) [1], leading to a strong dependency on critical raw materials as the RE elements Nd, Sm and Dy. Finding viable alternatives based on cheap high-performance RE-free PMs has become an important issue but also a major scientific and technological challenge. To this end, the experimental exploration of new PMs begins to be assisted and guided by computational approaches thanks to their advances in calculation speed, accuracy and reliability [2-4]. One of the key intrinsic properties of modern PMs is the Magnetocrystalline Anisotropy Energy (MAE) because it can greatly increase the overall coercivity [5]. Here, we discuss about the computational high-throughput strategy performed in the context of H2020 Novamag project [6] for identifying novel magnetic structures with high easy-axis MAE. We devised a script that controls the calculation of MAE in an automated way providing as the input only the atomic position file. For each structure, Density Functional Theory (DFT) calculations were performed in several steps: full structural optimization (volume, cell and atomic positions) using VASP code with standard precision, followed by more accurate calculations with optimal code parameters previously obtained by testing and reproducing experimental MAE data for a large set of representative known magnetic materials. For the optimized structure, accurate charge density and wave function were calculated for ferromagnetic arrangement of spins via collinear spin-polarized DFT calculations, which served as input for non-collinear spin calculations (NCL) with spin-orbit coupling. NCL-calculations were performed in a non-self-consistent manner for a set of polar and azimuthal angles. This procedure was fed by the crystallographic data of RE free/lean theoretical structures predicted by an Adaptive Genetic Algorithm (AGA) [7] using USPEX code and found in open Genome Material Initiative databases (like AFLOWlib and Materials Project) that were previously screened according to space group (only uniaxial phases are considered), formation enthalpy ($\Delta H_F<0$) and saturation magnetization ($\mu_0 M_S>1T$). A final procedure, written by bash scripting, was also prepared to upload the large amount of generated data from this approach to the open Novamag database [8,9] automatically, making them publicly available. We show that this methodology is capable to reveal many interesting hidden hard and semi-hard RE-free novel magnetic phases. Finally, some general strategies are discussed to design possible experimental routes for exploring most promising theoretical novel materials.

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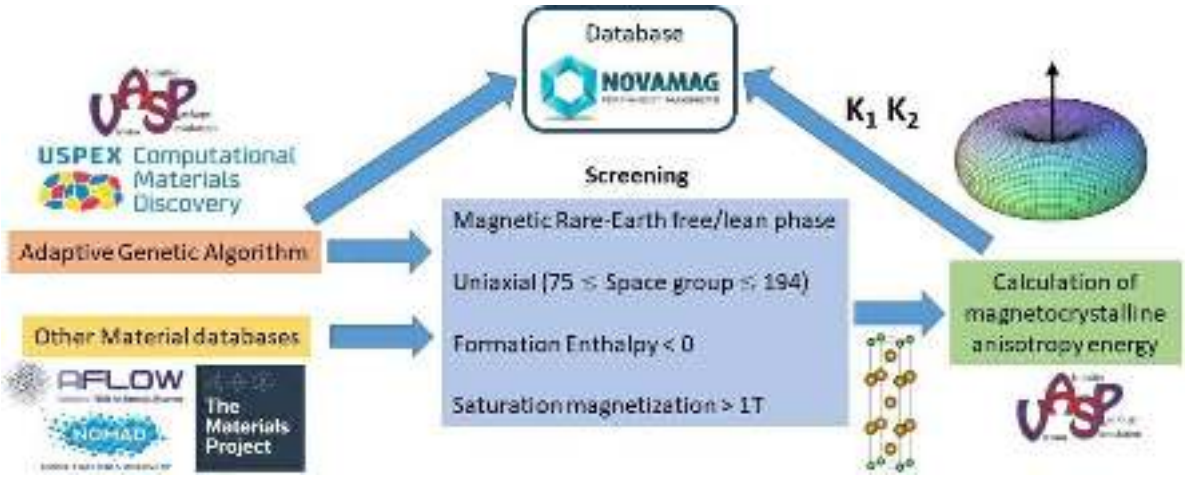

P194 - Current annealing crystallization of Co-rich amorphous microwires for hard-magnet applications

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

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Amorphous microwires of Co-rich compositions are known as excellent soft-magnetic materials exhibiting a number of outstanding effects such as magnetic bistability, giant magnetoimpedance and stress-impedance which are used in sensing and smart materials applications. For all these applications the use of hard magnetic elements of similar dimensions together with the sensing wire can provide additional functionality. Hard magnetic microwires are also of interest for bio-medical applications as they could be implanted within a targeted area of tissue or blood vessel to control the migration of living cells and targeted drug delivery. However, a preparation of hard magnetic microwires is a difficult task. The crystallization process strongly affects the wire magnetic properties. In the case of gradual heating with a constant temperature changing rate the crystallization proceeds in two main stages in the temperature range of 500-700 and results in deterioration of soft magnetic properties. The magnetic anisotropy increases but typically the coercivity does not exceed 1-2 kA/m. Utilising specific heating-exposure-cooling cycles the coercivity can be further increased up to 30 kA/m but the remanence magnetization remains small [1]. A process of directional crystallization was proposed in [2] to enhance the hard magnetic properties. In this case, the crystallization proceeds through a number of metastable states which makes it difficult to control the resulting microstructure and magnetic parameters. In the present paper, current annealing is proposed as an alternating crystallization technique to produce hard magnetic microwires. Depending on the annealing time (30-60 minutes) the coercivity of $Co_{71}Fe_5B_{11}Si_{10}Cr_3$ microwires was increased up to 50 kA/m (see Fig.1) with the remanence to saturation ratio of about 75%. Structural characteristics of samples before and after annealing were investigated by using XRD, SEM and TEM. The formation of needle-shaped crystals of Co and their arrangements by circular magnetic field may be responsible for giant increase in coercivity. Therefore, we put forward a novel technique for micro-magnet fabrication.

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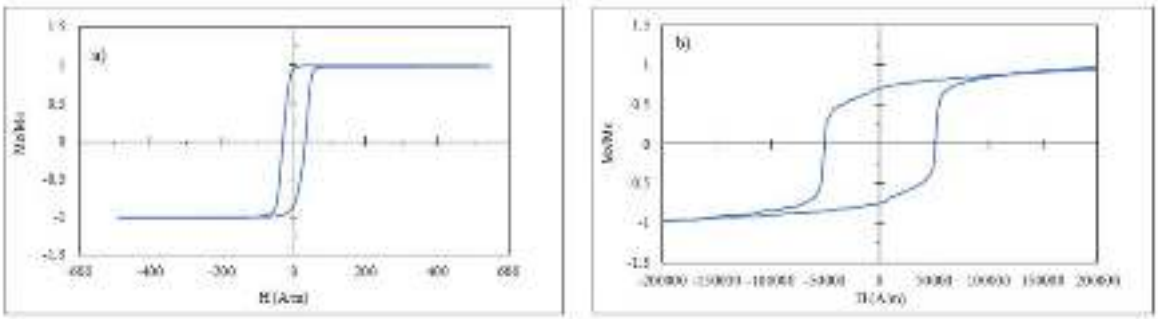
Fig.1. Hysteresis loop of as-cast (a) and current annealed (b) microwires of composition $Co_{71}Fe_5B_{11}Si_{10}Cr_3$. Annealing conditions are: dc current of 100mA during 35 min.



P195 - DC MAGNETIC PROPERTIES AND COMPLEX PERMEABILITY OF WARM COMPACTED NI-FE-MO POWDER

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

Peter Kollár[1] , *Ján Füzer[1], Miloš Jakubčin[1], Denisa Olekšáková[2], Peter Slovenský[1], Zuzana Birčáková[3], Radovan Bureš[3], Mária Fáberová[3]*

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NiFe (permalloy) and NiFeMo (supermalloy) alloys exhibit high permeability and low coercivity and are widely used as magnetic cores or magnetic shielding in electronics and electro technology components as cores of inductors, transformers and sensors.

The samples for investigations of DC magnetic properties and complex permeability were prepared by conventional powder metallurgy giving the opportunity to produce elements for magnetic circuits of precise 3D shapes, with minimum waste [1, 2].

The aim of this work was to investigate magnetization processes in compacted $Ni_{80}Fe_{15}Mo_5$ powder with powder elements with modified particle surfaces.

The sample preparation process started with preparation of filings from the $Ni_{80}Fe_{15}Mo_5$ sheet by a rotary drill grinder mounted in a lathe, followed by milling in a planetary ball mill. The sharp edges of the powder elements were subsequently smoothed by new developed method. Then the NiFeMo powder was warm compacted at a pressure of 700 MPa at the temperature of 410 °C, for 5 min to obtain ring shaped compact.

The DC relative initial permeability and DC relative maximum permeability were obtained from initial magnetization curve measured by fluxmeter based hysteresisgraph. The DC hysteresis loops at various maximum induction were measured also by fluxmeter based hysteresisgraph. The complex permeability spectra were measured by an impedance analyzer (HP4194A) from 100 Hz to 1 MHz.

We have compared magnetic properties of mechanically treated sample with ones for mechanically non-treated samples before heat treatment and after heat treatment (at 100 °C). The annealed sample with mechanically treated powder elements surface exhibits three times improved initial relative permeability (μ_i=8500) and three times higher maximum permeability (μ_{max}=27000) in comparison with mechanically non treated annealed sample.

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Acknowledgement

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P196 - Effect of ball milling on magnetic properties of Nd-Fe-B particles prepared by reduction diffusion

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

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Nd-Fe-B ($Nd_2Fe_{14}B$) particles with a micron size (1-3 µm) with good mangetic properties were attained using the leached monazite solution through spray dring and then reduction diffusion process. The ball milling in ethanol was utilized to refining of reduction diffused powders followed by washing with water to obtain the pure $Nd_2Fe_{14}B$ crystal phase. However, milling speed and time are very crucial to control the particle size, morphology which can be regulate the magnetic properties. At 200 rpm for 1 h, milling resulted spherical particles with average size of 1.58 µm. High corcivity value of 2504 Oe, and remanane vaue of 82 emu/g found for the $Nd_2Fe_{14}B$ particles obtained with milling conditions as 200 rpm for 1 h. The prepared $Nd_2Fe_{14}B$ particles are valuble due to their superior magnetic properties as well as its fabrication processes.

P197 - Effect of Chemical Pressure on Magnetic and Magnetocaloric Properties of La(1-x)PbxMnO3±δ

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

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The author has chosen not to publicise the abstract.

Field 5

Field 6

P198 - Effect of fluctuations suppression on magnetocaloric effect near magnetostructural phase transitions

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

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According to the recent experimental data [1], in magnetic materials with large magnetostriction, a large magnitude of the magnetocaloric effect (MCE) is observed near the phase transition. The study of the role of magnetostriction in the magnetocaloric effect is relevant and still remains open due to the complexity of taking into account all factors associated with this phenomenon. The interaction of the fluctuations of magnetic ordering and lattice deformation in an elastically isotropic matter can significantly change the behavior of the system near the phase transition point. Here we propose a new possible scenario of large role of the magnetostriction. One can significantly affect the behavior of the magnetic subsystem near the phase transition and lead to large entropy changes and, accordingly, large MCE. We have shown that at presence of the magneto-striction, the order parameter is a function of the strain. It is clear that the jump-like dependence of lattice deformation on the temperature will lead to the same behavior of the order parameter. In turn, this will lead to a more sharp dependence of the magnetization on temperature. External perturbations affecting the lattice parameters and, therefore, on fluctuations in the order parameter (ultrasound, corr-shell structure, etc.) can be considered as effective tools for the control of the MCE.

The research was supported by a grants of the Russian Science Foundation (Project No. 18-12-00415)

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P199 - Effect of Si oxide layer on the properties of PLD-fabricated Nd-Fe-B film magnets on Si substrates

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

Masaki Nakano[1] , *Tadahiko Shinshi*[2], *Masaru Itakura*[3], *Keisuke Takashima*[1], *Akihiro Yamashita*[1], *Takeshi Yanai*[1], *Hirotoshi Fukunaga*[1]

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Although a sputtering method is one of promising methods to obtain an anisotropic Nd-Fe-B film magnet on a Si substrate with a Ta buffer layer [1][2], the maximum thickness of the films is mainly 20 microns because peeling phenomenon occurred, and an increase in thickness is required to apply them to various miniaturized devices. On the other hand, we reported an isotropic Nd-Fe-B film deposited on a Si substrate with a 500 nm-thick thermal oxide layer using PLD (Pulsed Laser Deposition) method and succeeded in enhancing the thickness up to approximately160 microns [3]. In our previous experiment, the exfoliation of a Nd-Fe-B film couldn't be confirmed and mechanical destruction occurred from the inside of a Si substrate.

In this report, we investigated the adhesion between a PLD-fabricated Nd-Fe-B film and a Si substrate with a Si oxide layer such as a 1 nm-thick natural and a thermal oxide one (thickness : 20, 100, 500 nm). It was clarified that the sufficient thickness of the oxide layer is indispensable to avoid the peeling phenomenon. We also paid attention that a glass has an intermediate thermal expansion coefficient (10.0×10^{-6} K^{-1}) between a Si substrate (2.6×10^{-6} K^{-1}) and a $Nd_2Fe_{14}B$ phase (14.7×10^{-6} K^{-1}), and therefore the fabrication of a thick glass film instead of the use of a Si oxide layer was carried out. Resultantly, we could improve the magnetic properties of a Nd-Fe-B film deposited on a Si substrate.

A rotated Nd-Fe-B target was ablated using a Nd-YAG pulse laser in the vacuum atmosphere of approximately 10^{-5} Pa. To prepare a glass film on a Si substrate using the laser, a glass plate on a bulk metal was used as a target. A flash annealing method followed the deposition to crystallize an as-deposited Nd-Fe-B film with amorphous structure.

Investigation on the obtained maximum thickness of PLD-fabricated Nd-Fe-B film magnets without mechanical destruction deposited on Si substrates with various thicknesses of Si oxide layers was carried out. Nd content (Nd / (Nd + Fe)) in each Nd-Fe-B film was fixed at approximately 20 at. %. As the thickness of the oxide layer increased, the thickness of the film magnets could be enhanced after an annealing process. In addition, the peeling of a Nd-Fe-B film occurred in the case of each Si substrate with a natural oxide together with a 20 or 100 nm-thick thermal oxide layer. On the other hand, mechanical destruction from the inside of a Si substrate was always observed as the thickness of a Si oxide layer became 500 nm. It is considered that the dependence of the thickness of an oxide layer on the adhesion is attributed to the existence of a Fe-Si-O compound. We also prepared a Nd-Fe-B film on a Si substrate with a glass buffer layer.

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P201 - First-principles studies on the effect of lithiation on properties of magnetocaloric Fe2P compounds

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

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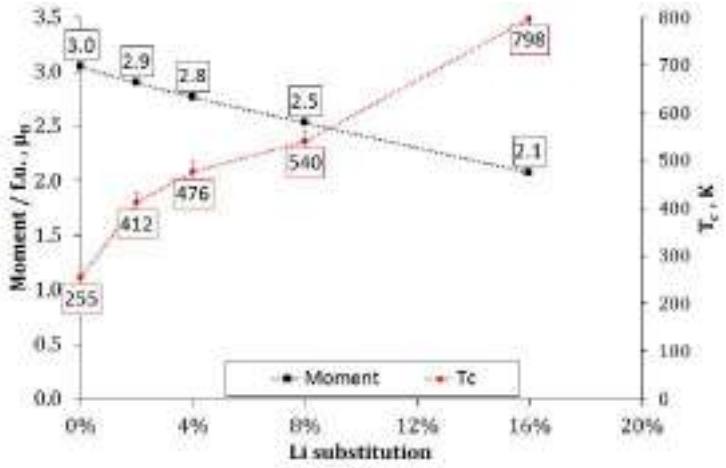
Properties of extensively studied $(Fe,Mn)_2(Si,P)$ system, well-known for its promising magnetocaloric properties are greatly influenced by the unit cell parameters of this hexagonal system, particularly by *c*/*a* ratio.
A change in the unit cell, due to the added element such as N, C, Li can induce changes in the Curie temperature and hysteresis. This allows finer control over these properties which is important for practical applications.

In this work crystal structure and magnetic properties of $Fe_{2-x}Li_xP$ are studied by a first-principles density functional theory calculations.
Two magnetic sublattices, one with bigger moment (1.99 μ_B on 3g positions) and other with lower (0.65 μ_B on 3f positions) are present in Fe_2P system. It was discovered that Li partially substitutes Fe on the 3g site, with a tendency to form clusters contrary to the initial notion of preference for interstitial occupancy. Since Li prefers 3g positions a bigger magnetic moment is lost on each substitution causing overall reduction of magnetization. The replaced iron atoms tend to form metallic Fe. The addition of Li introduces a small deformation to the unit cell without significant of change in volume. This process leads to a decrease of *c*/*a* ratio.
Preferred parameters for lithiated structures were determined by finding energy minima after series of calculations with set *a* and *c* values.
A steep increase of Curie temperature is predicted from ~250 K to ~800 K with increase of Lithium amount from 0% to 20%.



P202 - Gd2O3 nanofibers: influence of iron on magnetocaloric effect

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

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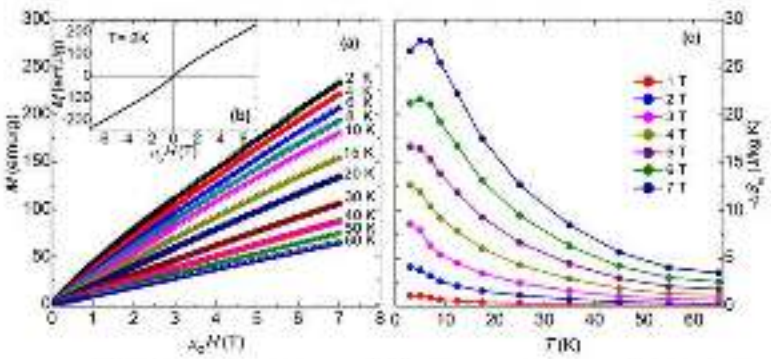
The magnetocaloric effect of *C*-type cubic gadolinium oxide Gd_2O_3 and Fe:Gd_2O_3 nanofibers with large length-to diameter aspect ratio has been investigated. The Gd_2O_3 nanofibers of 20-30 μm long and 40-100 nm in diameter were synthesized by electronspinning method. Gd_2O_3 fibers exhibited a large entropy change of 28 J/kg·K at cryogenic temperature of 5 K with a field change of 7 T. However, magnetocaloric effect significantly decreased with the presence of Fe in Gd_2O_3 nanofibers. Entropy change in Fe-doped samples was almost unchanged at various iron concentration (2-3 at.%) but it was halved compared with undoped sample. Moreover, both Gd_2O_3 and Fe-doped Gd_2O_3 samples after heating treatment at 1200 ^oC for 24 h showed even decrease of MCE. The maximum entropy change at approximation of 7 K was found to be 9.5, 10.5 and 5.8 J/kg·K with 6 T of field change for undoped, 2 and 3 at.% Fe:Gd_2O_3 samples after annealing, respectively.



P203 - Giant magnetocaloric effect driven by RKKY-exchange field in magnetic multilayers

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

Dmytro M. Polishchuk[1, 2] , *Yuliia O. Tykhonenko-Polishchuk*[1, 2], *Erik Holmgren*[1], *Anatolii F. Kravets*[1, 2], *Alexandr I. Tovstolytkin*[2], *Vladislav Korenivski*[1]

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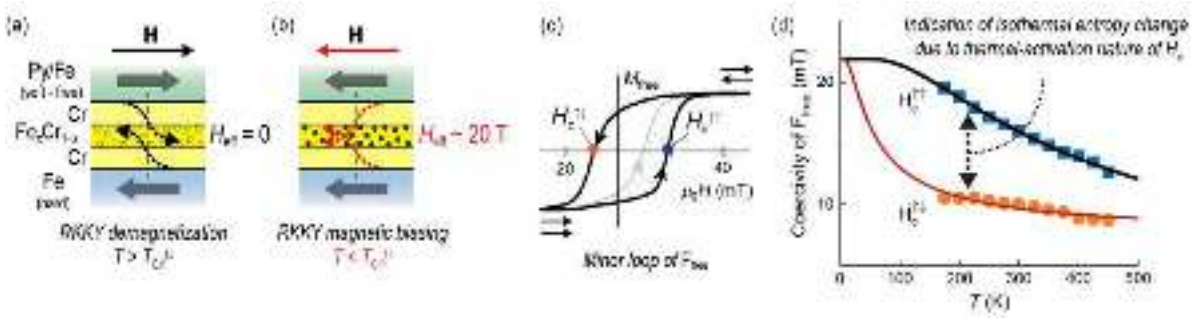
Enhancing the magnetocaloric effect (MCE) in low magnetic fields by tailoring intrinsic magnetic properties of nanostructures often yields only minor improvements [J. Appl. Phys. **107**, 144406 (2009); J. Appl. Phys. **111**, 07A930 (2012)]. The problem is that the field-induced changes in the energy balance of the systems with e.g. specially designed magnetic anisotropy properties are much lower than the energy of thermal fluctuations near room temperature [J. Appl. Phys. **107**, 09A922 (2010)]. However, an external control of magnetic exchange can lead to much more pronounced MCE because of the commensurate thermal and exchange energies. We have recently demonstrated that the MCE can be greatly enhanced when the applied field strength is amplified by the intrinsic Ruderman-Kittel-Kasuya-Yosida (RKKY) exchange in a magnetic multilayer [Phys. Rev. Mater. **2**, 114402 (2018)]. The observed large difference in the RKKY-driven coercivity of the free layer can be attributed to the isothermal entropy change in the system, resulting in a giant MCE. Our additional experiments and estimates indicate that the implemented low-field switching of the multilayer's magnetic configuration results in a thousand-fold change in the effective RKKY-exchange field focused onto a thin, low-T_C, ferromagnetic layer, which is thereby driven through its Curie transition [Figs. (a) and (b)]. As a result, the change in the magnetic state of the magneto-thermally active Fe-Cr layer considerably modifies the magnon population in the adjacent layers, detected as the difference between forward and backward field-sweep coercivities [Figs. (c) and (d)]. The estimated isothermal entropy change of –10 mJ cm^{-3} K^{-1} under an external field of ~10 mT greatly exceeds the low-field performance of the best rare-earth based materials used in the adiabatic-demagnetization refrigeration systems [Rep. Prog. Phys. **68**, 1479 (2005)]. The proposed system is promising for miniaturized refrigerators, heat exchangers, cooled micro- and nanosensors, etc.



P204 - Hard magnetic properties of melt spun NdFe10.5Mo1.5Nx for permanent magnet application

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

Alex Aubert[1] , *Rajasekhar Madugundo[1]*, ***Ana Maria Schönhöbel[1]***, *Daniel Salazar[1]*, *José Manuel Barandiarán[1, 2]*, *George Hadjipanayis[3]*

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Permanent magnets play an important role in improving the performance of devices in electric power generation (wind turbines) and transportation (electro-mobility and levitation systems). NdFeB magnets are widely used for these purposes as they exhibit the best magnetic properties among permanent magnets. The demand of Nd-Fe-B magnets rapidly increases as the world pursues energy efficiency and renewable energy. At the same time, magnetic materials are a prime example where the supply risk of strategic metals, i.e. rare-earth elements (REEs), can jeopardize the development of future technologies [1].

To overcome this issue, other compounds with a reduced amount of REE, suitable for permanent magnet applications have been investigated [2]. Among them, the $ThMn_{12}$-type structure (1:12) nitrides $R(Fe,T)_{12}N_x$ (where R=rare earth and T=Ti, Mo or V), and particularly the $Nd(Fe,Mo)_{12}N_x$, show promising intrinsic properties (i.e. Tc, Ms and Ha) [3]. However, the extrinsic ones – remanence and particularly the coercivity – still need to be optimized. These properties mainly depend on the fabrication process which determines the particle size and microstructure, directly related to the coercivity. Two methods have shown their ability in producing high coercive compounds: ball milling [4] and melt spinning [5,6].

In this work, we investigate the fabrication and nitrogenation process of melt spun $NdFe_{10.5}Mo_{1.5}$ ribbons in order to obtain high coercivity powders for bonded magnets. First, we focus our investigation on obtaining a pure 1:12 phase. In fact, the formation of α-Fe appears with the oxidation of the REE, decreasing the hard magnetic properties of the alloy. The parameters of melt spinning and nitrogenation hence play a key role to get a pure 1:12 phase. To optimize these parameters, we first melt spin the alloys at various wheel speed: 10, 30, 35, 40 and 44 m/s. The structural properties are then investigated by X-ray diffraction. An evaluation of the grain size is also carried out by SEM-FEG for each sample. Then, nitrogenation is performed for these samples. For the sample showing the highest coercivity, we perform an optimization of the nitrogenation parameters by varying the temperature and the time. The best nitrogenation conditions are found to be at 600 ºC during 3 hours for the 30 m/s melt spun ribbons once crushed into powder with particle size lower than 38µm. For this sample, we obtain a coercive field of 0.6T and a saturation polarization of 1T after nitrogenation (see Figure). These results are promising in the perspective of bonded permanent magnet application with reduced rare-earth content.

Acknowledgements
This work has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 686056 (NOVAMAG).

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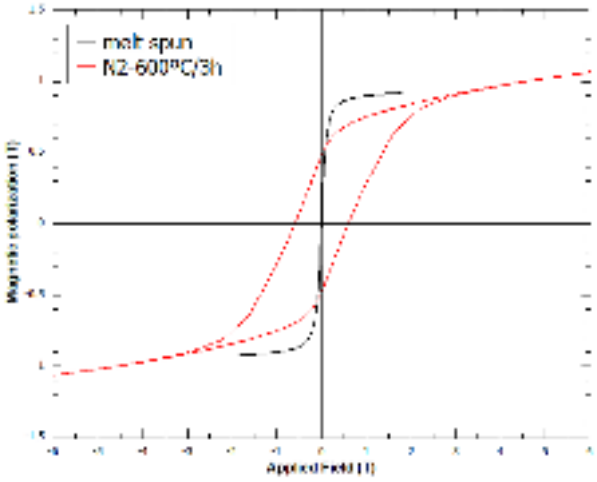
melt spun
N2-600°C/3h

P205 - High-field measurements of the thermal response, magnetization and strain in FeRh-based alloys

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

Alisa Chirkova[1] , *Konstantin P. Skokov[1], Yuri Skourski[2], Alexey Y. Karpenkov[1, 3], Nikolay V. Baranov[4, 5], Tino Gottschall[2], Oliver Gutfleisch[1]*

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Solid state cooling is an environmentally safe alternative to existing vapor compression refrigeration [1]. It is based on a property of magnetic materials to emit or absorb heat under the action of a magnetic field – the magnetocaloric effect (MCE). Revealing the mechanisms of the giant MCE at first-order transitions assists the development of magnetocaloric materials. Equiatomic FeRh compounds have a very high reversible MCE at a first-order magneto-structural phase transition from a low temperature antiferromagnetic (AF) state to the ferromagnetic (FM) state: under cyclic conditions, i.e. accounting for the hysteresis effect, it exceeds the MCE in Gd [2]. The transition can be tuned within a broad temperature range by substitution of Fe or Rh by other d-elements [3], e.g. a lower transition temperature is obtained by doping the binary compound by Ni, Co or Pd. Despite the high cost of the raw materials, FeRh is a perfect model object for studies of the first-order-transition physics and interaction between the structural and magnetic responses, from both experimental and theoretical points of view.
Magnetization M, thermal response ΔT and magnetostriction λ of two FeRh-based alloys with a substitution by other d-elements have been measured under adiabatic and isothermal conditions, in pulsed magnetic fields up to 30 T and static fields up to 14 T, respectively. Field and temperature dependences of M, ΔT and λ will be presented and the connection between these physical properties will be discussed, as well as the relevance of this approach for materials with magnetostructural transitions.

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P207 - Hydrothermal Decomposition of Chromium Trioxide to Form Magnetic Metastable Chromium Dioxide

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

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Investigation and development upon magnetic materials are important as they represent a broad span of applications such as energy storage, energy conversion, information storage, transportation technologies etc[1]. In the information storage industry chromium dioxide has been extensively used for audio tapes as it is a soft magnet with a low coercivity which enables the material to readily align with an applied external magnetic field. Sony recently showed the potential of audio tapes for information storage as they developed a magnetic tape material with a capacity of 201 Gb/in^2 which is 11.6 times as much as a Blue-ray dvd[2]. Prior research conducted has been relatively scarce compared to research conducted on permanent magnets[3] and primarily attempted with a trial-and-error approach which leaves behind a near undiscovered field of research. The magnetic properties of chromium oxides vary strongly, with chromium dioxide being the only one with ferromagnetic properties. Hydrothermal synthesis is a good technique to utilize as it is highly flexible to adjust on reaction parameters for corresponding products. Also, hydrothermal synthesis has its advantages of being cheap, energy efficient and simple to use.

In the present work, the formation and growth of chromium dioxide nanorods from chromium trioxide dissolved in water using hydrothermal- and oleylamine- synthesis routes. Additionally, the decomposition of Chromium dioxide under ambient pressure at elevated temperature have been studied by *in-situ* X-ray diffraction, *ex-situ* X-ray diffraction, vibrating sample magnetometer (VSM) and thermogravimetric analysis (TGA). The precursor chromium trioxide crystalline structure is an orthorhombic structure whereas the precipitate chromium dioxide is a tetragonal structure isostructural with rutile. The tetragonal chromium dioxide is surrounded by phases of lower formation energy therefore it is a metastable phase at ambient condition[4]. Saturation magnetization of chromium dioxide nanorods are in the range of 40-100 emu/g at room temperature depending on the particle size and the Curie temperature is about 126 °C. Preparation of pure chromium dioxide nanorods is important for studying its intrinsic properties and for applications in information storage techniques, energy storing solutions, exchange spring magnets and spintronic devices.

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P208 - Increasing the energy product by combining two types of SrFe12O19 nanocrystallites

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

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The M-type hexaferrites have drawn much attention as hard permanent magnets due to the combination of good magnetic properties, chemical stability, and low cost. In fact, $MFe_{12}O_{19}$ (M=Sr, Ba, Pb) represent 85 % (by weight) of the global sales of all permanent magnets.[1] Especially $SrFe_{12}O_{19}$ (SrM) is interesting due to its non-toxicity and a relatively large theoretical BH_{max} of 45 kJ/m^3.

$SrFe_{12}O_{19}$ can be made as magnetic single domain nanoparticles by which the magnetic performance can be optimised. The magnetic performance depends, among others, on the morphology, which for example influences the demagnetization factor and the particle's ability to align. It is important that the particles are easy to align, since they are compacted into pellets to become a useful magnet for applications. The morphology of the crystallites is highly dependent on the synthesis method: hydrothermal synthesis forms large plate-like nanoparticles, whereas a NaCl embedded sol-gel synthesis results in small platelets.[2]–[5] The large plates are easily aligned but have a relatively low coercivity at 130 kA/m, whereas the smaller plates have a high coercivity around 500 kA/m, but the alignement is relative poor, when compared with the bigger ones.

In present work, the $SrFe_{12}O_{19}$ powder was made using the two above mentioned synthesis methods. The powders were mixed in order to investigate, if the large plates are able to support the smaller plates to align. Furthermore, the small high-coercivity plates may have a positive impact on the net coercivity when the powders are sintered together. In that case, the best of two world will be combined to enhance the magnetic properties: High alignment and high coercivity leading to a large BH_{max}.

The powders were sintered in a conventional oven and by using Spark Plasma Sintering (SPS) press to ensure intergrowth between the powder and make them act as single phase. It was found, that the alignment of the SPS compacted pellets were improved when adding only 25 % autoclave synthesized powder. Furthermore, the sol-gel synthesized powder improved the coercivity relative to the pure compacted autoclave prepared powder

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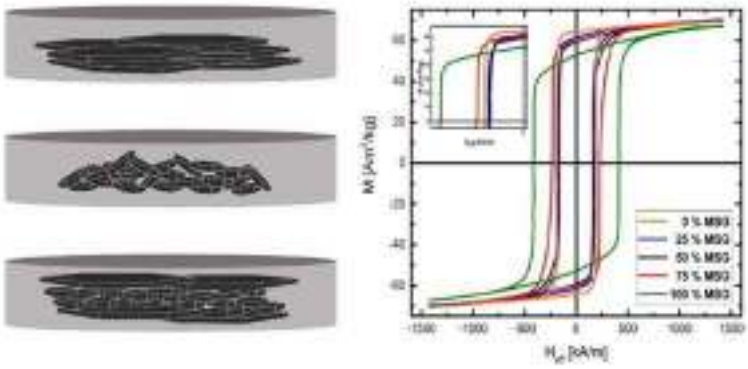
M [Am²/kg]
H_ext [kA/m]
3 % MSG
25 % MSG
50 % MSG
75 % MSG
100 % MSG

P209 - Interaction field in nanocrystalline Sm-Fe-Ti alloys

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

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Alloys of Sm-Fe-Ti were synthesized by mechanical milling for five hours, the hysteresis loop for nanocrystalline Sm-Fe-Ti alloys shows a bistable behavior partly repressed resulting from the presence of an effective field. The magnetic properties of remanence for nanocrystalline Sm-Fe-Ti alloys were measured to study the interactions between nanograins. By another hand, the plots of Henkel confirm the structural disorder of the nanocrystalline Sm-Fe-Ti alloys obtained by mechanical milling for five hours of milling, while for nanocrystalline Sm-Fe-Ti alloys obtained by mechanical milling for five hours of milling and annealing the effects dominate was due the mean field. For the study of magnetic interactions in the nanocrystalline Sm-Fe-Ti alloys also, Mössbauer Spectroscopy was used.

P210 - Interplay between chemical order and magnetic properties in L10 FeNi phase (tetrataenite)

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

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The high-cost of rare-earth-based permanent magnets has sparked great interest to explore alternative magnetic materials that are free from rare-earth elements. One interesting candidate in this quest is a chemically-ordered $L1_0$ $Fe_{50}Ni_{50}$ phase (tetrataenite) found in iron meteorites. The laboratory synthesis of the ordered phase is hindered because of the slow diffusion of atoms at relatively low order-disorder transition temperature. Since its discovery, several attempts were made to achieve a high degree of chemical order. Nevertheless, synthesis of a fully ordered system remains challenging.

Using first-principles-based density-functional theory calculations in combination with Monte Carlo (MC) simulations, we investigate the interplay between chemical order and the magnetic properties of the $L1_0$ FeNi phase. Our calculations for fixed ferromagnetic and paramagnetic configurations demonstrate a strong effect of the magnetic order on the chemical order-disorder transition temperature. Conversely, our results indicate that the chemically-ordered phase has a higher magnetic order-disorder transition than the chemically-disordered phase. Furthermore, we also investigate dependence of the magneto-crystalline anisotropy on the chemical long range order. Our results show that the magnetic properties in this alloy are strongly influenced by the degree of chemical order and vice-versa.

P213 - Large magnetocaloric effect at room temperature in La0.5Pr0.2Ca0.1Sr0.2MnO3 manganite

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

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The praseodymium doped $La_{0.7}Ca_{0.1}Sr_{0.2}MnO_3$ compound has been investigated as a potential candidate for magnetic oxide room temperature magnetic refrigeration. X-ray diffraction measurement reveals that the sample is crystallized in the orthorhombic structure with Pnma space group. The atomic concentration of the material has been demonstrated using Rutherford backscattering techniques. Also the ionic state of Manganese (Mn), present in the material was investigated using X-ray Photoelectron Spectroscopy. The isothermal entropy change and the relative cooling power were found to be 4 J/kg K and 372 J/kg, respectively, for a magnetic field change of 5T. From the comparison with Gd data as well as technological point of view, our data underline that our material can be considered as a relevant potential candidate material to be used in cooling system based on the magnetic refrigeration.

P214 - M-Type SrFe12O19 ferrites obtained directly from α-Fe2O3 as Fe sources

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

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As a kind of typical permanent magnet, $SrFe_{12}O_{19}$ has been widely used in variety of technical fields like household appliances, automobile, microwave devices and so on primarily due to its good thermal/chemical stability, moderate value of magnetization, a high Curie temperature and low production costs[1-3]. It has to be noted that the maximum energy product of $SrFe_{12}O_{19}$ is far less than the best permanent magnets available in the market like $Nd_2Fe_{14}B_3$ or Sm-Co compounds [4]. Research has been ongoing to improve the magnetic properties of this M-Type hexaferrite, so that the stress on employing rare earth based permanent magnets in various applications could be reduced. Currently, except preparing composite ferrites by employing exchange-coupling interaction between magnetically hard and soft phases, ion substitution is another extensively investigated way to improve the magnetic properties of $SrFe_{12}O_{19}$. In this context, it would be better to investigate another way of improving the magnetic properties of $SrFe_{12}O_{19}$ by employing α-Fe_2O_3 as a source for Fe.Studies describing the formation of magnetic nanoparticles are often found in literature, however little attention is given to turning these nanomagnets into bulk permanent magnets for applications. In recent studies self assembly of platelet shaped $SrFe_{12}O_{19}$ have been reported using spark plasma sintering (SPS) [5-8]. The spark plasma sintering studies involve a tedious synthesis step, where $SrFe_{12}O_{19}$ and a second step, where the nanocrystallites are compacted into bulk magnets.
We report the synthesis of M-Type $SrFe_{12}O_{19}$ hexaferrites directly from hematite (α-Fe_2O_3) as Fe sources. The hematite is synthesized by hydrothermal method to control size and shape of the nanocrystallites. The hydrothermal synthesis had been carried out at three different temperatures, T_s = 140, 160 and 180 °C. The as prepared powders comprising the Strontium precursor and hematite (α-Fe_2O_3) has been subjected to Spark Plasma Sintering (SPS) in order to directly form a compact $SrFe_{12}O_{19}$ pellet. X-Ray diffraction patterns were analyzed with Reitveld Refinements. The magnetic properties and morphology of the synthesized particles is subjected to a detailed study. These would be discussed in detail during the conference.

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P215 - Magnetic and structural properties of CeFe12-xMnx

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

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Out of the 4*f* elements Cerium is by far the most abundant, and thus it has the least inherent supply risk.
Thereby, Ce based permanent magnets could potentially be viable “gap magnets”, filling an important gap of high flux density Nd based magnets and low flux density magnets such as ferrites and alnico. Permanent magnets typically need a large magnetocrystalline anisotropy to retain magnetization upon demagnetization. This anisotropy can be achieved through the 3*d*-4*f* exchange interactions as in $Nd_2Fe_{14}B$, or potentially as in Ce-3*d* compounds.

Recently, Pauli paramagnets, such as $CeCo_3$ have been shown to be able to be “rehabilitated” into ferromagnets with large anisotropy through addition of Mg [1], and their transition temperature is well above room temperature. These materials are found to be near a ferromagnetic instability through band structure calculations [2] and it is possible to tip them over to a ferromagnetic state with large anisotropy. Here, we have focused on the Ce-Fe-Mn system [3] and more specifically on the τ_2 phase of $CeFe_{12-x}Mn_x$ ($5 \leq x \leq 9$). It crystallizes in the tetragonal *I*4/*mmm* space group and is of the $ThMn_{12}$ structure type.

$CeFe_5Mn_7$ and $CeFe_7Mn_5$ have been prepared through solid state reaction and their crystallographic parameters have been found (see Table 1) through Rietveld analysis of X-ray diffraction data. However, since the X-ray scattering power of Fe and Mn is too similar, it is not possible to fully refine the crystal structure. As can be seen in Figure 1 the samples display antiferromagnetic ordering (x=7, T_N = 162 K), and likely ferrimagnetic ordering (x=5, T_C=126 K). Further work will utilize neutron diffraction to resolve the crystal and magnetic structure. The data from the magnetic structure will be used as input for ab initio calculations to explore the potential as a large anisotropy system.

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Table 1: Selected crystallographic and magnetic properties of $CeFe_{11}Mn_x$

Sample	a (Å)	c (Å)	Proposed magnetic ordering
$CeFe_9Mn_2$	8.5574(2)	4.7574(1)	T_N = 162 K
$CeFe_9Mn_3$	8.5157(4)	4.7521(2)	T_C = 126 K

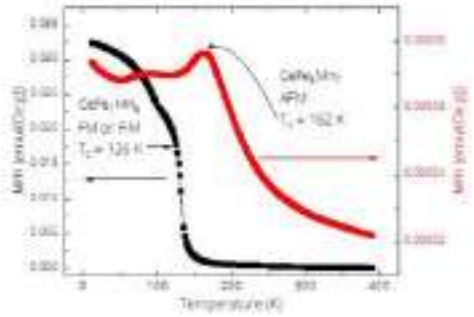

Figure 1: Magnetization versus temperature for $CeFe_9Mn_2$ (○) and $CeFe_9Mn_3$ (○) showing antiferromagnetic and ferromagnetic transition temperatures.

P216 - Magnetic degradation of Sm2Co17 magnets for use in electrical machines for aeronautical applications

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

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Due to their low reversible temperature coefficients of remanence and coercivity and their resistance to corrosion without a surface coating, Sm_2Co_{17}-type rare earth permanent magnets have remained the material of choice for applications where strong, stable fields are required in demanding environments over broad temperature ranges. One such application is within hybrid-electric propulsion systems for commercial aircraft, where they may be utilised in permanent magnet motors and/or generators. This work has aimed to assess the degree of magnetic and mechanical degradation of commercial grade Sm_2Co_{17} magnets if used in such an application. The aim is to produce experimental data that can feed into machine simulation models to aid in machine design. In the conditions likely to be seen by a Sm_2Co_{17} magnet during standard operation, this work has shown that no significant degradation of magnetic properties will occur. Despite the brittle nature of these sintered magnets, the stresses during operation are unlikely to cause mechanical failure.

However, when pushed to higher temperatures, oxidation of the surface results in an irrecoverable loss in magnetic properties. This is caused by the growth of an ‘internal oxidation zone’ (IOZ) from the surface into the bulk, transforming the hard magnetic Sm_2Co_{17} matrix phase into a soft magnetic Fe-Co phase [1,2]. A comparison of the degradation behaviour and the growth rate of the IOZ between commercial grades with significant variation in grain size, has been undertaken. If a link between microstructure and oxidation behaviour can be found, a microstructure could be tailored for high temperature applications.

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P217 - Magnetic interactions in nanocrystalline Sm-Y-Co alloys

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

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Magnetization curves were measured with the methods of isothermal remanent magnetization (IRM) and by the method of direct current demagnetization (DCD) for nanocrystalline $Sm_{0.5}Y_{0.5}Co_5$ alloys. Performed was the study of the magnetic properties for nanocrystalline $Sm_{0.5}Y_{0.5}Co_5$ alloys with the Physical Property Measurement System (PPMS), the alloys exhibit a high remanent coercivity of 2.1 MA/m. For nanocrystalline $Sm_{0.5}Y_{0.5}Co_5$ alloys, the remanence susceptibilities proportion was $\chi_{DCD}/\chi_{irr}=4.6$ that characterize the alloys with the presence of magnetic interactions. For the nanocrystalline $Sm_{0.5}Y_{0.5}Co_5$ alloys were studied magnetic interactions by measuring curves ΔM vs. the magnetic field, showing magnetic interactions.

P218 - Magnetic properties and cation distribution of Ni1-xZnxFe2O4 nanocrystallites

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

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The magnetic properties of ferrimagnetic cubic spinel ferrites ($M^{2+}Fe_2O_4$, M=Mn, Co, Ni and Zn) are heavily dependent on the distribution of cations on the different crystallographic sites. The ferrimagnetism stems from two sub-lattices with tetrahedral and octahedral sites, respectively, with an antiparallel orientation of the atomic magnetic moments with respect to each other. The magnetic properties of the material therefore not only depend on the chemical composition, but also on how the cations are distributed on the different crystallographic sites. The affinity of the different cations for one or another site depends on several parameters, such as their relative atomic radius, electronegativity, charge and crystal field splitting. For most transition metal cations, the preferred site has been extensively investigated for bulk material. When it comes to nanoparticles, only few studies of the cation size distribution exist, especially when considering mixed ferrites with two different divalent species. The characterization of the site occupancies is difficult due to the low X-ray scattering contrast between neighboring transition metal cations making them hardly distinguishable by conventional X-ray diffraction techniques.

We have investigated the cation distribution and its influence on the magnetic properties in $Ni_{1-x}Zn_xFe_2O_4$ (x=0-1) nanoparticles, prepared by a hydrothermal synthesis method in a steel autoclave. For the analysis of the cation site distribution, a combined Rietveld refinement of neutron powder diffraction, high resolution synchrotron powder X-ray diffraction (PXRD) and in-house PXRD data is used. The combination of datasets from different X-ray and neutron sources provides enough scattering contrast between the transition metal cations to provide a robust structural model of the investigated samples aided by resonant scattering and differences in neutron scattering lengths. It is shown that in spite of the preference of Zn^{2+} cations to occupy only tetrahedral sites in bulk materials, Zn^{2+} occupies up to 28 % of octahedral sites in the investigated as-prepared nanoparticles. However, annealing of the particles leads to a redistribution of the cations. The composition with the highest saturation magnetization is $Ni_{0.6}Zn_{0.4}Fe_2O_4$ with a saturation magnetization of 66.02(7) $Am^2\ kg^{-1}$. The saturation magnetization calculated from cation site distributions and site magnetic moments determined by Rietveld refinement was compared to the saturation magnetization measured with a vibrating sample magnetometer (VSM). The highest saturation magnetization agrees well, supporting the validity of assumptions made for the model of the cation site distributions. The combination of different powder diffraction datasets in a single Rietveld refinement are found to be a robust way of describing the cation distribution in challenging systems, consisting of elements with similar scattering power.

P219 - Magnetic properties enhancement of spark plasma sintered (MM)–FeCo–B magnets

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

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The strongest and mostly used permanent magnets available today are based on Nd-Fe-B alloys with additions of Dy, Pr, Tb, etc. However, elements such as Nd and Dy have become part of critical rare-earths category due to the cost pressure and availability. Therefore, in the recent years, many investigations have indicated that it is feasible to solve this problem by replacing critical rare-earths with others more abundant and low cost rare-earth elements, such as Ce, La or even Misch Metal (MM) which is a mixture of rare earths Ce, La, Nd and Pr.

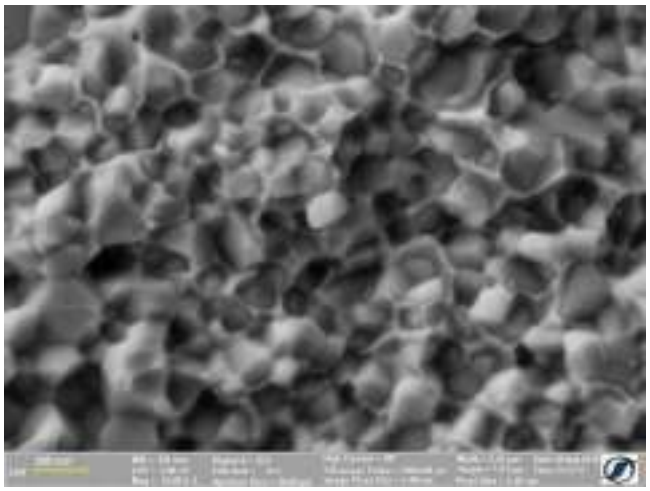
In this paper we report the effect of the MM content on the microstructure and magnetic properties of MM-FeCo-B permanent magnets prepared by SPS consolidation of the ball-milled powders obtained from $MM_{12+x}Fe_{80-x}Co_2B_6$ (x=0, 4, 8) nanocrystalline melt-spun ribbons. The evolution of the microstructure and magnetic properties was systematically investigated in ribbons, milled powders as well as in the spark plasma sintered samples. We found that the structure of the MM–FeCo–B permanent magnets is multi-phasic, typically consisting of a primary $MM_2Fe_{14}B$ phase with impurity phases of Fe, $(Ce,La)_2O_3$ and La_2O_3. By controlling both the composition and annealing conditions of ribbons we have managed to obtain permanent magnets with a good isolation of 2:14:1 grains by intergranular phases without ferromagnetism (Fig.1).

The highest values of coercivity of about 10.1 kOe and (BH)max of about 13.6 MGOe at room temperature was obtained in $MM_{20}Fe_{72}Co_2B_6$ SPS-compacted magnets.

Acknowledgements

This work was supported by the Romanian NUCLEU Programme (Project PN 19 28 01 01)

Fig.1 SEM micrograph of $MM_{20}Fe_{72}Co_2B_6$ SPS-compacted magnets.



P220 - Magnetic property improvement of melt spun LaCo5 ribbons with Y substitution

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

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Developing novel permanent magnetic materials is crucial in modern technology due to ever-increasing demand for the wide applications. The rare-earth (RE)-containing alloys with the excellent magnetic properties have been extensively developed. After price surge of critical RE elements in 2010, it is significant to explore the RE-free or other abundant RE-containing permanent magnetic materials possible for industrial applications. La, one of the most abundant RE elements, is much cheaper than Nd, Pr, Sm, and Y due to less usage. Unlike $SmCo_5$ alloy, $LaCo_5$ has attracted less attention due to the easy formation of impurity phases, such as $LaCo_{13}$, La_5Co_{19}, and La_2Co_7, despite its good magnetically intrinsic properties. Very few studies related to the magnetic properties of $LaCo_5$ alloys are available, and they were only focused on ball-milling and mechanochemical synthesis. However, so far no report concerns on the magnetic properties of $LaCo_5$ alloys prepared by melt spinning. Recently, YCo_5 alloy has drawn much attention due to potentially surplus Y and the attractive permanent magnetic properties, originated from high stability of 1:5 phase. In this work, effects of C doping and Y substitution for La on the magnetic properties, crystal structure, and microstructure of $La_{1-x}Y_xCo_{5-y}C_y$ alloys prepared by melt spinning are studied.

Very low ${}_iH_c$ = 0.1 kOe is obtained for binary $LaCo_5$ ribbon, and slightly improved to 0.1-0.3 kOe by doping C. Most interestingly, permanent magnetic properties of $LaCo_{4.7}C_{0.3}$ ribbons are significantly enhanced by Y substitution for La. They are increased from B_r = 1.9 kG, ${}_iH_c$ = 0.2 kOe, $(BH)_{max}$ ~0 MGOe for x = 0 to B_r = 3.5 kG, ${}_iH_c$ = 1.9 kOe, $(BH)_{max}$ = 1.1 MGOe for x = 0.1, and remarkably enhanced to B_r = 4.2-5.4 kG, ${}_iH_c$ = 8.0-14.5kOe, $(BH)_{max}$ = 4.0-6.6 MGOe for x = 0.25-1. The x-ray diffraction analysis indicates that considerable amount of impurity phases, including 5:19 and 1:13 phases is coexisted with hexagonal 1:5 phase for Y-free ribbons, and leads to low coercivity. The 5:19 and 1:13 phases diminished by Y substitution, and completely suppressed for x > 0.75 indicate Y substitution could be effective in suppressing the formation of impurity phases, stabilizing 1:5 phase, and accordingly enhancing permanent magnetic properties. The slightly changed lattice constants by Y substitution analyzed by XRD and the increased T_C with Y substitution analysized by thermomagnetic analysis reveal the entrance of Y into the crystal structure of 1:5 phase. Y entrance into 1:5 phase may improve magnetocrystalline anisotropy field and thus contribute to coercivity enhancement, and the increased T_C of 1:5 phase with Y substitution is beneficial in improving the thermal stability of the magnet. Transmission electron microscopy results shows C-doping is helpful in refining the grain size to 10-30 nm and accordingly remarkable improvements of ${}_iH_c$, the squareness of demagnetization curve, and therefore $(BH)_{max}$. Summarized with the above results, the suppressed impurity phase and increased M_s and H_A with Y substitution and the refined microstructure with C-doping improves the permanent magnetic performance of melt spun $LaCo_5$ ribbon.

P221 - Magnetization and Magnetocaloric Effect of MnFe4Si3 and Mn5Ge3

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

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The magnetocaloric effect forms the basis of magnetocaloric refrigeration, which is a novel energy efficient and environmentally friendly method for cooling that has the potential to replace conventional vapor compression technologies [1]. The MCE is based on entropy changes of magnetic materials in an applied magnetic field, which lead to a change of temperature of the material.

$Mn_{5-x}Fe_xSi_3$ as well as Mn_5Ge_3 compounds have been investigated as promising candidate materials, where hexagonal $MnFe_4Si_3$ and Mn_5Ge_3 are of special interest as they have a transition from the paramagnetic to a ferromagnetically ordered state close to 300 K and they feature a modestly large magnetic entropy change and contain only environmentally unproblematic and abundant elements.

In this contribution, we will present the direct measurements of the adiabatic temperature change (ΔT_{ad}) in pulsed magnetic fields using a home-built experimental set-up in HLD [2]. This technique provides nearly adiabatic conditions during the measurements and the sample is in conditions which are close to the real process used in applications. The results will be compared with the ones obtained from the magnetization and heat capacity measurements in static magnetic fields. For $MnFe_4Si_3$, this will also be combined with the results from neutron depolarization experiments [3] carried out using Cryopad setup at single crystal diffractometer POLI at MLZ [4].

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P222 - Magnetization in W-hexaferrites by neutron powder diffraction and magnetometry.

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

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Hexaferrites are a class of iron containing magnetic oxides, which are widely used as magnetic materials. Most common is M-type hexaferrites, but other types are also interesting, particularly the W-type hexaferrites (WHFs) $SrMe_2Fe_{16}O_{27}$, *Me* = (Mg, Co, Ni and Zn). These have a high potential for permanent magnet applications due to their large magnetocrystalline anisotropy and high cation tunability, additional potential applications include multiferroics (Song *et al.*, 2014) or magnetocaloric effect (Naiden & Zhilyakov, 1997). However, WHFs are rarely studied due to their challenging synthesis, and little is known regarding their complex structural and magnetic characteristics. Here, a series of WHFs (*Me* = Mg, Co Ni and Zn) were synthesized and their crystal and magnetic structures were investigated (Mørch M. I. *et al.*, 2019). Rietveld refinements of a constrained model to the X-ray and neutron powder diffraction data were carried out in order to determine the atomic positions of the *Me* atoms within the structure, along with the magnetic dipolar moment of the individual sites. All four investigated WHFs exhibit ferrimagnetic ordering. For Mg, Ni, and Zn substitution, the magnetic moments are found to order colinearly and with the magnetic easy axis along the crystallographic *c*-axis. In $SrCo_2Fe_{16}O_{27}$, however, the spontaneous magnetization changes from uniaxial to planar, with the moments aligning in the crystallographic *ab*-plane. Macromagnetic properties were measured using a vibration sample magnetometer. The measured saturation magnetization (M_S) of the different samples follows the same trend as the calculated M_S extracted from the refined magnetic moments of the neutron powder diffraction data. This agreement consolidates the robustness of the structural and magnetic Rietveld model, as a direct correlation exist between the calculated M_S and the refined atomic positions and occupancies of the different *Me* on specific crystallographic sites.

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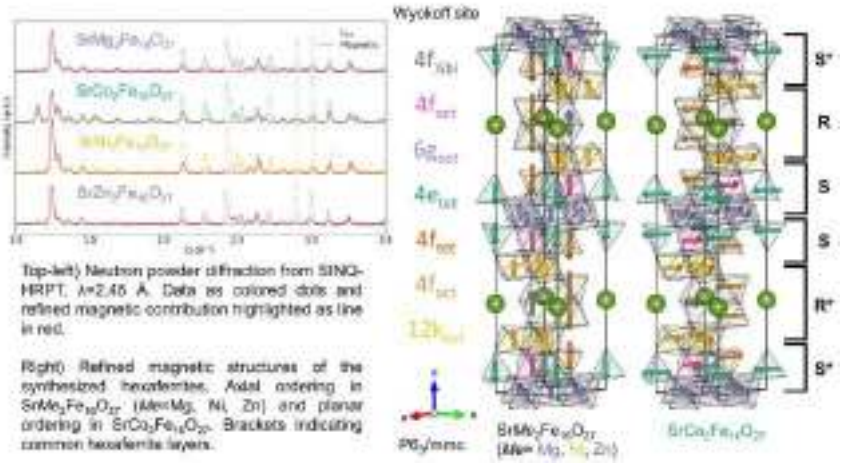

Top-left) Neutron powder diffraction from SINQ-HRPT, λ=2.45 Å. Data as colored dots and refined magnetic contribution highlighted as line in red.

Right) Refined magnetic structures of the synthesized hexaferrites. Axial ordering in $SrMe_2Fe_{16}O_{27}$ (Me=Mg, Ni, Zn) and planar ordering in $SrCo_2Fe_{16}O_{27}$. Brackets indicating common hexaferrite layers.

P223 - Magnetocaloric effect in cyclic magnetic fields: degradation and frequency dependency

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

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Since a refrigerating machine is a device with periodic sweeps of cycles, there is a substantial need to study the magnetocaloric properties of materials under repeated cyclic exposures to magnetic fields. Magnetocaloric properties of the materials under single and repeated application of the cyclic magnetic fields can exhibit significantly different behavior for a variety of reasons. Furthermore, the magnetocaloric properties of materials with a magnetostructural phase transition in cyclic fields can degrade over time. Obviously, practical applications require materials with time-stable and no frequency dependence magnetocaloric properties.
In this work, we present results of studying the magnetocaloric properties in various families of promising magnetic materials (La(FeSi)13-H, MnFe(AsP), FeRh, Gd5(GeSi)4 and Ni-Mn-X Heusler alloys in cyclic magnetic fields with frequencies up to 20 Hz. The dependency of the MCE on the frequency of alternating magnetic field and the effect of prolonged action of cyclic magnetic fields on magnetocaloric properties of the materials are studied in detail.
It was found that in most of the materials studied, the MCE value decreases with increasing frequency of change of the magnetic field. This means that for each material there is an upper limit of the frequency at which the cooling efficiency has a maximum. It was also found that in most materials the effect of degradation of the magnetocaloric properties is observed, namely, a decrease in the magnitude of the MCE, and in some cases a change in the temperature of the maximum of the effect under the action of a cyclic magnetic field. The effect of degradation is different in the studied materials. Namely, in some materials, this effect is irreversible at room temperatures and, in order to restore the initial properties of the alloy, a thermal procedure of heating the sample above its Curie point is required (FeRh). And in some cases, the original properties recover when approaching the austenitic phase at room temperatures (Ni-Mn-X), or by removing the external cyclic magnetic field. An explanation of the observed behavior of the MCE in cyclic magnetic fields is given in the report. It is shown that the degradation effect results in some limitations for using the magnetocaloric materials in magnetic cooling technology.

The research was supported by a grant of the Russian Science Foundation (Project No. 18-12-00415).

P224 - Magnetocaloric Effects of Nanocrystalline (Gd or Dy)VO4 Synthesized by Hydrothermal Methods

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

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Vapor-compression refrigeration system (VCRS) technology has practical limitations to improve against environmental destruction such as destruction of ozone layer and global warming. Recently, proposals and researches on new cooling technologies to replace these past cooling technologies have been underway. Magnetocaloric effect (MCE) is a magneto-thermodynamic phenomenon where the temperature changes when material is exposed to changing magnetic fields. These properties can be combined with cooling technology. The cooling technology with MCE has been used in a variety of cryogenic applications, such as cryogenic technology in space science, liquefaction of hydrogen or other fuel gases. In this study, we investigate the MCE properties RVO_4 (R = Gd and Dy) with nanostructures synthesized by microwave-assisted hydrothermal methods. The magnetic transition temperatures (Tc or T_N), effective magnetic moment, magnetic entropy changes, and relative cooling power (RCP) were obtained from MPMS measurements. It was found that RVO_4 nanopowders have intrinsic antiferromagnetic-paramagnetic and ferromagnetic-paramagnetic second phase transition for $GdVO_4$ and $DyVO_4$, respectively, indicating that they can be applied for cryogenic magnetic cooling materials such as hydrogen gas liquefaction [1].

Acknowledgements

This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (NRF-2019R1D1A3A03017434).

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P225 - Magnetostructural investigation of exchange-spring composites by combined X-ray & neutron scattering

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

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An ideal permanent magnet should be highly resistant to demagnetization (high coercivity H_C) and have a high value of maximum internal magnetization (high saturation magnetization M_S). In the real world, a single-phase magnet might not simultaneously possess high values of these magnetic properties. It is usually observed that rare-earth-free permanent magnets have either high H_C with low M_S ('hard' magnet – hard to demagnetize) or, low H_C with high M_S ('soft' magnet). The hexaferrite compound $SrFe_{12}O_{19}$ has relatively high H_C (due to pronounced magnetocrystalline anisotropy) – making it a 'hard magnetic' phase, but a higher M_S value would be highly appreciated.[1] Spinel ferrites (AB_2O_4 type) on the other hand, are 'soft magnetic' phases *i.e.* low H_C, but potentially strongly magnetic. Enhancement of H_C and M_S values simultaneously could be achieved by the mixing of two different nanomagnetic phases (hard-soft composite) – known as an exchange-spring nanocomposite.[2,3] The resultant magnetic properties of such composites would be hierarchically emergent – arising from the underlying atomic structure, via the nanoscale morphology of the individual particles, to the microscopic structural coupling of the different phases. While various studies have focused on the synthesis of exchange-spring magnets and their magnetic characterizations, detailed structural investigations are limited.[3–5] We report a comparative investigation on exchange-spring nanocomposites of $SrFe_{12}O_{19}$ (SFO – hard magnet) and $Zn_{0.2}Co_{0.8}Fe_2O_4$ (ZCFO – soft magnet) prepared by two different synthesis routes: mechanical powder mixing and sol-gel coating. *M-H* loops from VSM magnetometry showed a dependence of the exchange-coupling behavior on the technique used for nanocomposite formation. Crystallographic and magnetic structure of the samples were analyzed by combined Rietveld refinement of data from synchrotron X-ray diffraction (SR-XRD performed at MS X04SA beamline @ SLS) & thermal neutron powder diffraction (NPD performed using HRPT diffractometer at SINQ spallation source @ PSI). The difference in the scattering interaction for X-rays and neutrons allowed for complementary, robust & accurate structural analysis.[5,6] Combined Rietveld refinement of SR-XRD and NPD data of the nanocomposites enabled extraction of accurate values for lattice parameters, atomic positions, thermal motion, cation distribution, magnetic moments and microstructure. A detailed understanding of these correlated magnetostructural properties would be instrumental towards improving the performance of permanent magnets based on exchange-spring nanocomposites.

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P226 - Magnetothermal properties of amorphous alloys $Fe_{63.5}M_{10}Si_{13.5}B_9Nb_3Cu_1$ (M = Cr, Mn, Fe, Co, Ni)

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

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Magnetic refrigeration based on magnetocaloric effect (MCE) is a promising technology to replace the traditional refrigeration using vapor compression [1,2]. The well-known soft magnetic alloys of Finemet type can be considered as magnetocaloric materials having low cost and possessing acceptable operational performance. The effect of 3*d* metal partial substitution for Fe on the magnetocaloric effect of amorphous alloys $Fe_{63.5}M_{10}Si_{13.5}B_9Nb_3Cu_1$ (M = Cr, Mn, Fe, Co, Ni) has been studied. The metal glasses in the form ribbons were prepared by melt-spinning. Magnetic measurements were performed using a vibration magnetometer (Lake Shore VSM 7407) with a maximum magnetic field of 17 kOe in the temperature range from 298 to 700 K, and also in Helmholtz coils producing a uniform magnetic field up to 100 Oe.

In amorphous alloys $Fe_{63.5}M_{10}Si_{13.5}B_9Nb_3Cu_1$, the Curie temperatures were found of 317 K, 386 K, 579 K, 626 K, and 579 K for M = Cr, Mn, Fe, Co, Ni, respectively. The magnitude of the MCE can be expressed indirectly through the isothermal magnetic entropy change (ΔS_m). When Fe atoms are substituted by Ni or Co, the maxima value of $-\Delta S_m(T)$ curve decreases slightly in comparison with 1.75 J/(kg K) for the classical Finemet alloy under magnetic field change $\Delta H = 15$ kOe. When Fe atoms are substituted by Cr or Mn, then this value reduces to 1.09 J/(kg K) and 0.87 J/(kg K), respectively. At iron substitution for chromium or manganese the magnetic ordering temperature shifts towards lower temperatures, simultaneously decreasing significantly the maximum values of the magnetic entropy change. Substitution of iron for nickel does not entail a change in the Curie temperature, while substitution by cobalt leads to its increase slightly, and this accompanied by a minor regression in the magnetic entropy change. The peak value of isothermal magnetic entropy change rises with increasing magnetic field as . Analysis of the $n(T)$ dependences near T_C for investigated samples reveals that the values of local exponent n are in the range 0.68-0.73, that slightly exceeds the theoretical value of 2/3 predicted by the mean-field approximation [3].

The research was carried out within the state assignment of Minobrnauki of Russia (theme «Magnet» No. AAAA-A18-118020290129-5).

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P227 - Microstructure, soft magnetic properties and magnetocaloric effect in Fe-Co-Si-B-Mo-P alloy

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

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Fe-based metallic glasses belong to a class of amorphous materials, that are still attractive because of their unique combination of soft magnetic properties. Low coercivity, low core losses, high initial susceptibility, high saturation induction as well as lack of any topological order in the structural arrangement of the constituent atoms cause that these materials are interesting from both scientific and a variety of practical applications point of view. It is well know that microstructure and magnetic properties of Fe-based soft magnetic materials can be easily affected by additions such atoms as Co, Mo, Mn, Nb, etc. and/or structural modifications that are introduced during or after the production process.

In this paper the relationship between microstructure and soft magnetic properties in the amorphous and partially crystallized Fe72Co6Si4B9Mo1P8 alloy is studied. The magneticaloric effect in the vicinity of the Curie temperature is also investigated. The sample was produced by rapid quenching method in a form of thin ribbon of 0.025 mm thick. XRD and TEM microstructure investigations of the as-quenched Fe72Co6Si4B9Mo1P8 precursor confirm amorphicity of the as-quenched material. Crystallization kinetics performed with a help of DTA shows that the primary crystallization temperature at about 766 K is well visible. After 30 min annealing at 828 K the presence of bcc Fe nanograins was observed. The annealing of the ribbon at 1150 K leads to creation of bcc FeCo and FeBP-type phases. Topography of ribbon in the as-quenched state and after annealing was analyzed by AFM/LFM in contact mode. Thermomagnetic characteristics were investigated as magnetization versus temperature M(T) in zero-field cooled mode in a wide range of temperatures (up to 1000 K) and external DC magnetic fields (up to 3 T) by VersaLab system. The Curie point of the amorphous Fe72Co6Si4B9Mo1P8 alloy obtained from M(T) curve is about 643 K. The analysis of the hysteresis loops M(H) recorded at different temperatures shows that the coercivity depends on temperature and also annealing condition. The magnetocaloric effect was studied as magnetic entropy change from sets of isothermal magnetization curves recorded for the as-quenched and annealed Fe72Co6Si4B9Mo1P8 alloy in wide range of temperature and magnetic field. The positive slop of Arrott plots at Curie point of the investigated material confirms second order ferromagnetic to paramagnetic phase transition. From obtained data it is seen that microstructure strongly affects soft magnetic properties and magnetocaloric effect in the Fe72Co6Si4B9Mo1P8 alloy.

P228 - Nanocrystalline 1:12 Sm-Fe-(M, V) (M= Cu, Ti, Mo) magnets

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

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The criticality of the RE-metals has encouraged material scientist researchers to produce RE-lean/free permanent magnets[1]. In this context, the Sm-based compounds with $ThMn_{12}$ (1:12) structure [2] are one of the alternatives to develop a permanent magnet [3,4].
A nanocrystalline bulk magnet based on Sm-Fe-(M,V) (M = Cu, Ti, Mo) with the $ThMn_{12}$ crystal structure has been fabricated by hot-compaction of mechanically milled powders. The optimally Sm-Fe-V isotropic magnet exhibits a maximum coercivity of 1.06 T with a magnetization of 0.59 T, a remanent magnetization of 0.42 T and a $(BH)_{max}$ of 28 kJ m^{-3}. The Curie temperature is found to be 330 °C and the temperature coefficients of remanent magnetization and coercivity are 0.14% C^{-1} and 0.39% C^{-1}, respectively. Minor hysteresis loops indicate a coercivity mechanism similar to that of the nanocrystalline Nd-Fe-B magnets. The isotropic magnets were hot-deformed up to 75% of its height, a small texture perpendicular to compaction direction was detected in the Sm-Fe-V and Sm-Fe-V-Mo magnets, in the former when the amount of vanadium was reduced, and the deformation temperature was increased from 800 to 1000 °C.
Work supported by the European Union's Horizon 2020 research and innovation programme under grant agreement No 686056 (NOVAMAG) and DOE DE-FG02-90ER45413.

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P229 - On the correlation between glass formation & soft magnetism of Ni-substituted Fe-based glassy alloys

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

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Ultra-soft magnetic properties and high bulk-forming ability are essential attributes to brand glassy alloys a novel functional material. The major attributes of soft magnetic glassy alloys include ultra-low coercivity (H_c), high permeability (μ), high saturation magnetisation (M_s), high Curie temperature (T_c), and large electrical resistivity as compared to their crystalline counterparts. The bulk-forming ability of soft magnetic Fe-based glassy alloys can be significantly enhanced by substituting *non-ferrous* glass formers. However, at the same time, the superior bulk-forming ability compromise the soft magnetic properties of the amorphous alloys due to the high content of non-magnetic glass formers and hence limits the flux concentration advantage of these materials for miniaturisation of passive components. Alternatively, the substitution of ferrous glass formers (like Co, Ni), instead of non-ferrous elements, could potentially enhance the functionality of Fe-based alloys. The effect of substitution of ferrous elements on the bulk-forming ability and soft magnetic properties of Fe-based glassy metals, therefore, needs further investigations to utilise these alloys as a functional material.

The present work aims to investigate the mechanism of glass formation and correlates it to the soft magnetism of Ni-substituted Fe-B-Nb alloys. The impact of *ferrous* glass formers on the mechanism of glass formation and soft magnetism of Fe-based bulk metallic glasses was critically analysed. By quantifying glass forming ability and soft magnetic characteristic (coercivity, H_c) for varying degrees of substitution, we observe a maximum in glass forming ability together with a minimum coercivity, H_c = 20 A/m, which we suggest is due to an increased atomic packing density of the glassy phase. Interestingly, a monotonic increase of Curie temperature (T_c) with increasing substitution of Ni was observed, which could be attributed to a reduction of an antiferromagnetic Fe-Fe interaction in the glassy iron-rich matrix. The overarching goal of this study is to explore the underlying mechanisms of enhanced GFA, improved soft magnetic properties and increased T_c of Ni-substituted Fe-based glassy alloys.

P230 - On the martensitic transformation of Ni-Mn-In in pulsed magnetic fields

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

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The author has chosen not to publicise the abstract.

Field 5

Field 6

P231 - Preparation and electro-magnetic properties of Fe- based SMCs with resin bonded ferrite

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

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In recent years, the research on soft magnetic composites (SMCs) has shown their vast potential for electromagnetic applications, such as transformers, inductors, sensors, fast switching solenoids and electrical motors [1, 2]. SMCs are composed of electrically insulated magnetic powder particles and provide several unique properties, as the eddy current loss reduction resulting in low total core losses at elevated frequencies, relatively high saturation induction, magnetic permeability and Curie temperature, relatively low coercivity and 3-D isotropic physical properties behaviour. Soft magnetic composites based on Fe-based powder with resin bonded ferrite insulation were fabricated to investigate the effects of ferrite insulation on the electromagnetic properties. SMC samples were prepared by powder metallurgy techniques and by compaction in the forms of a ring and a cylinder. The structure of material was documented and the magnetic and electrical properties were analysed. A low porosity and high values of mechanical hardness and flexural strength were found in prepared soft magnetic composites. Our results show that the electro-magnetic properties of soft magnetic composites can be enhanced by appropriate content of ferrite in the resin and value of electrical resistivity is very high. It results that the magnetic properties of the prepared composite material with resin bonded ferrite insulation were reached better than for previous iron-resin composites and the relatively high real part of complex permeability was obtained together with its relatively high frequency stability. The results presented can be used for future materials design of soft magnetic composites.

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P232 - Quad Flexural Beam based Magnetic Composite Device for Harvesting Low Frequency Ambient Vibrations

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

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Powering the collective of pervasive interconnected sensing, computing and actuating systems that comprise the internet of things, which is needed to deliver breakthrough applications in the fields of medical diagnostics, healthcare monitoring, remote sensing and security, is proving to be a major challenge of the current century. Lithium ion batteries are used to power such systems, but they need to be recharged and eventually replaced. A better alternative is to power these systems by exploiting low frequency ambient vibrations, originating from electrical appliances, air conditioning vents, human motion, acoustic signals, etc. [1].

In this work, a low frequency energy harvester is developed, which comprises of a magnetic composite proof mass suspended by four flexural magnetic composite beams above a surface microfabricated planar coil. A low frequency resonant response is achieved through the use of flexural beams made up of highly flexible and permanent magnetic composite material. A 7.5 µm thick layer of selectively electroplated copper forms the planar coil, which occupies an area of 1 cm^2 and consists of 40 turns. The flexible polymer polydimethylsiloxane is mixed with permanent magnetic NdFeB microparticles (50% by weight) to form the magnetic composite material [2]. This is then molded to form the flexural beam - proof mass structure, which occupies a volume of 1.9 cm^3 on top of the planar coil. When subjected to vibrations, the flexural beams oscillate back and forth, changing the distance between the proof mass and the planar coil. This results in an oscillating magnetic field, which induces a voltage in the planar coil.

FEM simulation of the structure revealed that the resonant frequency of the magnetic composite structure is 50.45 Hz. Experimentally, when excited by a 3.0g amplitude vibration, the structure resonated at 47 Hz and produced an open circuit rms voltage of 2 mV (fig. 1). It delivered a power density of 8.66 mW/m^3 and a large normalized bandwidth of 0.23, when coupled to a 60 Ω matched load.

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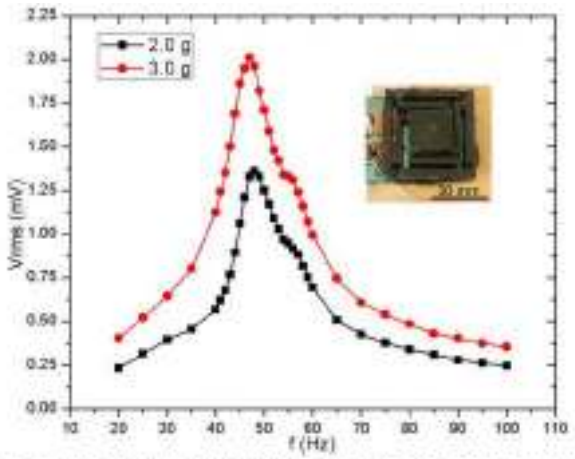

Fig. 1 frequency response of energy harvester, (inset) flexural beam based energy harvester

P233 - Relationship between target materials and various properties of PLD-made isotropic Nd-Fe-B films

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

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A lot of researchers prepared Nd-Fe-B thick film magnets thicker than 10 μm using a sputtering method in order to apply them to miniaturized devices [1][2], and an use of a Nd-Fe-B alloy or a Nd-F-B alloy target with various sheets such as Fe, Fe_3B, and Nd has been mainly reported [3] in the experimental procedure. On the other hand, our group has demonstrated PLD (Pulsed Laser Deposition)-fabricated Nd-Fe-B thick-film magnet with the thickness above 10 μm on metal substrates and introduced several small motors comprising the films [4]. Although we used a Nd-Fe-B alloy target in the previous experiments [4], a sintered Nd-Fe-B target is considered to be one of hopeful candidates to improve various properties of the PLD-made Nd-Fe-B films. This contribution reports the effect of target materials on various properties of PLD-fabricated isotropic Nd-Fe-B thick-film magnets.

In the experiment, a defocused laser beam with energy density less than several J/m^2 on a surface of three sintered Nd-Fe-B targets with each density of 5.69 (target A), 6.14 (target B), and 6.64 g/cm^3 (target C), respectively, were used. Moreover, all the as-deposited films on Ta substrates had amorphous structure, therefore a flush annealing process was carried out to obtain $Nd_2Fe_{14}B$ crystalline grains.

The usage of all sintered targets enabled us to obtain the deposition rate above 40 μm/h, however the different Nd content (Nd/(Nd+Fe)) between each film and the corresponding targets increased as the density decreased. A surface composition analysis using a SEM-EDX revealed that the ablated area showed exceeding Nd amount compared with each target composition in the targets of A and B. Furthermore, in the case of an ablation for the target C, the composition transfer between a target and a film showed a similar result of an alloy Nd-Fe-B target [4]. We, therefore, compared the magnetic properties of isotropic films prepared using an alloy target and target C with the both Nd contents of approximately 14.5 at. %. Although the values of resiidual magnetic polarization and $(BH)_{max}$ showed similar ones of approximately 0.6 T and 60 kJ/m^3, the average coercivity value of the samples prepared using target C was smaller by about 200 kA/m than that of films prepared by an alloy target. In addition, the comparison of normalized demagnetization curves for each sample prepared using an alloy target and target C was carried out. It was found that the reproducibility of squareness in the curves for the samples prepared using the sintered target was superior compare to that of others. It is considered that the tendency is attributed to the different homogeneous microstructure in the both samples.

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P234 - Size effects on the energy product of CoFe2O4 magnet

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

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The size effects on the magnetic properties of $CoFe_2O_4$ hard ferrite have been studied using Monte Carlo simulation with Ising model. Free boundaries conditions were used to simulate cubic nanoparticles with different sizes. Saturation and remanent magnetization increase with the increase of the particle size. A rise of the squareness ratio (Mr/Ms) towards high values is observed. Furthermore, a maximum value of the coercive field is shown for a size of 20nm. In addition, we evaluated the performance of the cubic shaped $CoFe_2O_4$ permanent magnet in term of the maximum energy product (BH_{max}). The obtained results of the model allowed us to determine, at least, the theoretical limits of the magnetic properties of the cubic shaped $CoFe_2O_4$ nanoparticles for permanent magnet applications.

P235 - Stabilization of tetragonal FeCo structure with high magnetic anisotropy by VN addition

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

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The continuously increasing power consumption of motors utilized in electrical vehicles and air conditioners, and magnetic devices inside hard disk drives and random access memory has become a serious issue. Permanent magnets represent very important components of these applications. The energy utilized by the magnets depends on the magnitudes of the saturation magnetization (Ms) and uniaxial magnetic anisotropy (Ku) of magnetic materials, whose high thermal stability can be achieved at high values of the Curie temperature (Tc).

FeCo with the body-centered cubic (bcc) structure is a well-known magnetic material characterized by the highest Ms and very high Tc values among various transition metal alloys. Although FeCo-based materials exhibit strong magnetic properties, their low Ku magnitudes make them unsuitable for the fabrication of permanent magnets. However, if the Ku of FeCo could be increased to a sufficiently high value, one of the strongest permanent magnets would be obtained.

Recent first-principles calculations and our experimental studies[1] revealed that the epitaxial FeCo thin films with the body-centered tetragonal (bct) structure and thicknesses of several nanometers exhibited Ku values of 10^6 J·m^{-3} due to epitaxial stress, which required further stabilization. In the equilibrium phase diagram constructed for FeCo, the fcc phase is stable at temperatures higher than 1258 K. Its transformation to the bcc phase occurs at lower temperatures, leading to the formation of the CsCl-type (B2) ordered bcc structure at temperatures below 1003 K without producing a bct intermediate. However, after considering the Bain transformation (inset in figure a), two methods can be used to stabilize the bct structure: (A) applying a uniaxial stress to the FeCo lattice via epitaxial effects and (B) adding a third element to the FeCo structure.

Various experimental studies based on method (A) have been performed to investigate the magnetic anisotropy of FeCo by epitaxially growing it on several buffer layers. Several experimental studies based on method (B) have been conducted as well. The addition of certain third elements is expected to generate a tetragonal distortion in the FeCo lattice leading to the relaxation of the local stress in their vicinity. In our previous study,[2] we focused on the use of the combination of V and C, N elements as the third additive element because of its ability to form a bcc, which was subsequently transformed into the fcc with an increase in the third element content. A stabilization of the bct phase was expected to occur at the boundary between the bcc and fcc phases. In this study, the effect of the N addition to FeCoV films on their tetragonal deformation was investigated.

The bcc-bct-fcc transformation depending on the N content, and the high Ku magnitudes exceeding 10^6 J·m^{-3} are observed in figures (a) and (b). The obtained bct structure remained stable even for the films with thicknesses of 100 nm, suggesting its possible use in bulk systems.

This work was supported by NEDO.

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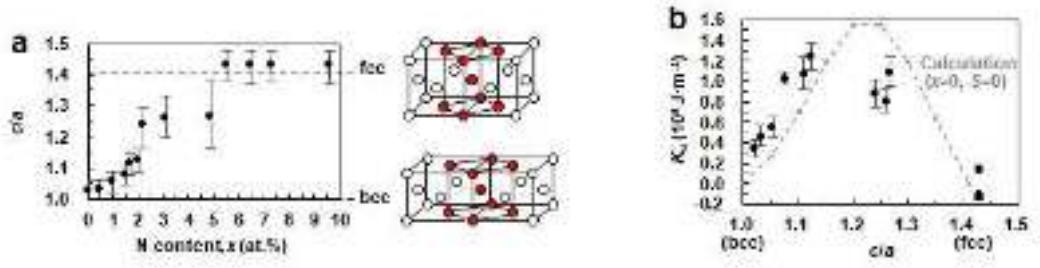
a
c/a
fcc
bcc
N content, x (at.%)
b
Calculation
(x=0, S=0)
(bcc)
(fcc)
c/a

P236 - Structural and magnetic properties of SrFe12O19-NiO nanocomposites for electromagnetic absorption

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

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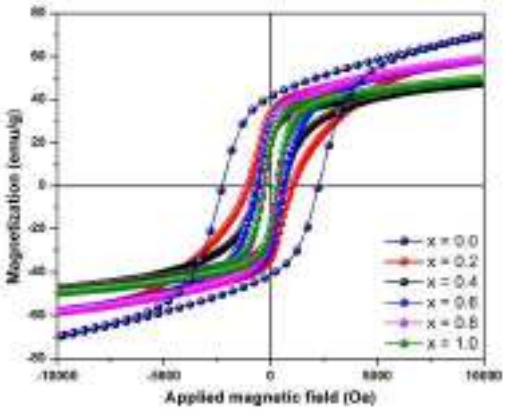
The $SrFe_{12}O_{19}$-xNiO (x = 0.0, 0.2, 0.4, 0.6, 0.8 and 1.0) composite samples were prepared by using microwave-hydrothermal method. The structural and morphological studies were carried out using x-ray diffraction and field emission scanning electron microscopy. The densification of these composites was carried out at 950°C/90 min using microwave sintering method. The solubility of Ni^{2+} into hexaferrite crystal lattice is observed for x = 0.2 from the diffraction patterns. The coexistence of both $SrFe_{12}O_{19}$ and NiO phases were observed for x > 0.4, thus confirming the formation of $SrFe_{12}O_{19}$-NiO composites. The samples with x = 0.0, 0.2, and 0.4 shows the hexagonal $SrFe_{12}O_{19}$ with plate like shape while x > 0.4 shows changes in the shape of the platelet grains. The magnetic properties of present samples were explained on the basis of strong preferential occupancy of doped cations at 12k sublattice sites in the hexaferrite lattice.



P237 - Structural and magnetic properties of the magnetocaloric compound Mn3Fe2Si3

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

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The magnetic and the structural properties of the magnetocaloric compound $Mn_3Fe_2Si_3$ which belongs to the $Mn_{5-x}Fe_xSi_3$ series ($0 \leq x \leq 5$) are investigated macroscopically and with diffraction methods to reexamine their structural and magnetic phase diagram using single crystalline specimen. Similar to the parent compound Mn_5Si_3, the $Mn_3Fe_2Si_3$ compound exhibits two antiferromagnetic phase transitions AF1 and AF2. In Mn_5Si_3, the transition from AF1→AF2 gives rise to an inverse magneto-caloric effect (MCE), i.e. the magnetic entropy is increased by the application of a magnetic field. Dynamically the AF1 and AF2 phases are characterized by a spin wave dominated and fluctuation dominated excitation spectrum, respectively, which provides the microscopic explanation of the inverse MCE [1].
We are now interested in the changes of the magnetic structure when Mn is replaced by Fe. The preferential incorporation on one of the two distinct lattice sites for the transition metal sites seems to result in only slight changes of the phase diagram while increasing the Fe occupation on the second site drives the compound towards ferromagnetism.

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P238 - Synthesis of SrZn2Fe16O27 using a solid salt matrix

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

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Hexaferrites have in the last years seen of huge interest as a cheap rare-earth free magnetic material. Control of crystallite size and shape is critical when optimizing the magnetic performance. Eikeland *et. al.* have in the syntheses of M-type hexaferrite (*e.g.* $SrFe_{12}O_{19}$) used a matrix approach to control the growth of the nanocrystallites and achieve freestanding nanocrystallites [1]. W-type hexaferrites (Ba/Sr$M_2Fe_{16}O_{27}$, where M = divalent transition metal) have further shown high potential for permanent magnetic applications with high saturation magnetization (M_s). You et.al. report a high M_s-value of 77.3 Am^2/kg for $SrZn_2Fe_{16}O_{27}$.[2] Synthesizing of $SrZn_2$ $Fe_{16}O_{27}$ using the matrix approach could result in crystallites which are more easily aligned and hence the magnetic performance can be optimized.

$SrZn_2Fe_{16}O_{27}$, was synthesised by a two-step synthesis route. First the synthesis of $SrFe_{12}O_{19}$ and $ZnFe_2O_4$ were conducted using a solid salt matrix (SSM). Second the powders were hand pressed into pellets and sintered to achieve $SrZn_2Fe_{16}O_{27}$. In the SSM synthesis, crystallite growth takes place in a solid matrix to achieve freestanding nanocrystallites of $SrFe_{12}O_{19}$ and $ZnFe_2O_4$. The product was analyzed using powder x-ray diffraction and Rietveld refinement to determine the size of the crystallites and the purity of the sample before and after sintering. Macromagnetic properties were measured using a vibrational sample magnetometer (VSM). VSM data showed that M_s up to 72.5 Am^2/kg were obtained, but no appreciable coercivity were observed for the samples.

It was also attempted to directly synthesise $SrZn_2Fe_{16}O_{27}$ in the SSM, here high melting temperature salts were used *e.g.* $MgSO_4$ and CaO. However, it was found that both salts reacted with the reactants preventing formation of $SrZn_2Fe_{16}O_{27}$. Instead formation of $MgFe_2O_4$ and $Ca_2Fe_2O_5$ occurred in their respective SSM.

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P239 - The effect of Ti addition on the stability and workability of the τ-phase in MnAl-C alloys

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

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The intrinsic magnetic properties of the $L1_0$ structured τ-phase in MnAl-C alloys show the strong potential as a rare earth free permanent magnet. Until now the best magnetic property was achieved through hot extrusion [1]. As the material is relatively hard, a large stress is required for the extrusion, which leads to rapid wear of the die tool. It has been proved that adding Ti would increase the ductility of the MnAl alloy [2], which may help extend the lifetime of the extrusion dies; however, no detailed investigation of the microstructure and magnetic properties of alloys with Ti additions appears to have been carried out. In this work, homogenised, as-transformed and hot deformed samples of Mn-Al-C alloys with Ti additions have been produced and have been characterised using magnetometry, scanning electron microscopy, electron backscatter diffraction, transmission electron microscopy and x-ray diffraction. Precipitates of TiC were identified in the Ti-containing alloys and the effect of these on the stability of the τ-phase, the magnetic properties and the flow stress during hot deformation was investigated.

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P240 - The effects of Zr+Fe2B on NdFeB strip-cast material during the Hydrogen Ductilisation Process (HyDP)

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

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NdFeB-type alloys are difficult to process into aligned fully dense magnets because the material is extremely brittle. Therefore, in order to shape the material, it is either reduced to a powder and then pressed and sintered at high temperatures, around 1000-1200°C [1,2], or it is hot pressed at temperatures between 800-900°C [1]. Recent studies have clearly shown that it is possible to overcome the brittle nature of NdFeB-type starting cast alloys by pre-processing the material in hydrogen prior to mechanical deformation, using a process termed the “Hydrogen Ductilisation Process (HyDP)” [3-5].

During the HyDP the alloy is processed in hydrogen to produce a solid disproportionated (s-HD) material that can be pressed at room temperature. However, during pressing trials, it has been shown that small fractures occur in the minority phase $NdFe_4B_4$, which will affect the magnetic properties of the final magnet after recombination and possibly limit the range of plastic deformation techniques which can be applied.

One way to reduce the amount of $NdFe_4B_4$ phase in NdFeB alloys is to move towards a stoichiometric $Nd_2Fe_{14}B$ alloy. However, this is associated with the formation of free -Fe which in turn is detrimental to the magnetic properties. It has previously been shown that by adding zirconium and Fe_2B to cast NdFeB alloys it is possible to avoid the formation of free -Fe [6]. This study investigates the effect of Zr and Fe_2B additions on the microstructure and deformation behaviour of NdFeB alloys during the Hydrogen Ductilisation Process (HyDP).

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P241 - The Magnetic Phase diagram of Electrochemically Cycled NaxCoO2

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

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The discovery of thermoelectricity and superconductivity in Na_xCoO_2 (NCO) has aroused a high interest for this triangular lattice compound from both scientific and industrial communities. The physical properties of NCO are governed by the number of conduction electrons in the CoO_2 layers, but also by the Coulomb potential (U) caused by ordered Na ions. Upon Na doping, a plethora of magnetic and electronic ground states emerges leading to a very rich phase diagram. However, the present phase diagram is controversial. For specific Na concentration (e.g. x = 0.5 - 0.7 or x = 0.85), samples grown by the solid-state reaction method display inhomogeneous Na content, which makes the identification of the magnetic properties as function of doping challenging **[1]**. To obtain a better understanding of the magnetic and electronic states, we have performed muons spin rotation (μ^+SR) experiments on NCO samples prepared by the electrochemical reaction technique **[2]**. This growth method gives a succession of single- and order-phases for various Na concentrations with high accuracy and reproducibility. Based on our μ^+SR results, we re-establish a new NCO magnetic phase diagram **[3]** for $0.5 \leq x \leq 0.85$. In comparison with the original NCO phase diagram, we show that the antiferromagnetic order state only appears at specific Na doping ($x = 0.72$, 0.76 and 0.79), the ground state of $Na_{0.85}CoO_2$ is unlikely a random spin-glass, and the x range for the AF phase of $Na_{0.5}CoO_2$ is refined. Our results demonstrate the importance of having high quality samples to understand the intrinsic magnetic and electronic properties of materials.

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This research is funded by Swedish Foundation for Strategic Research (SSF) within the Swedish national graduate school in neutron scattering (SwedNess), a Marie Skłodowska-Curie Action, International Career Grant through the European Commission and Swedish Research Council, VR (INCA, Dnr. 2014-6426), a VR neutron project grant (BIFROST, Dnr. 2016-06955), a VR Starting Grant (Dnr. 2017-05078) as well as Carl Tryggers Foundation for Scientific Research (CTS-18:272).

P242 - Theoretical study of doped Fe3Sn compounds in the quest for good rare-earth free permanent magnets

9. Materials for energy (permanent magnets, magnetocalorics and soft magnetic materials)

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Permanent magnets have many areas of applications such as power generation, electric motors, transportation, conditioning, clean energy technologies etc. Recently emerging limitations in availability and cost increase of rare-earth elements, crucial components of permanent magnets, have stimulated interest in the search of alternative rare-earth-free materials with advanced magnetic properties. A competitive permanent magnet must have high Curie temperature, high saturation magnetization, and uniaxial magnetocrystalline anisotropy. Rare-earth free hexagonal close-packed Fe_3Sn compound is a promising candidate due to high concentration of iron and good magnetic properties. However, it has in-plane rather than uniaxial magnetocrystalline anisotropy. Alloying is a possibility to change the easy axis of magnetization.

We have studied theoretically in the framework of the density functional theory the electronic structure and magnetic properties of ferromagnetic Fe_3Sn compound doped with M = Si, P, Ga, Ge, As, Se, In, Sb, Te, Pb, and Bi on the Sn sublattice, as well as with the Mn phase-stabilizer on the iron sublattice. We discuss the influence of the different dopants on the magnetocrystalline anisotropy and Curie temperature of $Fe_3(SnM)$ and suggest new stable/metastable ferromagnetic phases with uniaxial anisotropy suitable for the development of advanced permanent magnets.

10. Micromagnetics and magnetization processes

P243 - 1D classical spin-dinamics simulation of two-sublattice compensated ferrimagnets

10. Micromagnetics and magnetization processes

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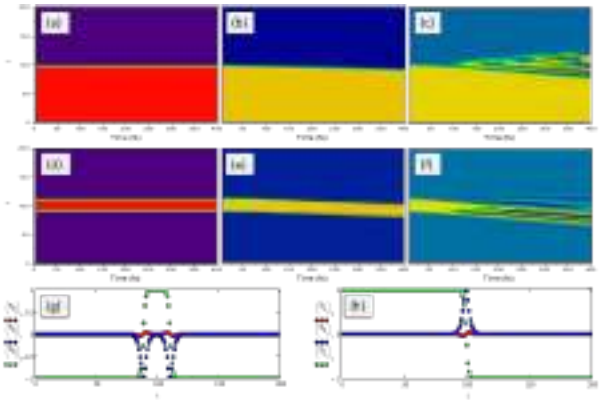
Net-compensated ferrimagnets, exhibiting high spin polarisaiton at the Fermi level are some of the most promising candidate materials to help bring spin electronics and spin orbitronics into the realm of THz physics. As only a couple of systems, akin to Mn_2RuGa, have been shown to exhibit the majority of properties characteristic of of this rather unique class of magnetic materials, there is a rather weak experimental and theoretical understanding of the full suite of interactions which determine, not only the equilibrium state, but also the all-important spin dynamics. The essential experimental observations can be summarized as: net magnetic compensation on at least two chamical-environment-distinct magnetic sub-lattices in a broad and tuneable temperature interval; large, often close to half-metallic spin polarisatoin at the Fermi level; extremely large anisotropy and coercive fields (often in excess of 10 T, close to compensation); high intronsic ferromagnetic and especially antiferromagnetic resonance frequencies (in excess of 100 GHz in some cases) and last but not least high spin-transfer and spin-orbit scattering coefficients. Extensive studies of these materials, using *ab-initio* methods are under way in a number of research groups, but are limited in scope, because of their complex crystalographic disorder and complicated magnetic structure.
Here we focus on the development of of minimal-paramater set dynamic model for such materials, which would be able to capture the essential physics of the problem, within a classical 1D spin Hamiltonian. The essential characteristics of the model are as follows. Two distincs sub-lattices, which are each characterised by spin magnitude, uniaxial anisotropy, inter-sublattice exchange, damping and DM interaction. Intra-sublattice exchange couples the two sublattices and additional terms of the Hamiltonian represent the Zeeman interaction with an external magnetic field and spin-transfer and/or spin orbit torque.
As the materials of interest have essentially no net magnetic moment, a quite significant simplification can be made to the computational problem by neglecting the n^2-scaling demagnetisaiton field and energy. A numerical dynamic evolution scheme is then utilized for the classical Poisson bracket of what is essentially an extended LLG Hamiltonian. The main effecive representation of the system is using a discrete set of spins (at least 100-200) which are recomputed (in parallel) at each of the complete (sub-fs) time steps. In order to compute the terms of the Hamiltonian to do with spin-torques, the first and second spatial-derivative profiles are also required. These are obtained using an optimal β-spline interpolation of the spin-density, wich is continuous at least to third order of the spatial derivatives. The dymanic is affected via a discrete time-step direct forward or leap-frog algorithm. Steady-state equilibrium is achieved by evolving at fiite damping analytical approximations for the required sub-lattice magnetisation profiles, as shown on the figure. After these are succesfully converged, time-integrations at finite external fields and current densities are performed, in order to track the dynamical trajectories of the topological configurations for different choises of the characteristic paramaters.
With this code, we simulate the dymanics of both domain walls and 1D skyrmions and effectiveness of their pinning by defects.



(a-c) Time evolution of the z-axis spin density for the first sub-lattice of a ferromagnetic chain of 200 spins, initialised in a ground state with a single domain wall in the middle, for three different values of the externally applied magnetic field. (d-f) Same as the above, but for a system initialized with a 1D skyrmion in the middle, which is rendered stable by finite DMI interactions. (g) and (h) represent the vector spin density in the ground state for a skyrmion and a domain wall, respectively, which are used as initial conditions for the dynamic propagation.

P244 - A GPU Accelerated MicroMagnetic Simulator for Modelling Complex Magnetic Systems

10. Micromagnetics and magnetization processes

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This paper demonstrates a GPU accelerated MicroMagnetic modelling tool designed to explore the material characteristics of complex thin film magnetic alloys. Due to the large number of cells required to accurately discretize the particular magnetic alloy thin film, these systems can have intractably large simulation runtimes when modelled using traditional CPU based MicroMagnetic simulators, such as OOMMF. In order to reduce these runtimes, the GPU is used to solve the traditional Landau-Lifshitz-Gilbert equation accounting for shape demagnetisation, exchange interaction, internal anisotropies, and external excitations. Furthermore, this simulation software is able to assign individual magnetic properties to each of the discrete cells comprising magnetic alloy system. Hence, various anisotropy, phase, and material composition distributions in X,Y,Z can be investigated by appropriately assigning the magnetic properties of the i^{th},j^{th},k^{th} cells.

The simulator is verified against standard problem 4 of the “Micromagnetic Modeling Activity Group” (Mumag). Standard problem 4 is chosen as it provides a benchmark for the modelling tools ability to accurately predict the magnetisation dynamics of a 500nm X 150nm X 3nm permalloy thin film. In this problem the thin film is first brought to an equilibrium state through the application of an external field along the [1,1,1] axis and then gradually diminishing that field to zero. After the equilibrium state is achieved, a small reversal field is applied to the thin film. This problem illustrates the role of exchange energy, shape demagnetisation, and the external applied field in magnetisation dynamics. Finally, in this paper an in plane anisotropy is introduced to standard problem 4. The amplitude and orientation of the in plane anisotropy are varied in order to show their respective roles in the magnetisation reversal process of the thin film.

Through the use of a GPU to solve the LLG equation and all the internal energies of the magnetic system (exchange interaction, demagnetisation field, etc…), the simulation runtime is drastically reduced. Hence researchers can use this GPU Accelerated MicroMagnetic simulator to investigate magnetic systems of a complexity that would be intractable for a CPU based MicroMagnetic simulator to solve.

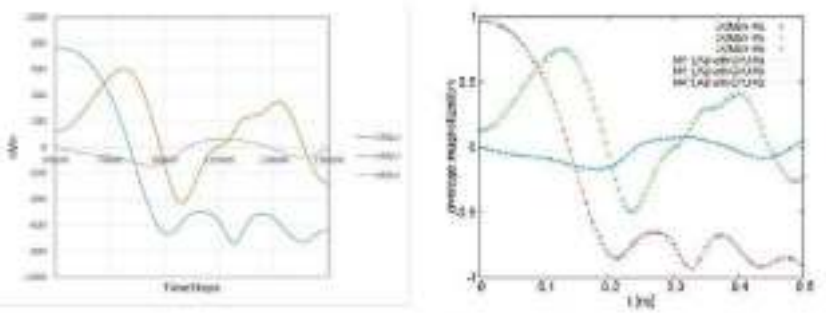

Figure 1 (Left) GPU simulator's output for Standard Problem 4. (Right) Standard Problem 4 from [1]

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P245 - A multiscale approach for magnetisation dynamics: Unraveling exotic magnetic states of matter

10. Micromagnetics and magnetization processes

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New and exciting physical phenomena in magnetic materials are usually characterized by the perturbation of physical properties at local and very small length scales. For example, dislocations or defects of atomic positions influence plastic deformation of materials and in magnetic media are a source of the Barkhausen effect. At the same time, in many cases, local properties cannot be disentangled from the global properties of the material in which they are embedded and consequently, both spatial scales are required to be treated on equal footing. We argue here that in the field of magnetism, this becomes apparent in magnets with trivial as well as non-trivial topology, and illustrate our findings in systems with localized non-trivial topological excitations, in form of skyrmions. Technical aspects of this report involve a multiscale implementation that connects an atomistic and continuum description of magnetism. The method is demonstrated here to be capable to evaluate rapidly the Landau-Lifshitz-Gilbert equation in mesoscopic regions of a magnetic material, coupled with atomistic accuracy in selected regions. It is demonstrated here for the first time that this methodology allows for simulations of realistically sized magnetic skyrmions interacting with material defects, and we describe several new phenomena connected to this development.

P246 - ACCELERATION OF RESONANCE STATE CALCULATION USING THE LLG EQUATION

10. Micromagnetics and magnetization processes

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Recently, a method of solving the LLG equation to analyze the dynamics of magnetization state is generalized. However, efficient simulation is desired when physical constants to inversely be obtained by simulation of experimental results. Machine learning and deep learning are effective methods for deriving the mathematical model to analyze the research object [1, 2]. In this research, we describe the derivation of a learning model describing the magnetization distribution in targeting materials, and the statistical prediction method to obtain the magnetic resonance condition using it.

To describe the statistical prediction model, we introduced the polynomial function as a descriptor of magnetization state, which corresponded the fitting curve of magnetization distribution in the magnetic films. Then, instead of direct search of magnetic resonance by using LLG equation, the prediction function was obtained to optimize data set consisting of descriptors. The prediction model was tested for plausibility by cross validation and regularization.

The calculations and prediction are plotted in **Fig. 1**. The direct calculations of LLG equation show open circles, open triangles and cross marks, respectively indicating cause parameter search, intermediate parameter and fine parameter settings. On the other hand, open and filled squares mean data points for regression curve. The regression curve is obtained from data points both for open and filled squares, which shows dashed line. The resonance conditions can be determined from the peak values of a series of direct calculations. The statistical prediction value is given by the minimum value of the regression curve. In this examination, the values of both were 1318.8 Oe and 1314.6 Oe, respectively, and the error was 4.2 Oe. The ratio of the error to the resonance magnetic field was 0.32%. Furthermore, even if the prior data was reduced to only six points, which was cause search indicating by open squares, the deterioration in reliability was suppressed to 1.38%. As a result, it has become clear that there is a possibility of reducing the number of calculation steps from about 30% to about 60%.

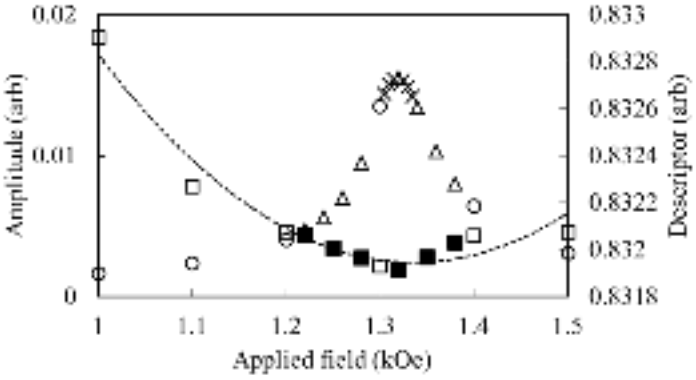

Fig. 1 The resonance condition searches by direct calculations and by statistical prediction of regression curve.

P247 - Adaptive geometric integration applied to a 3D micromagnetic solver

10. Micromagnetics and magnetization processes

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The numerical integration of the Landau-Lifshitz-Gilbert (LLG) equation can be computationally very demanding due to the need of simulating phenomena at the exchange length scale (5-10 nm) and long-range interactions as the magnetostatic field. Additionally, particular care has to be devoted to the choice of the time integration scheme, which should guarantee the preservation of the magnetization amplitude and the Lyapunov structure of the LLG equation, with sufficiently large time steps [1]. This task becomes very critical in the computation of static hysteresis loops, since at each field update the magnetization time evolution has to be calculated up to the reaching of equilibrium.
To face the above problems, we have implemented a 3D micromagnetic solver that implements an FFT-based approach for the magnetostatic field evaluation, exploiting GPU-parallelization. The time integration of the LLG equation is performed by means of a time integration method based on the Cayley transform [2, 3], to guarantee the preservation of magnetization constraint independently of scheme order and time step size. To further increase the code performance, we have implemented an adaptive time integration scheme based on Euler-Heun method, exploiting a technique developed for the embedded Runge-Kutta methods for the evaluation of the local truncation error [4].
In the present study, we test the developed solver analyzing the computational efficiency of the adaptive geometric integration. Furthermore, we investigate the peculiarities of the Cayley transform implementation when applied to the calculation of the static hysteresis loops of 3D nanostructures, highlighting the advantages in terms of equilibrium convergence.
As an example, the figure below analyzes the performance of the adaptive Euler-Heun scheme by comparison to non-adaptive Euler (one-step) and Heun (two-steps) schemes. All the schemes are implemented after the application of the Cayley transform to the LLG equation. The algorithms are tested on the μMag standard problem #4 [5], using a mesh size of 3 nm. On the left, we have reported the time evolution from s-state of the x-component of the magnetization after the application of a field around 36 mT, directed 190° counterclockwise from the positive x-axis. On the right, we show the variation of the time step size along the transient for different values of the tolerance ε. The Euler scheme becomes unstable for time step size in the order of 25 fs, while the Heun scheme starts losing stability for Δt higher than 190 fs. The adaptive Euler-Heun implementation presents a steep increase in the time step size when the magnetization reversal happens, stabilizing around 190 fs when the magnetization starts precessing around the new equilibrium point.

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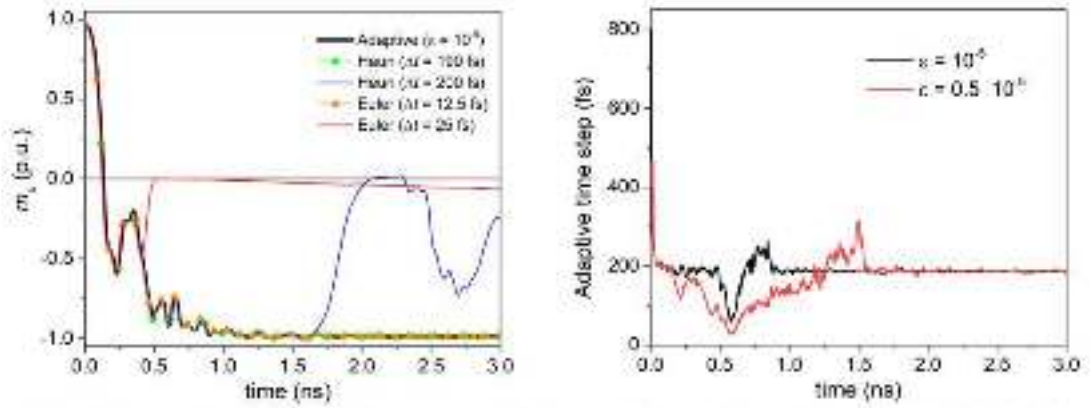

On the left: time evolution from s-state of the *x*-component of the magnetization after the application of a field directed 190° from the positive *x*-axis. On the right: variation of the time step size along the transient for different values of the tolerance ε.

P248 - Adequate meshing for micromagnetic simulations in systems with cylindrical boundary conditions

10. Micromagnetics and magnetization processes

Josep Castell-Queralt[1] , *Leonardo González-Gómez*[1], *Nuria Del-Valle*[1], *Carles Navau*[1]
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Micromagnetic simulations in confined geometries are essential to model novel spintronic devices. Adding confinement into micromagnetics implies changing the more convenient periodic or Dirichlet boundary conditions by Neumann's, which are more sensitive to the geometry of the boundary. Micromagnetic simulations are usually done using finite differences in regular hexahedral (3D) or quadrilateral (2D) meshes, which do not fit accurately curved boundaries. This induces numerical error that is critical when the dynamics at the boundaries are relevant. In particular, when simulating ultrathin ferromagnetic disks with a cylindrically symmetric initial distribution of magnetization, and all the external perturbations are also symmetric, the magnetization should also remain cylindrically symmetric. This can be derived from energy minimization or from the Landau-Lifshitz-Gilbert when assuming cylindrical symmetry. However, quadrilateral meshes used for a disk have rotational symmetry of 90º, which produces a numerical error distribution of the torques with the same symmetry. This distribution of the error breaks the symmetry of the system, and, in long (in time steps) simulations , the accumulation of this error gives rise to non-realistic non-cylindrical magnetic structures with a rotational symmetry of 90º.

We present a new numerical scheme that allows to do micromagnetic simulations in systems with cylindrical boundary conditions and arbitrary magnetisation distribution and perturbations, without neither obtaining artificially stable structures nor increasing the computational power required: a finite differences mesh based in cylindrical coordinates with adaptive polar angle discretization. The proposed mesh has the same symmetry as the boundaries and, with the adaptive polar angle discretization, the numerical error is kept of the same order for both the radial and the angular derivatives. With our numerical method, we are also able to model thin ferromagnetic rings with a central small hole, a case which would result in critical numerical error with a quadrilateral mesh. Additionally, a one-dimensional model is presented for the cases where both the magnetisation distribution and the geometry have cylindrical symmetry. Hysteretic loops in thin ferromagnetic disks and rings with interfacial Dzyaloshinskii-Moriya interaction are simulated to show the convenience of the presented mesh and the potential of thin rings for future applications in magnetic memory devices.

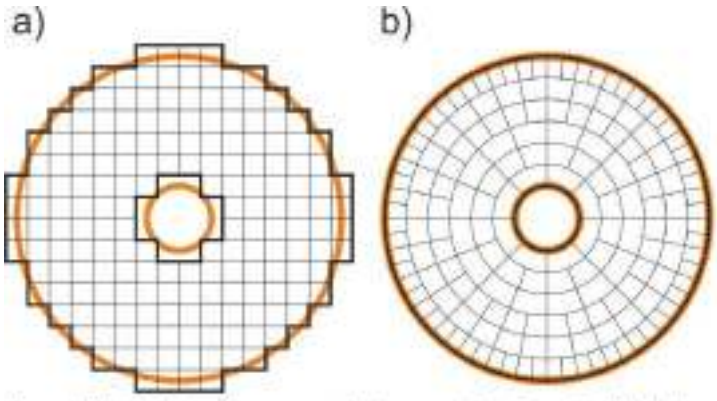

Figure 1: Sketch of the meshes compared in the presentation. Orange(bold black) lines represent the material(mesh) boundaries. a) Quadrilateral mesh, b) Cylindrical mesh with adaptive polar angle discretization.

P249 - Angular dependence of the magnetization process in amorphous glass-coated nanowires

10. Micromagnetics and magnetization processes

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The displacement of magnetic domain walls in ferromagnetic wires having the diameters in the nanoscale range (£ 100 nm) is a topic of high interest due to its potential applications in domain-wall-based magnetic logic devices, as well as in the development of novel sensing applications [1].

We analyzed by micromagnetic simulations the angular dependence of magnetic hysteresis in rapidly quenched amorphous nanowires with two compositions - the low magnetostrictive $(Co_{0.94}Fe_{0.06})_{72.5}Si_{12.5}B_{15}$ and the highly magnetostrictive $Fe_{77.5}Si_{7.5}B_{15}$, respectively.

The investigated samples were 30 and 100 nm in diameter. The magnetization process depends on the angle at which the external magnetic field is applied. $Fe_{77.5}Si_{7.5}B_{15}$ amorphous nanowires with smaller diameters exhibit larger coercivity than $(Co_{0.94}Fe_{0.06})_{72.5}Si_{12.5}B_{15}$ ones, irrespective of the angle at which the external field is applied. Moreover, both types of nanowires have similar remanence values at 30 nm diameters. However, nanowires with larger diameters (100 nm), exhibit a more complex behavior, since the $(Co_{0.94}Fe_{0.06})_{72.5}Si_{12.5}B_{15}$ samples exhibit a slightly larger coercivity as compared to the $Fe_{77.5}Si_{7.5}B_{15}$ ones.

We have found no report in the literature focused on the comparative study of the angular and dimensional dependence of the magnetic properties of rapidly solidified amorphous nanowires with cylindrical symmetry and different compositions. We found in the literature studies of the angular dependence of coercivity made by Tejo et al. [2] which give helpful information about the rotation mechanisms in modulated $Ni_{80}Fe_{20}$ nanowires.

The hysteresis curves for the $(Co_{0.94}Fe_{0.06})_{72.5}Si_{12.5}B_{15}$ amorphous glass-coated nanowires with 30 nm in diameter, as a function of the angle between the applied field ant the nanowire axis are shown in the Figure 1.

The magnetization reversal process is influenced by the interplay between the preponderant factors that affect the overall magnetic properties of amorphous nanowires with different compositions and dimensions. The results allow one to accurately tailor the magnetic behavior of rapidly solidified amorphous nanowires for various applications.

Acknowledgement – Work supported by the Romanian Ministry of Research and Innovation (MCI) under NUCLEU Program – contract no. 33N/2019, project PN 19 28 01 01.

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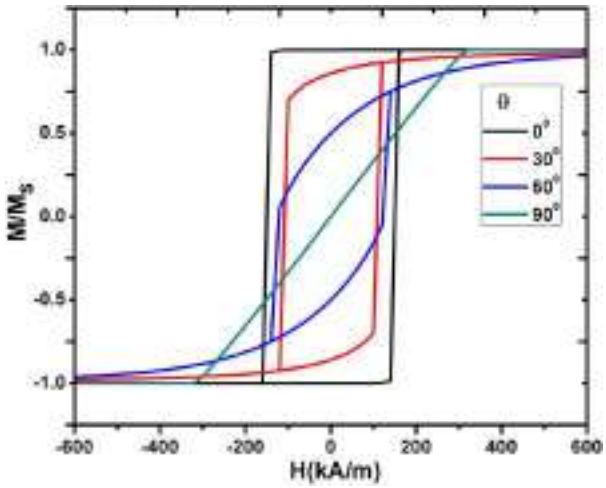
1.0
0.5
0.0
-0.5
-1.0
M/M_S
-600
-400
-200
0
200
400
600
H(kA/m)
θ
0°
30°
60°
90°

P250 - Complex magnetic permeability determination for magnetic microwires

10. Micromagnetics and magnetization processes

Nikolai Perov[1, 2] , *Iuliia Alekhina*[1], *Lyudmila Makarova*[1], *Marat Khairullin*[1], *Irina Baraban*[2], *Valeria Rodionova*[2], *Valeria Kolesnikova*[2]

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Amorphous magnetic materials have attracted huge research interest since the 60s-70s of the last century and do not lose their relevance. The widest prospects for practical use, as well as the fundamental significance of understanding of processes taking place in amorphous materials, give reason to the research interest in this area. A number of effects in amorphous materials is now well understood. However, many problems, for example, the distribution of the magnetic permeability over the volume of material, remain unsolved.

Cylindrical symmetry of amorphous magnetic microwires allows to make simplifications in equations describing their magnetic state. Maxwell's equations solution for uniformly magnetized medium under the low amplitude AC magnetic field allows one to determine the relations between the magnetic permeability of the material and the effective permeability of the sample. The effective magnetic permeability can be obtained from the measurements of the amplitude of magnetic flux density and its phase shift in reference to the magnetizing field. Numerical calculations of the coupling equation gives real and imaginary parts of the magnetic permeability of the material. The applicability is limited by the accuracy of the determination of the relations between the real and imaginary parts of the permeability.

In case if the samples are non-uniform over the cross section, it is possible to evaluate the dependence of magnetic properties on radius of the wire. It is known that frequency determines the thickness of the skin layer. Thus, changing the frequency it is possible to change the sample part, which contributes to the magnetic properties. Frequency sweep can provide the information about the magnetic properties of the wire layer by layer what is necessary for reconstruction of the permeability dependence on the radius of the wire. Such evaluation can also help to control the structure and phase composition of the wire.
The authors acknowledge the Russian Foundation for Basic Researches, project 18-02-00137.

P251 - Control of a Skyrmion motion by an angelfish racetrack

10. Micromagnetics and magnetization processes

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[2] Gifu University

The author has chosen not to publicise the abstract.

Field 5

Field 6

P252 - Current-driven Domain Wall Motion in Noncollinear Antiferromagnets

10. Micromagnetics and magnetization processes

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The author has chosen not to publicise the abstract.

Field 5

Field 6

P253 - Different Interpretations for the Exchange Energy Term in Micromagnetic Models

10. Micromagnetics and magnetization processes

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The range of exchange coupling has been discussed. Antiferromagnetic, as well as ferromagnetic coupling, have been found in Fe, Ni and Co compounds. Thus the concept of exchange length that assumes always positive exchange (ferromagnetic) can give misleading results. The existence of oscillation of exchange sign implies that the micromagnetic simulation should be atomistic. Thus, micromagnetic models need to consider other next-neighbors, and not only the first. In the case of first next neighbor, Heisenberg exchange is a scalar product, represented by a cosine function.
However, when a cosine function is approximated by an order two polynomial, other results can happen.
It is discussed that different functions can give different results, especially when the derivatives are considered. The domain wall thickness for Terbium was estimated in 18 atomic planes, in a model considering up to fourth next neighbors. For Dysprosium it was found 8 atomic planes of thickness at 78K, in a model taking into account up to seventh next neighbor. The Lilley definition for domain wall underestimates the domain wall thickness, especially for phases with high magnetocrystalline anisotropy.

P254 - Digital signal processing analysis for Barkhausen noise response in soft magnetic amorphous ribbons

10. Micromagnetics and magnetization processes

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We present a digital signal processing and analysis in Barkhausen noise response to establish the experimental conditions, which ensure the repeatability of this response in soft magnetic amorphous ribbons with different magnetostriction. For this objective, the measurements were performed on amorphous ribbons using different experimental conditions, such as: the magnetization frequencies, sampling rates, and using a single yoke magnet. The sample magnetization was controlled by means of inductor sensor. We use a discrete approximation of multiple magnetic states and which is necessary within the same measurement process, because the magnetization in material involves linear and non-linear stages and that are discussed in detail.

P255 - Ferromagnetic resonance simulations for stochastic Landau-Lifshitz-Gilbert equation

10. Micromagnetics and magnetization processes

Harald Oezelt[1] , *Alexander Kovacs*[1], *Johann Fischbacher*[1], *Markus Gusenbauer*[1], *Bernhard Stiftner*[2], *Dirk Praetorius*[2], *Michael Winklhofer*[3], *Gergely T. Zimanyi*[4], *Thomas Schrefl*[1]

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[2] Institute for Analysis and Scientific Computing, Vienna University of Technology, 1040 Wien, Austria

[3] Institute for Biology and Environmental Sciences IBU, Carl von Ossietzky University of Oldenburg, 26129 Oldenburg, Germany

[4] Department of Physics, University of California, Davis, California 95616, USA

Finite element micromagnetic (FEM) modeling has been proven to be a reliable tool to describe many magnetic phenomena. Usually the micromagnetic model utilizes a form of the Landau-Lifshitz-Gilbert (LLG) equation. If the computation of magnetic features requires the incorporation of varying temperature and sequentially spin fluctuations, the model can be extended by an additional stochastic thermal field in the LLG equation [1]. FEM solvers for the stochastic LLG use either microscopic parameters, determined from ab-initio studies appropriate for microscopic length scales, or macroscopic parameters, measured by macroscopic experiments on macroscopic length scales. However, fluctuations modify the material parameters relative to their values on microscopic or macroscopic scales [2].

A physics inspired method for rescaling the magnetization M_S was derived from spin-wave theory. The temperature dependence of the magnetization is closely linked to the thermal spin-wave spectrum. However, spin-waves with a wave-length that is shorter than the mesh-size, cannot be represented numerically. The proposed scaling of the magnetization corrects for spin-waves with a wave-length smaller than the mesh-size. In this way, the correction term is computed by an analytic integration over the spin-wave spectrum up to wave numbers corresponding to the mesh-size.

In this work we perform simulations of the ferromagnetic resonance (FMR) experiment to investigate the mesh size dependency of the stochastic LLG. We chose a simple hard magnetic grain of $Nd_2Fe_{14}B$ as test sample. The model is a cube of 40 nm edge length for which we generate uniform finite element meshes of different mesh sizes. The FMR is set up by applying an oscillating field of 5 mT amplitude with 216 GHz orthogonal to the easy axis of the grain. The frequency is chosen to yield a theoretical bias field of 1 T for the magnetic moments of the cube to be in resonance. A bias field parallel to the grain's easy axis is applied. At a temperature of 300 K the time evolution of the magnetization configuration is calculated for each mesh size and different values of the bias field from 0.6 T to 1.9 T. At this temperature the saturation polarization J_S=1.61 T, the exchange coupling constant A=7.7 pJ and the magnetocrystalline anisotropy K=4.3 MJ/m³. The FMR curves are calculated by taking the maximal magnitude in the frequency spectrum of the resulting magnetic signal orthogonal to the bias field.

Initial FMR simulations showed that additional renormalization of the anisotropy constant K is required. With K proportional to $M^{2.7}$ the resonance curves become almost independent of the finite element mesh. Figure 1 compares the resonance curves computed by solving the stochastic LLG with and without renormalization. Due to the demagnetization field, bulk and edge modes can be observed in the FMR curves [3].

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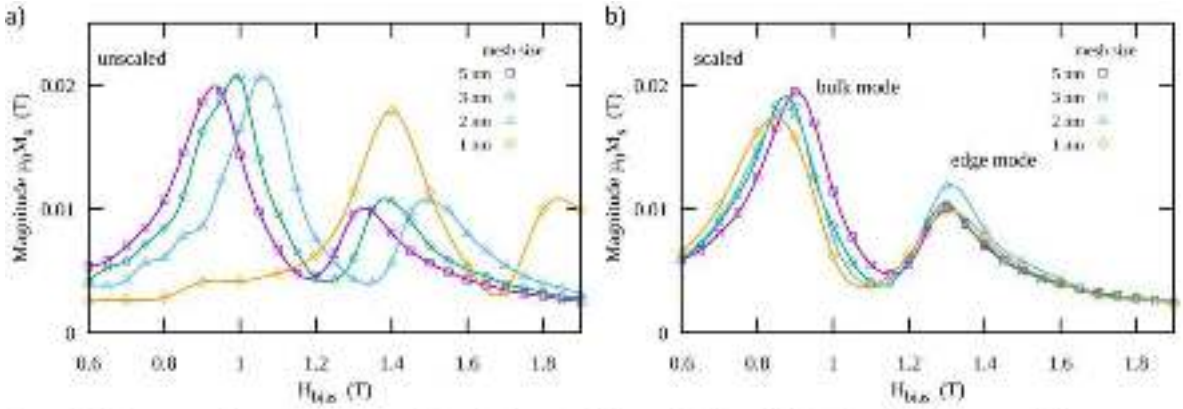

Figure 1: Ferromagnetic resonance curves for various mesh sizes of a 40 nm $Nd_2Fe_{14}B$ cube a) for unscaled magnetic properties and b) for renormalized properties J_s, A, and K.

P256 - Finite size scaling and temperature dependent properties of magnetite nanoparticles

10. Micromagnetics and magnetization processes

Daniel Meilak[1] , *Richard Evans*[1]
[1] University of York

Magnetite has continued to be one of the most well studied materials over the last century, being an oxide of iron, it is an extremely cheap and attractive material to make use of. Magnetite nanoparticles are promising for a range of medical applications including magnetic hyperthermia, MRI contrast enhancement and targeted drug delivery.

Due to the nanoscale nature of the particles, predicting the size dependent magnetic properties is challenging. We present finite size scaling (FSS) analysis for single crystal Fe3O4 nanoparticles using an atomistic spin model. In the model we explicitly model the sublattice ferrimagnetic magnetisation dynamics with an exact representation of the crystal structure and local ionic magnetic moments on the octahedrally and tetrahedrally coordinated Fe sites.

We compare the effects of surface faceting on the finite size scaling for spherical and cubic particles and find different scaling behaviours depending on the surface Fe coordination. In particular, we find a strong dependence of the saturation magnetisation on the surface coordination for smaller particle sizes. We also calculate the magnetic susceptibility which gives an additional determination of the Curie temperature. The susceptibility shows a strong size dependence in both the magnitude and position of the peak, and is significantly different for the different magnetic sublattices due to the antiferromagnetic coupling between sublattices.

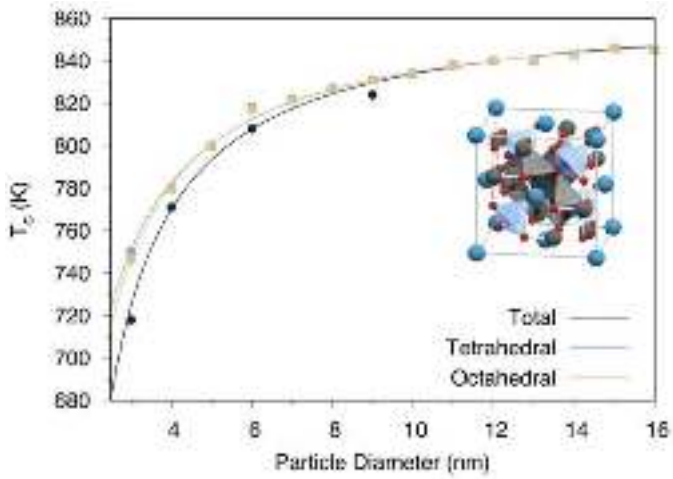

Figure 1. Curie temperature scaling of spherical magnetite nanoparticle with respect to particle diameter. The sublattices of the material predict slightly different Curie temperatures than the overall particle around low temperatures. Inset: magnetite unitcell.

P257 - From spiral to circular magnetic domain structure in microwires with negative magnetostriction

10. Micromagnetics and magnetization processes

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[2] Departamento de Física de Materiales, Universidad del Pais Vasco, UPV/EHU, San Sebastian, Spain

[3] Faculty of Physics, University of Białystok, Białystok, Poland

Recently, we demonstrated experimentally and numerically the nucleation and migration of a spiral-like magnetic domain structure in amorphous glass-covered microwires with a small positive magnetostriction constant λ [1]. Here, in order to control the transformation of domain structures between spiral and circular states, we present the micromagnetic modeling of the magnetization in a microwire with negative sign of magnetostriction constant. The model of effective uniaxial anisotropy [1] was adapted to the case of $\lambda < 0$. Simulations of the magnetization reversal process have been performed using the mumax[3] program. The calculations were carried out for a cylindrical microwire with a radius of 1 μm and a length of 15 μm, which was divided into $3*10^7$ cells, which volume was $10*10*5$ nm^3. The magnetic domain structure of glass-covered amorphous microwires was determined by the distribution of internal stresses [2]. The value of the magnetostriction constant is treated as a control parameter of the simulations. This allows to demonstrate a transition from the spiral domain structure obtained for $\lambda = -2*10^{-7}$, (Fig. 1a), to the circular magnetic domains obtained for $\lambda = -3*10^{-6}$, (Fig. 1b).

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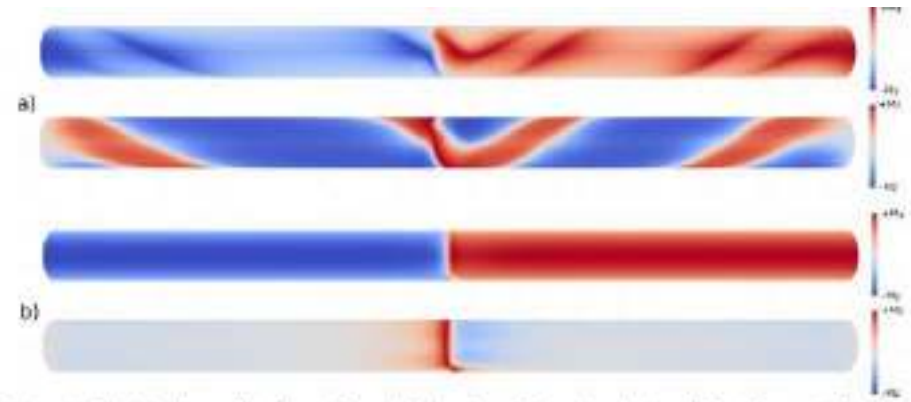

Figure 1. The My (perpendicular to the axial direction of the microwire) and Mz (along axial direction) projections of the simulated magnetic domain structures at the remanence state for different values of the magnetostriction constant: a) $\lambda = -2\times10^{-7}$ b) $\lambda = -3\times10^{-6}$.

P258 - Hybrid FFT algorithm for fast demagnetization field calculations on nonequispaced layers

10. Micromagnetics and magnetization processes

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Micromagnetic simulations are an important tool for investigating the behaviour of magnetic materials. In the following, we present a hybrid FFT approach to calculate the demagnetization field of nonequispaced layers. This method is particularly suitable for the simulation of multiple magnetic thin films with unequal thickness, as is often the case for SST-MRAM devices [1] or materials exhibiting magnetic skyrmions [2].

In the micromagnetic model, the demagnetization interaction is the only global interaction and therefore the computationally most expensive one. In a naive approach, the calculation of the demagnetization field scales with N*N, where N is the number of nodes. For large samples, this quickly becomes unfeasible.

In finite difference methods, the regularity of the equispaced grid allows the usage of Fast Fourier Transform (FFT) methods. By taking advantage of the Fast Convolution Theorem, one can reduce the computational complexity from N*N to N log(N). In general, however, the film thicknesses are not multiples of each other and choosing a discretization length for which each film thickness is a multiple of becomes computationally expensive.

In the presented algorithm we take a hybrid approach where we calculate the demagnetization field of nonequispaced layers, where each layer consists of a regular grid. In this image the layers are regular along the xy-plane and nonequispaced in the z-direction.

We adapt the formulation of the demagnetization tensor from [3] by generalizing the interaction from two homogeneous magnetic cuboids of the same size to two cuboids with different dimensions. With this generalized formulation we calculate the global demagnetization tensor. For the calculation of the demagnetization field, we perform a 2D FFT for each layer and calculate the convolution analytically along the third dimension. This method is implemented with GPU-acceleration and shows numerical agreement when compared to the Newell formulation.

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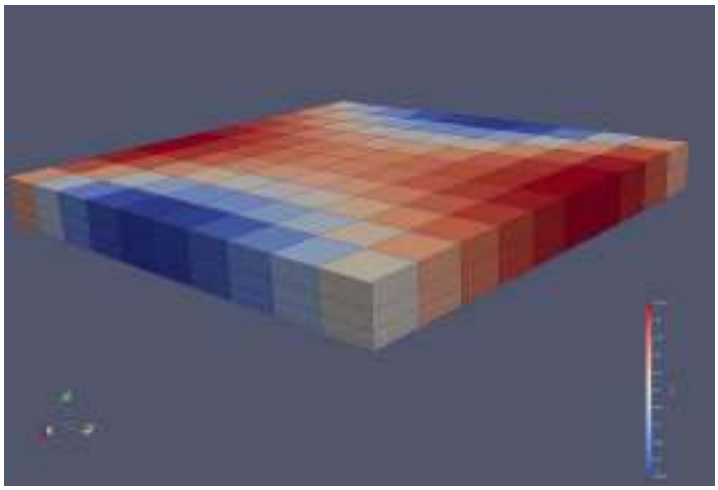

P259 - Hysteresis loop of skyrmionic structures confined in thin rings

10. Micromagnetics and magnetization processes

Nuria Del-Valle[1] , *Josep Castell-Queralt*[1], *Leonardo González-Gómez*[1], *Carles Navau*[1]
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Both existence and stability of magnetic structures such as uniform, and skyrmionic π and 2π states have been widely studied in confined geometries like nanodots. However, the dynamical transition between these states under an externally applied field remains unexplored.
Here we present a system where a symmetric hysteresis loop with changes between the uniform, π and 2π states and their negative counterparts can be found as a function of small-applied magnetic fields. The system consists in an ultra-thin ferromagnetic ring on top of a heavy metal substrate that induces interfacial Dzyalonshinskii-Moriya interaction. The transitions between the aforementioned states are studied as a function of the ring external and internal radii when a uniform perpendicular magnetic field is applied. We perform micromagnetic simulations, numerically solving the Landau-Lifshtiz-Gilbert equation in cylindrical coordinates, imposing radial symmetry on the magnetization. With this approximation, we can achieve higher numerical resolution while decreasing the computational complexity of the problem.

P260 - MagTense - a new micromagnetism code

10. Micromagnetics and magnetization processes

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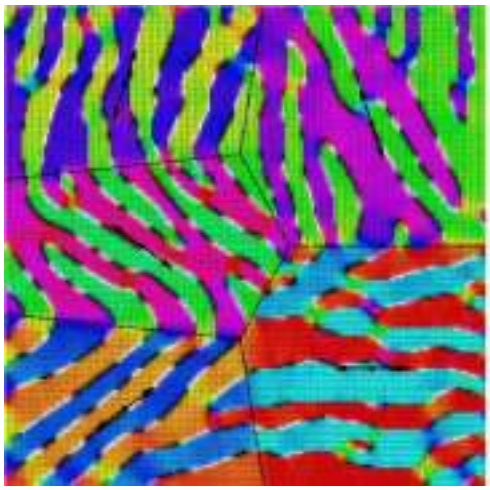
We introduce MagTense, a new open source micromagnetism modeling framework. The model is implemented in Fortran, but also comes with a direct Matlab interface through the MEX system. The code is publicly available on GitHub and documented on the MagTense.org webpage.

The computationally demanding calculation in micromagnetic problems is the computation of the demagnetizing field. In MagTense, the demagnetization field is calculated analytically from the magnetic field created by the computational elements of the code, so-called tiles. These can be prisms or tetrahedrons of any size and shape. The magnetization is assumed homogeneous within each tile and from this, the analytical expression of the demagnetizing field can be derived. This approach is somewhat similar to that employed by the OOMMF framework from NIST for calculation of the demagnetization field, except for the fact that MagTense does not currently employ the fast Fourier transformation technique to compute the field. However, because of the variety of tiles supported, the demagnetization field can be computed for more complex geometries.

The analytical calculation of the demagnetization field can be expedited through the use of a mesh hierarchy where the interactions over long distances are approximated by averaging the contributions from many tiles. The benefits of this approximation are a reduction of the memory consumption and of computation time.

In the current implementation of the code, the exchange interaction is computed by assuming a cubic crystal lattice. The time evolution of the magnetization is computed by numerically integrating the Landau-Lifshitz-Gilbert equation, which causes the magnetization distribution to evolve towards the equilibrium configuration while precessing around the effective field at any point.

To demonstrate the validity of the code, we present the computed solutions to the standard problems in micromagnetism as defined by NIST. Furthermore, in the two images below we present two examples of simulations with the model. In both cases, the resulting patterns can be explained as a consequence of the trade-off between competing interactions. The simulation on the left figure shows the magnetization within a thin permanent magnet consisting of five grains, delimited by the black dashed lines. Each grain has a different easy axis direction, which is indicated by the double-tip arrow. In absence of an external field, the magnetization distribution has a tendency to form closed loops in order to minimize the demagnetization energy. The resulting magnetic domains exhibit a striped pattern of alternating magnetization directions. Inside each domain the direction of the magnetization vector is oriented fairly precisely along either the positive or negative easy axis direction. The macroscopic effect of this configuration is that the total magnetic moment of the magnet is almost zero, or equivalently that the magnetic field generated outside the sample is minimized. For the simulation shown on the right figure, the easy axis is perpendicular to the surface of the film. Here we observe the emergence of a maze-like pattern that occurs in many different physical and biological systems.



P261 - Micromagnetic study on reversal nucleation of magnetization induced by magnetic nanoparticles

10. Micromagnetics and magnetization processes

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Chip based biodetection systems using spintronic sensors and magnetic nanoparticles (MNPs), used to label biological structures, have demonstrated very high sensitivity and easy integration in read-out electronic circuits for data acquisition and signal processing. These sensors are based on giant magnetoresistance effect (GMR), planar Hall effect (PHE) or tunnelling magnetoresistance effect (TMR). The detection is based on the magnetostatic interaction between the MNPs and the sensor's free layer (sensing layer). From technological reasons, most of the MR sensors used for magnetic field detection were patterned into rectangular stripes in order to utilize the shape anisotropy for linearization of the transfer curve. Therefore, many analytical or numerical models used to describe the interaction between MNPs and the spintronic sensors are based on a uniform magnetized sensing layer. However, it was shown that such micrometre sized structures, with large aspect ratio, have a limited dynamic range in terms of MNPs detected. At the low end, the limitation comes from the signal to noise ratio (SNR) which establishes the minimum number of MNPs that can be detected. At the high end, the limitation comes from the maximum number of MNPs that can be placed over the sensor's surface. In this contribution we present a study on the optimum design of the sensing layer in order to increase the MNPs detection dynamic range. The sensing scheme is based on the PHE which can assure a quite large detection area, large SNR and a very good thermal stability. The structures are of the type Permalloy/NM/AFM, where AFM denotes antiferromagnetic layer and NM denotes nonmagnetic layer. In previous studies, we found that (i) the detection sensitivity depends on the position of the MNPs over the sensor surface and (ii) the magnetization reversal in the sensing layer is strongly affected by the presence of the MNPs and their magnetization state. Now, we carried out micromagnetic simulations, using OOMMF, to explore the magnetic reversal nucleation in the sensing layer assisted by MNPs. Three geometries of the Permalloy sensing layer were used for simulations: square 2 µm wide, disk 2 µm in diameter, and ring with 2 µm the external diameter. The layer thickness is 10 nm. An exchange biasing field in between 1 and 20 mT was considered. We analysed the effect of the local field generated by MNPs (cubes with 20-50 nm each side) with different saturation magnetizations between 350 kA/m to 480 kA/m. To acquire a high magnetic moment, the MNPs are magnetized under a field in between 10 and 20 mT, applied perpendicular to the sensor surface. We found a strong local interaction between the MNPs and the sensing layer so that a single MNP could be detected from the shift, through the coercive field, and the shape of the magnetization curve. The results are compared with experimental data.

Acknowledgements: *This work was supported by a grant of the Romanian Ministry of Research and Innovation, CCDI-UEFISCDI project number 3PCCDI/2018, within PNCDI III.*

P262 - Realistic finite temperature description of magnetic systems with quantum statistics

10. Micromagnetics and magnetization processes

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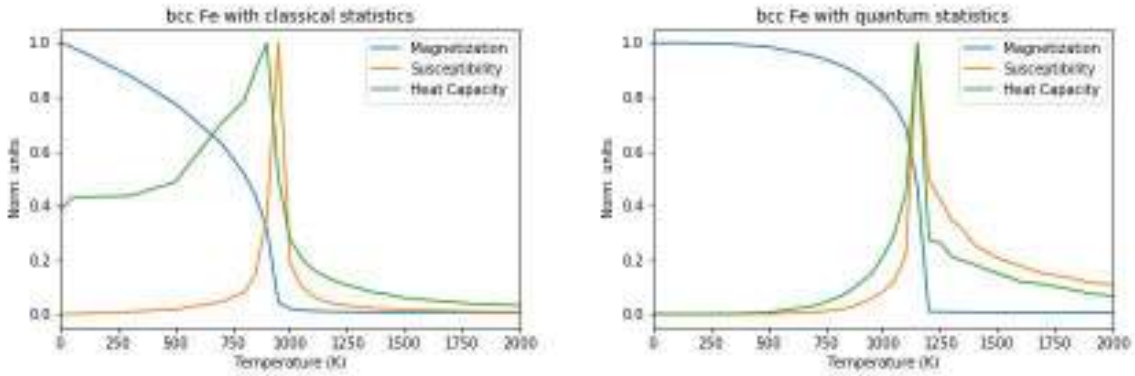
State-of-the-art simulations based on electronic structure theory and atomistic models have evolved to a point where computer-guided materials design has become a realistic option for many classes of materials. For theoretical phase stability determinations, an accurate calculation of the free energy is crucial. When using classical statistics, the spin contribution to the free energy is however typically overestimated, especially at low temperatures. Introducing quantum statistics into atomistic simulations has been shown to improve the observed temperature dependence of the magnetization and of the magnetic specific heat. This allows for a more realistic modeling of the magnetic contribution to the free energy which can be exploited for a better description of phase-stabilities and related properties.

In this talk we will present how quantum statistics can be modelled with varying levels on complexity and combined with atomistic spin dynamics and Monte Carlo spin simulations. The methods rely on the magnon density of states at finite temperatures, and we will discuss how this magnon density of states can be obtained and what effect it has on the behavior of the quantum statistics. We demonstrate the method for both elemental systems as bcc Fe as well as magnetic alloys including Fe-Co alloys.



P263 - Reducing the switching current with an antiferromagnetic coupling structure in nanomagnets

10. Micromagnetics and magnetization processes

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The author has chosen not to publicise the abstract.

Field 5

Field 6

P264 - The profile of chiral skyrmions for a small radius

10. Micromagnetics and magnetization processes

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Chiral skyrmions have been observed in ferromagnetic materials with the Dzyaloshinskii-Moriya interaction (DMI) and techniques have been developed for individual skyrmions to be created and annihilated. Skyrmions are examples of magnetic solitons in ferromagnetic films that exhibit particle-like behavior in the sense that they are localized robust entities both regarding their statics and their dynamical behavior. These features make them attractive for theoretical studies in order to understand the details of their behavior while it also gives them a strong potential for applications.

Chiral skyrmions are derived as stable particle-like solutions of the Landau-Lifshitz equation for ferromagnets in the presence of DMI. The existence of such solutions has been rigorously proved, but so far no analytic formula for the skyrmion profile has grown out of rigorous mathematical reasoning. Instead, an ad-hoc ansatz based on explicit domain wall profiles is widely used to examine structural and dynamic properties.

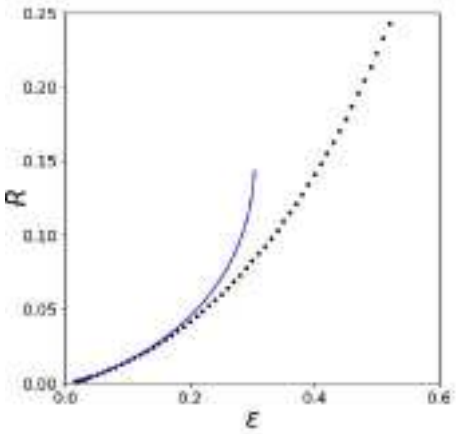
We derive formulas for the skyrmion profile by employing asymptotic methods that give analytic approximations for the solutions of the Landau-Lifshitz equation. Our methods are valid for small DMI constant or large anisotropy and they can readily be extended to the case of a large external field. We derive formulas for the skyrmion core (near field) and the skyrmion tail (far field). The derived solutions show the detailed features and the different length scales which are present in the skyrmion profile. The role of the DMI for the existence of skyrmion solutions is revealed.

The Belavin-Polyakov (BP) solution of the pure exchange model is shown to play the role of a universal limit of skyrmion profiles, and the deviation from this profile is given quantitatively. The picture is created of a chiral skyrmion that is born out of a BP solution with an infinitesimally small radius, as the DMI constant is increased from zero. The skyrmion retains a quasi-BP profile over and well-beyond the core before it assumes an exponential decay.

A product of our calculations is the formula $\varepsilon = -2R \ln(R/0.413)$, where R is the skyrmion radius (in domain-wall width units) and ε is a small parameter proportional to the DMI constant and inversely proportional to the anisotropy. The formula is obtained as a matching condition of the near and the far fields. It explicitly shows that the skyrmion radius decreases with decreasing DMI (or increasing anisotropy). The figure shows numerically obtained results by black dots and the above formula by a solid line. The approximation is exact in the limit $\varepsilon << 1$.

The availability of mathematically derived formulas will facilitate the comparison of experimentally observed profiles, particularly focusing on some of their special features, and may be useful for a variety of other purposes. Specifically, the skyrmion profile enters in an essential way in formulas for dynamical phenomena, for example, skyrmion translation and rotation modes, and it is crucial for quantitative calculations.

This project has received funding from the Hellenic Foundation for Research and Innovation (HFRI) and the General Secretariat for Research and Technology (GSRT), under grant agreement No 871.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P265 - Thermally driven dynamics of Néel-type skyrmion in a ferromagnetic nanodisk

10. Micromagnetics and magnetization processes

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The author has chosen not to publicise the abstract.

Field 5

Field 6

P266 - Topological spin textures inside easy cone medium

10. Micromagnetics and magnetization processes

Alexander Kolesnikov[1] , *Maxim Stebliy*[1], *Alexander Samardak*[1], *Alexey Ognev*[1]
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Topological spin states are proposed for integration in spintronic circuits as information carriers in nonvolatile logic and memory devices [1, 2]. Particle-like spin structures such as vortices, merons and skyrmionic states have different static and dynamic features which are determined by their topology. An important task is the study of conditions and medium for the stabilization of such topological states. Dzyaloshinskii-Moriya interaction (DMI) is usually used to obtain skyrmions in ferromagnetic films [3-5]. Here we show observation skyrmionic or meron-like states in thin films without DMI, where strong second order anisotropy constant (K_2) tilts the magnetization away from the normal and stabilizes easy-cone state (insert Fig.1(b)) [6].

The stability of topological spin textures was investigated using MuMax^3 [7]. Four initial states were set inside the film Neel-type and Bloch-type skyrmions with positive and negative chirality. After the relaxation in zero field meron-like spin states with Bloch domain wall are remained. First observation we found that easy cone anisotropy allows stabilize different chiralility of topological states (left-handed and right-handed) in comparison with DMI [5]. The Nudged Elastic Band Method was used for the energy barrier simulation between meron-like and ferromagnetic state in our structure (Fig. 1(a)). Meron-like states have topological charge $N<1$ because magnetization rotates less than 180 degrees from the core to periphery. Evidence of the similar spin textures was shown in our previous paper [9].

Since the canting angle of the magnetization depends on the values of perpendicular magnetic anisotropy constants $\theta_c=\arccos(\sqrt{-K_1/2K_2})$ it possible to modulate the winding angle inside the domain wall. We performed micromagnetic simulations of the film with variable θ_c, changing the relation of K_1/K_2. Figure 1(b) shows that topological charge of our spin textures could be precisely controlled in range from 0,5 to 0,9. The value of N influences on the dynamic properties under the action of spin current. Skyrmion and topological Hall angles become flexible parameters in such topologically tunable magnetic states.

This work was supported by the Russian Ministry of Education and Science under the state task №3.5178.2017/8.9, Russian Foundation for Basic Research (№19-02-00530, №18-32-20057, №18-32-00867).

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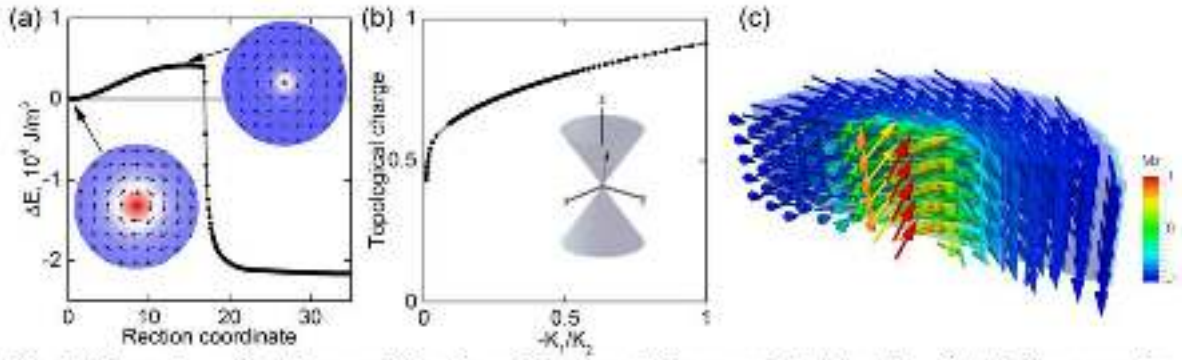

Fig. 1 (a) Dependence of total energy of the spin configurations during meron-like state collapse into the ferromagnetic state. (b) Topological charge for meron-like as a function of anisotropy constants ratio. (c) Cross section of meron-like state observed in easy cone medium.

11. Nanomaterials, patterned films, nanoparticles and molecular magnetism

P267 - Analytical model of magnetization switching in amorphous glass-coated nanowires and submicron wires

11. Nanomaterials, patterned films, nanoparticles and molecular magnetism

Tibor-Adrian Ovari[1] , *Cristian Rotarescu*[1], *Horia Chiriac*[1], *Nicoleta Lupu*[1]
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Glass-coated amorphous nanowires and submicron wires having diameters between 100 and 900 nm have been prepared using an improved variant of the glass-coated melt spinning method [1]. Their main characteristic is a single-step magnetization reversal that takes place when the applied magnetic field is larger than a certain threshold value called switching field, H^*. This magnetically bistable behavior has been widely investigated in the thicker glass-coated amorphous microwires with diameters between 1 and 50 micrometers [2]. Magnetic bistability in such cylindrical wires was found suitable for use in pulse generating elements and in various sensing devices, such as position, field sensors, magnetostrictive delay line sensors, encoded security tags, etc.
Here we propose a general analytical method for the calculation of the magnetic switching field in rapidly solidified amorphous nanowires and submicron wires with various diameters. The calculated values are checked against experimental ones determined from the hysteresis loop measurements. Hysteresis loops have been measured using an inductive method in the case of $Fe_{77.5}Si_{7.5}B_{15}$ amorphous nanowires and submicron wires.
Magnetization switching in such samples has been described as a nucleation at coercivity process. Nucleation means that a new magnetic domain wall is formed. The reversal process is thus controlled by the balance of three energy terms: domain wall energy, magnetostatic energy variation, and Zeeman energy (applied field). The energy balance has resulted in an analytical expression for the switching field, in which H^* is proportional to $(K/D)^{2/3}$, where K is the average magnetoelastic anisotropy due to the magneto-mechanical coupling between magnetostriction and the internal stresses induced during the rapid solidification entailed by the glass-coated melt spinning technique, whilst D is the diameter of the considered nanowire or submicron wire samples.
The experimental and calculated values of the switching field H^* are shown in Table I. One observes that there is a very good agreement between the results of the measurements and the calculated results, which validates the proposed phenomenological approach.
This analytical model of magnetization switching allows one to accurately tailor the magnetization reversal process and its parameters within the cylindrical amorphous nanowires and submicron wires through dimensions, and, at the same time, to understand their specificities at the nanoscale, in order to develop novel sensing devices with significantly reduced dimensions and power requirements.

Acknowledgement - Work supported by the Romanian Ministry of Research and Innovation (MCI) through the Executive Agency for Higher Education, Research, Development and Innovation Funding (UEFISCDI) under project PN-III-P4-ID-PCE-2016-0358 (contract no. 149/2017).

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Wire diameter (nm)	Glass thickness (μm)	Experimental switching field (kA/m)	Calculated switching field (kA/m)
134	6.0	7.40	7.27
350	15.0	4.20	3.92
535	12.0	2.60	2.82
850	12.0	1.60	1.87
900	15.0	1.40	1.71

P268 - Asymmetry and resonant pinning spectroscopy of spin vortex pairs

11. Nanomaterials, patterned films, nanoparticles and molecular magnetism

Milton Persson[1] , *Erik Holmgren[1], Artem Bondarenko[2], Boris Ivanov[2], Vladislav Korenivski[1]*

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The spin vortex state in magnetic nanoparticles has shown promise as a candidate for memory [Pigeau APL 96 132506 (2010); de Araujo PRApplied 6 024015 (2016)] and oscillator [Pribrag Nat Phys 3 498 (2007); Wintz Nat Nano 11 948 (2016)] applications. Nano-devices, however, contain imperfections due to the always present fabricational uncertainties. Spin vortices, in particular, are affected by the presence of magnetic imperfections and morphological defects. Due to the highly localized Gaussian profile of the vortex core, local variations at the nano-scale in the device properties can affect the performance. Core-pinning has been shown to lead to Barkhausen-like noise as the vortex core moves through the respective magnetic film.[Burgess Science 339 1051 (2013)] Additionally, defects can significantly alter the dynamics, which is well represented by the motion of the core of the vortex.[Compton et al. PRL 97 137202 (2006); Chen et al. PRL 109 097202 (2012)]

We show, experimentally as well as using analytical and micromagnetic modeling, how magnetic asymmetry in a strongly coupled spin-vortex pair with parallel core polarization and antiparallel chirality (the P-AP state) can be used to differentiate, magneto-resistively, the otherwise degenerate multiple topological states of the pair. The imperfections studied include vortex-core length asymmetry, biasing-field asymmetry (due to imperfect flux-closure of the reference SAF), and pinning (due to interface roughness and intrinsic magnetic imperfections) of one of the two vortex cores in a P-AP pair. Our results should be useful in light of the recent proposals of coding information onto multiple topologically protected states, such as multiple vortex polarization/chirality states.

Further, the same type of vortex pairs, with pinning of one of the cores by a morphological defect, are used to perform resonant pinning spectroscopy, in which a microwave excitation applied to the nanopillar produces pinning or depinning of the cores. A shift in the two eigenmodes' frequencies of the coupled vortex pair, as the cores are excited between the pinned and depinned states, is determined experimentally and explained theoretically. We show how the resonant pinning spectroscopy technique can be used as a sensitive nanoscale probe for characterizing morphological defects in magnetic films.

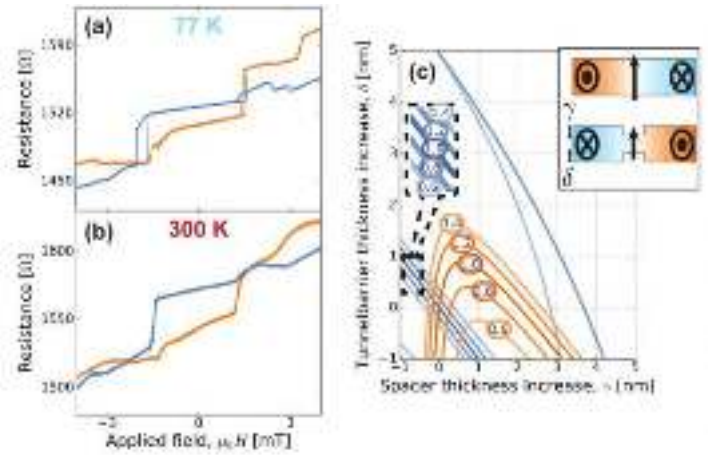

Figure 1: Measured R-H loops at (a) 77 K and (b) 300 K for two P-AP states with opposite chiralities (blue versus orange) within the same junction. The two states are non-degenerate due to a pinning site shifting the zero field position of the pair. The states can still be distinguished at high temperature as the pinning site, due to the particular energetics of the P-AP state, does not create a second minimum in the potential. (c) Contour lines of the relative frequency shifts, $\Delta f_r/f_r$, of the gyrational (blue curves) and rotational (orange curves) modes of the coupled P-AP state when one of the cores is pinned by surface roughness. The roughness is characterized by parameters δ and γ as illustrated in the inset.

P269 - Biocompatible magneto-elastic membrane with NiFe arrays: optical response under magnetic actuation

11. Nanomaterials, patterned films, nanoparticles and molecular magnetism

Hélène Joisten[1, 2] , *Alain Truong[1], Svetlana Ponomareva[1], Cécile Naud[1],* ***Robert Morel***[1], *Yanxia Hou[3], Isabelle Joumard[1], Stéphane Auffret[1], Philippe Sabon[1], Bernard Dieny[1]*

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Biocompatible suspended magneto-elastic membranes were developed and characterized, in particular through their optical response. They consist of PDMS (Polydimethylsiloxane) films, optionally sandwiched between Au/layers, embedding arrays of micrometric magnetic pillars, made by lithography techniques (see **Fig.1**) - partially derived from previous permalloy-vortex particles studies **[1]-[2]**. The magneto-elastic membranes were characterized, focusing on: **i)** the membrane magnetic properties, **ii)** the determination of the applied magnetic field amplitude and gradient, generated by the permanent magnet used for the membrane actuation, **iii**) the resulting magnetic forces exerted on the deformable membranes, **iv)** the determination of the corresponding elastic membrane deflection, **v)** the resulting optical responses to magnetic actuation when the membrane, becoming concave under the application of the magnetic field, is illuminated by a laser beam. For visible light wavelengths, our membranes constitute magnetically tunable optical diffraction gratings, in transmission and reflection. The optical response has been quantitatively correlated with the membrane microscopic structure and its deformation, using our optical and magneto-mechanical models. (See Ref **[3]**).

In contrast to the case of planar membranes, as could be expected, the diffraction patterns measured in reflection and transmission vary very differently upon magnetic field application. In reflection, even weak membrane deformation can produce significant changes of the diffraction patterns, whereas the transmitted patterns remain almost unchanged. This field controlled optical response may be used in adaptive optical applications, photonic devices, as well as for biological applications. The next aim will be to include this type of biocompatible magneto-elastic membrane in biological applications, and to study the effects of its magnetic actuation on biological samples.

Acknowledgement

This work has been supported by the European grant ABIOMATER 665440.

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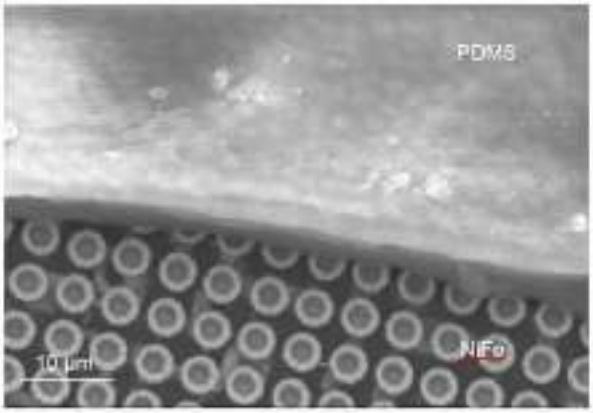

Figure 1. Scanning electron microscopy image of a magneto-elastic membrane detail, showing the permalloy pillars array, covered by the PDMS layer, partially removed for imaging.

P270 - Complex Refractive Index and Inhomogeneity of Electromagnetic Fields inside 3D Magnetic Materials

11. Nanomaterials, patterned films, nanoparticles and molecular magnetism

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Complex Refractive Index and Inhomogeneity of Electromagnetic Fields inside 3D Magnetic Materials

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Abstract

Metamaterials based on opal matrix and containing magnetic particles are studied both experimentally and theoretically. Their magnetic and electromagnetic properties are investigated. Complex refractive indexes at frequencies of millimeter waveband are obtained by comparing the results of calculations with the experimental data on transmission and reflection coefficients and their variations with an applied magnetic field.

The metamaterials under study contain metallic cobalt, nickel and iron particles, nickel-zinc ferrite and silver particles, or ferrite-garnet $Nd_3Fe_5O_{12}$ particles into the interspherical voids.

Magnetic properties of the nanocomposites are studied with MPMS-XL set up from Quantum Design in magnetic fields to 50 kOe at temperatures 2 and 300K. It is shown that for the nanocomposites with metallic particles the magnetization and coercive field change slowly with temperature whereas for the nanocomposites with ferrite particles changes of magnetic properties are very essential.

Microwave measurements are carried out in two frequency ranges from 12 to 38 GHz and from 12 to 17 GHz by using the conventional rectangular waveguides operating on TE_{10} mode. A single-mode regime is realized in the whole frequency range. All microwave measurements are carried out at room temperature with the scalar network analyzer. The modules of transmission and reflection coefficients were measured as well as their relative variations in external magnetic field. Frequency dependences of transmission and reflection coefficients were measured in order to obtain the complex dielectric permittivity and microwave conductivity. The highest microwave conductivity belongs to the nanocomposite with $Ni_{0.5}Zn_{0.5}Fe_2O_4$ + Ag particles. The point is that the silver particles are added in this nonocomposite intentionally in order to increase conductivity. Particles of ferrite-spinel $Ni_{0.5}Zn_{0.5}Fe_2O_4$ in the nanocomposite have highest magnetization. The lowest microwave conductivity and magnetization are inherent to the nanocomposite with ferrite-garnet $Nd_3Fe_5O_{12}$ particles.

Then the magnetic field dependences of the microwave refractive index are calculated on macro- and micro-scales. It is established that the shape of magnetic field dependency and the value of the resonance field are quite different on micro- and macro-scales in materials with metallic particles and with high magnetization of particles.

The parameter is proposed by using of which one can estimate the heterogeneity of the microwave field on different space scales. The algorithm how to calculate this parameter is developed. It can be calculated accordingly to the rules for refraction index calculation of

the media which dielectric permittivity is equal to the same for the studied media and the complex conjugated magnetic permeability is taken. Our calculations confirmed that nonuniformity of electromagnetic field inside the metamaterial is extremely high and essentially depends on magnetic field. The refraction modulus tends to its macroscopic value if averaging is carried out at the distances of 8 – 10 lattice parameters of the artificial opal crystal.

P271 - Cr, Mn, Fe transition metal clusters on defected graphene: A First-principles study

11. Nanomaterials, patterned films, nanoparticles and molecular magnetism

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The author has chosen not to publicise the abstract.

Field 5

Field 6

P272 - Decorated Manganese Ferrite Nanoparticles on MWCNTs for Faster Dye Removal without the External aide

11. Nanomaterials, patterned films, nanoparticles and molecular magnetism

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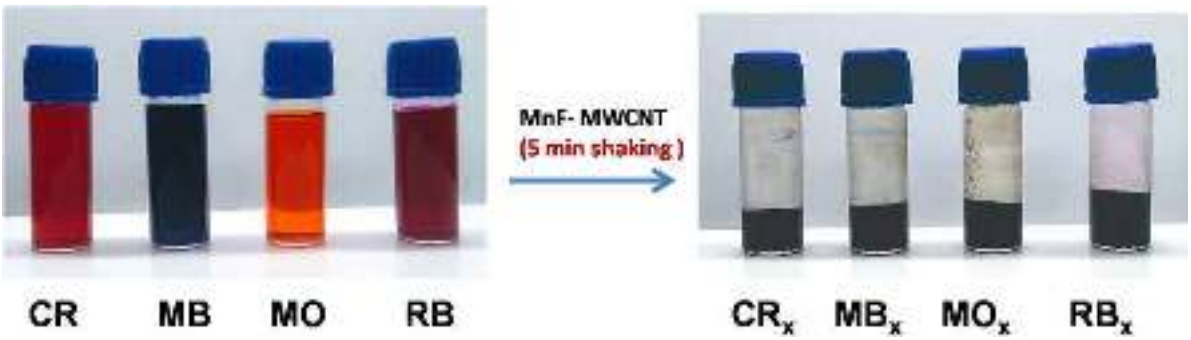
A uniform distribution of manganese ferrite ($MnFe_2O_4$,i.e., MnF) nanoparticles (NPs) decorated on MWCNTs was synthesized using simple microwave-assisted chemical and sonication method. Structural spinel phase from the XRD study and high specific surface-area of 142.93 m^2/g from BET analysis was revealed. FESEM indicated MnF NPs uniformly decorated over MWCNTs with NPs below 20 nm. Further, the obtained MNPs were used in dye degradation studies for the removal of various dyes (here Congo red, Methyl orange, Methylene blue, Rhodamine B) dissolved in water. The UV-VIS spectrophotometer was used to measure percent dye removal from water which showed successfully and through removal of high concentration of all the four dyes in relatively few minutes without any external aide (see figure below). Moreover, these MNPs show strong magnetic properties revealing the reusability. This study indicates the ability of instant dye removals due to highly porous nature as well as high adsorption properties of decorated MnF NPs on MWCNT.

Keywords: MWCNT, Dye removal, Manganese ferrite



P273 - Defect ferromagnetism in SnO2:Zn 2+ hierarchical nanostructures

11. Nanomaterials, patterned films, nanoparticles and molecular magnetism

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We report on the ferromagnetism of $Sn_{1-x}Zn_xO_2$ ($x \leq 0.1$) hierarchical nanostructures with various morphologies synthesized by a solvothermal route. A room temperature ferromagnetic and paramagnetic response was observed for all compositions, with a maximum in ferromagnetism for $x = 0.04$. The ferromagnetic behaviour was found to correlate with the presence of zinc on substitutional Sn sites and with a low oxygen vacancy concentration in the samples. The morphology of the nanostructures varied with zinc concentration. The strongest ferromagnetic response was observed in nanostructures with well-formed shapes, having nanoneedles on their surfaces. These nanoneedles consist of (110) and (101) planes, which are understood to be important in stabilizing the ferromagnetic defects. At higher zinc concentration the nanostructures become eroded and agglomerated, a phenomenon accompanied with a strong decrease in their ferromagnetic response. The observed trends are explained in the light of recent computational studies that discuss the relative stability of ferromagnetic defects on various surfaces and the role of oxygen va0cancies in degrading ferromagnetism *via* an increase in free electron concentration.

P274 - Drug-release controlling nanoparticles with field-dependent spin-correlated radical pair system

11. Nanomaterials, patterned films, nanoparticles and molecular magnetism

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Up to now, numerous techniques have been developed to make a careful examination of magnetic nanoparticles for biomedical engineering applications to drug-delivery system (DDS). Our previous reports also provided precious findings about the drug-release potential of liposomal DDSs with magnetic controls [1]–[5]. And it goes without saying that the methodology will depend to a large degree on technological improvements in the membrane structure of liposomal nanoparticles equipped with various ions and properties. As further research, we used some radical pair-forming compounds (e.g., flutamide (FM): 2-methyl-*N*-[4-nitro-3-(trifluoromethyl)phenyl]propanamide) to examine whether magnetic fields can control the drug release through changes in the physical properties of liposomal membranes.

The relative yields of FM-corresponding escape-radicals with magnetic field effects Φ_{ER}were determined referring to the reported method [6], based on the following relation:

$$\Phi_{ER} = \Phi_{-FM} - \Phi_{UP} - \Phi_{CP} \quad (1)$$

where $\Phi_{-FM}$is the FM-photodegradation yield, $\Phi_{UP}$is the yield related to the radical pair-unrelated photoreaction product, and $\Phi_{CP}$is the yield related to the radical pair-deriving cage product.

According to the results of our liposomes prepared in this research, the escape-radical releases obtained using a magnetic field of 0.25 Thad not gone as completely as it could have gone.We postulated the possibility that the precision of liposomal drug releases with magnetic controls may be obtained by having no bis-allyl proton in its membrane structures. Additionally, it may be supposed that at least 0.1 T is needed for detectable magnetic field effects.Such differences in the field dependence must be overall results of the liposomal membrane packing, the influence of a singlet radical pair-deriving escape radicals, radical pair-unrelated photoreaction products, and so on, independently of the escaping process of a triplet radical pair-derivingfree radicals.

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P275 - EFFECT ON MAGNETIC SATURATION WHEN ADDING COATINGS TO MAGNETITE

11. Nanomaterials, patterned films, nanoparticles and molecular magnetism

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Magnetite has become the focus of attention for its research thanks to its magnetic properties such as magnetic saturation, blocking temperature, superparamagnetismo and biocompatibility. In recent years have been addressed studies on the applications of nanoparticles in medicine for the treatment and diagnosis of cancer, and have been the iron oxide nanoparticles (magnetite Fe_3O_4, maghemite – Fe_2O_3) which have taken great importance in this type of applications , either by transporting drugs, improving the quality of diagnostic medical images, or by being used in teranostic procedures: combined uses for cancer therapy, detection and diagnosis.

In this work we studied the effect that it could cause on the magnetic saturation by having more than one coating on the magnetite. The magnetite was synthesized by the thermal decomposition method, obtaining magnetite nanoparticles of size between 20 and 50 nm, which is shown with SEM images, a magnetic saturation of 60 emu / gr for pure magnetite, 53 emu / gr for magnetite with biopolymer coating, in this case gum arabic, 61 emu / g of magnetite with biopolymer plus gold. The x-ray diffraction patterns (XRD) of the magnetite, confirming that the crystalline phase corresponds to nanoparticles of reverse spinel magnetite was obtained (JCPDS No.82-1533). Were attributed to the (220), (311) (400), (333) and (440) crystallographic plans of face centered cubic (FCC) in the Fe3O4. For the magnetite with the coating of the gum arabic and gold, the peaks attributed to (200) and (400) are not observed.

P276 - In-detailed study of Magnetic, Dielectric and Microwave properties on MnFe2O4 Nano-Hollow Spheres

11. Nanomaterials, patterned films, nanoparticles and molecular magnetism

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From the detail studies of structural, magnetic, dielectric and microwave properties, $MnFe_2O_4$ (MFO) nano-hollow spheres (NHS) are found interesting towards its application in high-frequency devices as well as in bio-medical fields. Single crystal MFO NHS of size ~ 250 nm is synthesized in one step template free solvothermal method and the morphology is analyzed through FESEM and TEM micrographs. The crystallographic phase is determined using profile analysis of XRD pattern. Room temperature magnetization (M) study on MFO NHS displays its soft ferrimagnetic nature with H_C, M_R and M_S values of 127.7 Oe, 15.3 emu/g and 57.8 emu/g respectively. Domain structures of NHS and temperature dependence of M are predicted from the Day plot and Bloch's power law. Variation of dielectric properties such as permittivity (ε), and ac conductivity (σ) of these NHS with frequency is explained on the basis of Maxwell-Wagner two-layer model for space charge and cationic interactions in between tetra- and octahedral sites. Permeability (μ), ε, and Reflection loss (RL) are studied in 2-18 GHz frequency range on composites filled (20 wt% and thickness of 4.1 mm) with sample. Hollow cavity of NHS leads to a lower density as well as multiple internal reflections enhances Electro-Magnetic wave absorption (optimal RL ~ -52 dB). These properties ensure its potentiality as light-weight, size efficient microwave absorbing material.

P277 - Influence of Co nanocluster inclusions on magnetic hardness of L10-FePt films

11. Nanomaterials, patterned films, nanoparticles and molecular magnetism

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Nanocomposite magnets, consisting of a fine mixture between a large magnetocrystalline anisotropy phase and a large magnetization phase, is a promising route to develop new permanent magnets with unprecedented performances. Theoretical calculations predicted a potential energy product of 1 MJ/m3, which is twice as large as the one of best Nd2Fe14B magnets produced today [1]. But these calculations also pointed out the absolute necessity to confine the softer phase in nano-sized grains, typically smaller than 10 nm, which cannot be obtained with conventional process for mass scale material fabrication. So far only very few experimental works with encouraging results have been reported on such exchange-spring magnet [2].

We recently prepared Co@FePt transition metal (TM)-based nanocomposite films from low energy cluster beam deposition technique (LECBD) of Co clusters, in situ embedded in FePt matrix independently produced by alternative electron gun evaporation on the same substrate [3,4]. This nanofabrication technique gives a fine control over the microstructure. The Co cluster inclusions can be selected in size prior their deposition, between 1 and 10 nm. The cluster to matrix volume ratio is adjusted controlling the thickness of each Co, Fe, Pt individual layers. Annealing is a crucial step to drive the initial Fe and Pt multilayers to the high-magnetic anisotropy L10 phase with a limited diffusion of the clusters in the matrix. Specular X-rays Diffraction revealed a thermal transition to a chemically ordered L10-FePt alloyed matrix with a partial texture on Si substrate while environmental-TEM and EDX analyses allowed us to observe the partial diffusion of the Co clusters in the hard matrix.

Recently, X-ray absorption spectroscopy measurements (EXAFS, XLD and XMCD) were performed on annealed Co@FePt nanocomposite with various clusters concentrations and compared to equivalent multilayer samples at Fe and Co K-edges at BM30 and ID12 beamlines at the ESRF. The structural analysis proved that the Co cluster doesn’t entirely mix with the matrix during annealing contrary to multilayers. The study of such model system could give insights about the role of the nanostructure on magnetic hardness and could thus guide the development of mass scale synthesis processes.

This work is supported by the ANR collaborative project “SHAMAN”: Soft in HArd MAgnetic Nanocomposites (2017-2020).

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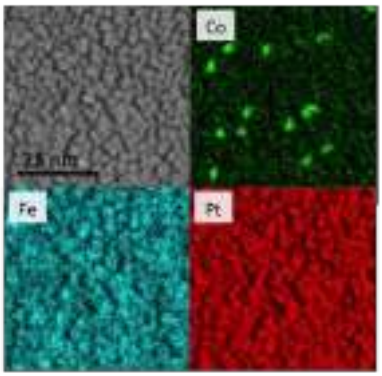

Figure: EDX-TEM chemical analysis of Co@FePt nanocomposite made by combined LECBD and ebeam evaporation techniques

P278 - Large coercivity Cr2Te3 ultrathin nanosheets synthesized by codoping Co and Se

11. Nanomaterials, patterned films, nanoparticles and molecular magnetism

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Permanent magnetic materials (also called hard magnetic materials) are widely used in the fields of wind power and electric vehicles because of their high coercive force (Hc) and high magnetic energy product $(BH)_{max}$. In recent years, with the rapid development of the above technologies, the demand for permanent magnet materials has increased in recent years. Because rare earth elements can generate strong spin-orbit coupling with 3d transition elements, they become the first choice for the preparation of permanent magnetic materials [Adv. Mater., 23, 821 (2011)]. However, due to the disadvantages of high price, easy corrosion, and difficult processing of rare earth materials, reducing rare earth content in hard magnetic materials or developing rare earth-free hard magnetic materials is the inevitable trend for the global sustainable development of permanent magnetic materials.

Several novel rare-earth-free hard magnetic materials have been theoretically predicted and synthesized experimentally [Chem. Mater., 23, 3769 (2011)]. In particular, transition-metal chalcogenide nanostructures such as Fe_3Se_4 with giant coercivity exceeding 4 Tesla at low temperature have been reported. It is well known that some Cr-Te based compounds have the similar lattice structures with Fe-Se compounds and most of them are ferromagnetism. However, the hard magnetic Cr-Te compounds with large coercivity are rarely investigated [Nanoscale,10, 11028 (2018)].

Here $Cr_{2-x}Co_xTe_3$, $Cr_2Te_{3-y}Se_y$ and $Cr_{2-x}Co_xTe_{3-y}Se_y$ series of rare earth-free hard magnetic nanomaterials were prepared by a facile high-temperature organic liquid-phase reaction method, and the effects of doping on the structure and magnetic properties of the obtained nanosheets were studied. Co doping can obviously increase the coercivity (Hc) and Se doping can significantly improve the saturation magnetization (Ms). When the Se doping was x=0.6, the coercivity reaches the largest value. The maximum was increased from Hc = 8.8 kOe and Ms = 18.4 emu/g of pure Cr_2Te_3 to Hc = 12.0 kOe, Ms = 24 emu/g, which is related to its order degree and Cr-Cr distance. The results showed that when Co doping was x=0.40, $Cr_{1.6}Co_{0.4}Te_3$ showed a flower-like nanomaterial, the maximum coercivity was reached, Hc=16.0 kOe. When Co and Se were co-doped, Hc and Ms of codoped $Cr_{1.8}Co_{0.2}Te_{2.85}Se_{0.15}$ can reach to about 13.7 kOe and 29.8 emu/g, respectively, as shown in Fig. 1(a). Also the sample exhibited a leaf-like ultrathin nanosheet in Fig. 1(b). Compared with the pure Cr_2Te_3, the magnetic energy product has significantly increased. Such results indicate that Cr_2Te_3 will become a potential Cr-based hard magnetic nanomaterial.

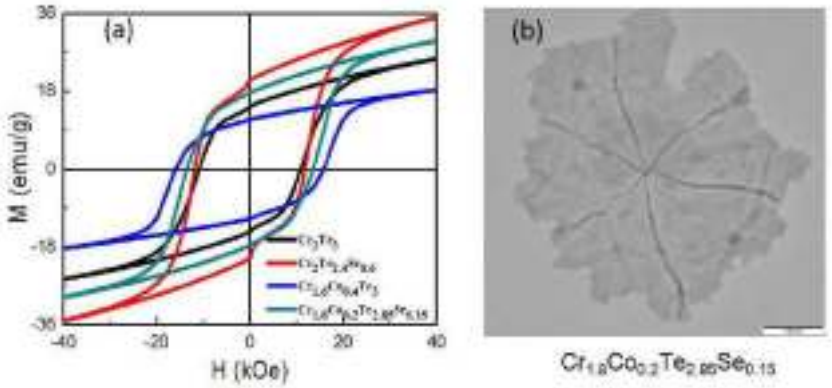

Fig.1 (a) Magnetic hysteresis loops of pure and doped Cr_2Te_3 samples measured at 5 K, (b) TEM image of Co and Se codoped $Cr_{1.8}Co_{0.2}Te_{2.85}Se_{0.15}$ nanosheet.

P279 - Magnetic and Morphological Properties of Zn-Fe-Oxide-Based Core-Shell Nanoparticles

11. Nanomaterials, patterned films, nanoparticles and molecular magnetism

Javier Lohr[1] , *Adriele A Almeida[1, 2], **Luiz C C M Nagamine**[3], M Sergio Moreno[1], Horacio Troiani[2, 4], Gerardo F Goya[5, 6, 7], Teobaldo H T Molina[6, 7], Rodrigo Fernandez-Pacheco[6, 7], Elin L Winkler[1, 2], Marcelo V Mansilla[1], Renato Cohen[3], Luis M Rodríguez[1], Daniel E Fregenal[1], Roberto D Zysler[1, 2], Enio Lima, Jr[1]*

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One-step synthesis by thermal decomposition is used to prepare three Zn-Fe-oxide-based core-shell bi-magnetic (Antiferro-/ferrimagnetic) nanoparticles. Zn/Fe ratios (0, 0.06 and 0.10) are obtained from the analyses of PIXE spectra. High resolution transmission electron microscopy images clearly show core-shell structures for the particle in all samples and an average particle size between 25 and 30 nm is inferred from size hystogram. X-ray diffraction profiles and structural analyses indicate that the core is composed by an antiferromagnetic (AFM) Wüstite ($Fe_{1-y}O$) phase, whereas the shell is composed by a ferrimagnetic (FiM) $Zn_xFe_{3-x}O_4$ spinel one. Electron-energy-loss spectroscopy analysis indicates that Zn is distributed almost homogeneously in the whole particle. This result indicates that Zn/Fe ratio of the first formed phase (Wüstite) is kept when the superficial oxidation occurs and results in the FiM ferrite phase. For this reason, the measured Zn/Fe ratio results always smaller than the initial value foreseen by the Fe and Zn acetylacetonate concentrations, due to the low solubility of the Zn in the Wüstite. Magnetization of the samples indicated that AFM phase is strongly coupled to the FiM structure of the ferrite shell resulting in a bias-field (H_{EB}) appearing below the Néel temperature (T_N) of FeO, with H_{EB} values that depend on the core-shell relative proportion. The effective anisotropy of the shell decrease with an increase in the Zn content; at the same time, the AFM ordering of the core leads to an increment in the anisotropy of the whole system below T_N. In-Field Mössbauer spectroscopy of the Zn richest sample reveals a strong magnetic frustration mainly to the site B of the ferrite, even at 5K.

P280 - Magnetic coupling in bi-magnetic nanocomposites: a qualitative evaluation

11. Nanomaterials, patterned films, nanoparticles and molecular magnetism

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Magnetic nanocomposites are multi-component materials consisting of nanosized particles. They offer exciting opportunities for many technical applications. New magnetic nanocomposites synthesized using different techniques and their properties are being reported every day. However, what is often ignored, but is crucial for a smooth transition from basic research to applications, is an accurate determination and a proper understanding of these properties.

In this work, we will show how the extent of magnetic coupling and thus the magnetic properties of nanocomposites can vary depending on the synthesis technique, even when the individual components of the nanocomposites remain chemically unchanged. We have used $LaFeO_3$-$CoFe_2O_4$ (LFO-CFO) and $LaFeO_3$-$Co_{0.5}Zn_{0.5}Fe_2O_4$ (LFO-CZFO) as prototypical nanocomposite systems. LFO is a high-temperature antiferromagnet (ordering temperature ~750 K) and is often used as the magnetic component to prepare multiferroic composites, while CFO is a typical ferrimagnet (ordering temperature ~800 K) exhibiting high magnetic anisotropy that can be tuned by doping with zinc. The two individual components, LFO and CFO, can be synthetized with controlled structural and morphological properties using relatively easy synthesis routes. In addition, the flexible crystal chemistry of the spinel structure of CFO opens up the possibility of designing different nanocomposites with tunable magnetic properties. As an example, we chose Zn-doped CFO, $Co_{0.5}Zn_{0.5}Fe_2O_4$ (CZFO), to demonstrate the effect of magnetic anisotropy. We will show that the followed synthesis routes have a profound effect on the properties of the resultant nanocomposite. More importantly, the effect is not always obvious from routine magnetization measurements, and requires more detailed and in-depth studies. The magnetization measurements are strongly supported by structural and morphological studies to explain the origin of the differences that can be traced back to the differences in the synthesis techniques. Our results are representative of a general trait in magnetic nanocomposites where the degree of agglomeration that is dependent on the synthesis technique is inversely related to the extent of magnetic coupling. These results will be of interest to all material scientists, and in particular, to those working with nanoscale magnetic materials and composites.

We thank Carl Tryggers Stiftelse för Vetenskaplig Forskning (grant number KF 17:18), Swedish Research Council (VR starting grant number: 2017-05030), Stiftelsen Olle Engkvist Byggmästare (grant number: 188-0179), and the Royal Physiographic Society of Lund (the Märta and Eric Holmberg Endowment) for financial support.

P281 - Magnetic properties of molecular chain magnet based on Cu(II) and Fe(III): a semiclassical approach.

11. Nanomaterials, patterned films, nanoparticles and molecular magnetism

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Molecular magnetism is a rapidly expanding branch of science being of great interest for physicists and chemists around the world. It has introduced a vast variety of novel materials with unique properties promising potential applications in spintronics, magnetic recording, magnetic refrigeration as well as magnetic sensing technology operated by light, pressure or humidity level.

Molecular magnets displaying a low dimensionality of the coordination network call for tailor-made models to describe their physical properties. It is often the case that the magnetic structure comprises two coupled spin subsystems alternately arranged along a line, the first of which consists of a single high-spin paramagnetic ion while the other one is an arbitrary assembly of spin centres. While for the latter one a rigorously quantum approach must be taken, the former one may be treated classically. If the intramolecular couplings are isotropic, such a semiclassical approach allows one to obtain an explicit formula for the zero-field magnetic susceptibility as a function of temperature [1].

This approach was assumed to analyze the susceptibility of a novel molecular magnet $[Co(bpy)_2(ox)][Cu_2Fe(bpy)_2(ox)_4]\cdot 8.5H_2O$ crystallizing in the monoclinic system (space group: P 21/c). The compound consists of chains in which two Cu(II) ions carrying spin 1/2 (the quantum subsystem) are alternately coupled with the Fe(III) ion with spin 5/2 (the classical subsystem). The best fit of the theoretical prediction to the susceptibility data implies a strong antiferromagnetic exchange coupling between the Cu(II) ions together with a relatively weaker antiferromagnetic interaction between the Cu(II) and Fe(III) ions. The antiferromagnetic character of all the exchange couplings in the studied compound gives rise to a weak geometric frustration.

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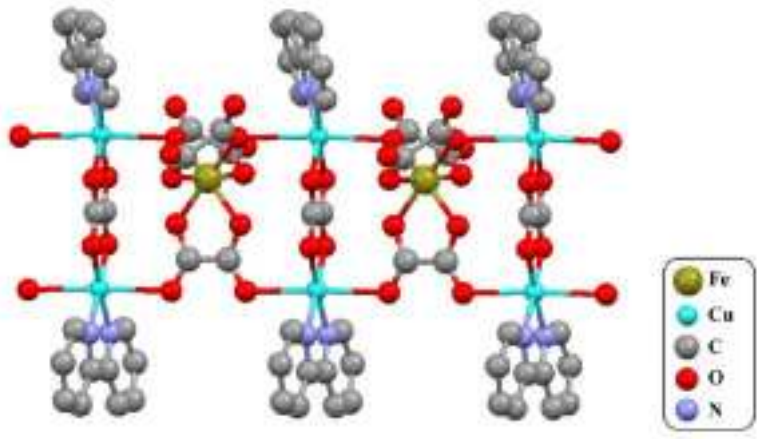

P282 - Magnetic properties of wet chemically prepared Cu0.8Ni0.2 nanoparticle

11. Nanomaterials, patterned films, nanoparticles and molecular magnetism

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1. INTRODUCTION

Magnetic materials in the form of nanoparticles have received a lot of interest because of their unique magnetic properties, which is named as superparamagnetism. These materials can be used in a broad range of fundamental and technological applications, including the production of magnetic fluids. Ni-based bimetallic nanoparticles containing Cu have gained considerable attention in the last decade due to the high catalytic conversion and selectivity properties [1] and potential giant magnetoresistance materials [2].

We have studied the magnetic properties of $Cu_{0.8}Ni_{0.2}$ alloy prepared by wet chemical method.

2. EXPERIMENTAL

$Cu_{0.8}Ni_{0.2}$ was prepared by borohydride reduction of $NiCl_2$ and $CuCl_2$ solutions with CTAB as the capping agent [3]. The polycrystalline sample was characterized by x-ray diffraction (XRD) at room temperature and transmission electron microscopy (TEM). XRD studies shows diffraction peaks coming only from *fcc* Cu phase confirming alloy formation. The clear broadening in XRD peaks w.r.t. bulk Cu indicating formation of nanostructed samples. From XRD line width and using Williamson Hall method the average particle size is calculated 50 nm. From TEM micrographs the average particle size is calculated as 46 nm. TEM energy dispersive x-ray spectroscopy (EDS) study confirms elemental compositions of the sample as Ni-23.20% and Cu-76.80%.

3. MAGNETIZATION MEASUREMENT

In zero field cooled and field cooled magnetization the sample shows a clear branching around 350 K. Analyzing this ZFC-FC data at different field we have calculated the highest significant blocking temperature for this sample is 376 K. At initial temperatures 14 K, the ZFC curves show a sharp small peak at low fields 100 Oe and a rapid decrease and a minimum at higher fields. ZFC/FC data at a higher field of 5000 Oe, the peak in low temperature is not observed. Such behaviour is observed in spin glass materials having short range magnetic interaction that is suppressed at high external magnetic field. The blocking temperature distribution is representing variations in particle size and inhomogeneities of their chemical compositions.

Our $Cu_{0.8}Ni_{0.2}$ sample exhibits hysteresis at all temperatures between 4K and 300K. From the nature of the field dependence of magnetization it is clear that, the magnetization is a combination of ferromagnetism and superparamagnetism. At low temperature a larger contribution comes from the ferromagnetic part. But as temperature is increased, the ferromagnetic part reduces and superparamagnetic contribution becomes stronger.

4. CONCLUSION

In summary, we have successfully prepared $Cu_{0.8}Ni_{0.2}$ granular nanoparticles by borohydride reduction. The average particle size from XRD and TEM is 48 nm. It is clear from the ZFC-FC magnetization data that the sample is superparamagnetic with a small glassy contribution in low temperatures. We infer from the magnetization data that the

sample magnetization is a combination of superparamagnetism and ferromagnetism in the temperature range of our measurement.

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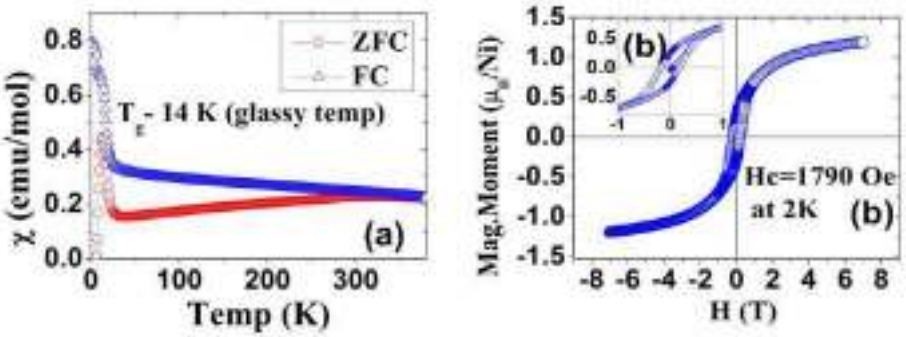

Fig.1.(a) Temperature dependence of ZFC/FC susceptibility of $Cu_{0.8}Ni_{0.2}$ nanoparticle, (b) field dependence of magnetization at 2 K, and (c) hysteresis loop at 2K.

P283 - MAGNETISM OF GREIGITE NANOPARTICLES OF DIFFERENT SIZES

11. Nanomaterials, patterned films, nanoparticles and molecular magnetism

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The greigite, Fe_3S_4, is the sulfur analog of magnetite Fe_3O_4. Fe_3S_4 exhibits inverse spinel structure and ferrimagnetic arrangement at temperatures below ~ 677K [1]. Considering the low toxicity of greigite particles, they seem to be a promising material for high-performance lithium ion batteries, medical applications, such as cancer treatment by magnetic hyperthermia, MRI and magnetically guided drug delivery and, finally, for its metallic nature presuming applications in electronics [2]–[4]. For all these applications, the size of nanoparticles represents a crucial parameter as it influences the fundamental physical properties. The present study aims to probe the impact of the size of hydrothermally prepared greigite nanoparticles on magnetic properties.

The samples studied were characterized by the mean size of crystallites $d_{XRD} \approx 30$nm and $d_{XRD} \approx 120$nm according to powder XRD, a rather broad size distribution according to TEM was confirmed. For the magnetic characterization, the magnetometry, FMR and Mössbauer spectroscopy were used. Exhaustive investigation of magnetic response was carried out by SQUID magnetometer. The measurements of ZFC-FC (100Oe) curves showed that both samples remained predominantly in the blocked state and did not reach the superparamagnetic state up to room temperature. Furthermore, FC cooling-heating-cooling temperature scans between 5-390K insinuated the gradual transition of particles between the blocked and superparamagnetic state above 300K.

In order to search the phase transitions between 4K and 300K, the FMR experiments have been carried out. Analysis of the results obtained at T=300K (frequency f=9.99GHz) and T=4.2K (f=72.5GHz) enabled to evaluate the anisotropy fields. The change of the total anisotropy field between 300K and 4.2K was found for the sample with 120nm and was not observed for the sample 30nm by FMR. We thus infer that some kind of magnetic phase transition likely takes place below 300K for the sample 120nm.

The ^{57}Fe Mössbauer spectra acquired for the sample 30nm in the temperature range 4.2-300K were interpreted bt using a model consisting of magnetically splitted sextets of three non-equivalent Fe sites: one tetrahedral and two octahedral ones. The two magnetically non-equivalent octahedral sites with ratio of intensities 1:2-3 differed in the mutual orientation of the magnetization vector and the principal axis of the electric field gradient (EFG) tensor, which is parallel for the tetrahedral and perpendicular for the octahedral site, respectively. Interestingly, the temperature dependence of the intensities and quadrupole shifts of sextets assigned to Fe atoms in octahedral sites suggests a possible spin reorientation transition at temperature close to 100K for the sample 30nm. This finding correlates with magnetic and FMR results for greigite of different size.

The financial support from the Czech Science Foundation, Project No.18-12761S, and SOLID21-CZ.02.1.01/0.0/0.0/16_019/0000760 from the Ministry of Education, Youth and Sports of the Czech Republic is acknowledged.

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P284 - Magnetization ratchet in cylindrical nanowires

11. Nanomaterials, patterned films, nanoparticles and molecular magnetism

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Magnetic Domain Wall, DW, manipulation either by the application of magnetic fields or by the injection of electric current is commonly accomplished in planar patterned ferromagnetic nanostrips. Various alternatives for the DW pinning were attempted by geometrical notches and corners, or under the action of local stray-fields [1]. In cylindrical nanowires, NWs, the geometry leads to novel domain structures and DW motion. The circular symmetry promotes the development of vortex domains [2, 3].

Their unidirectional motion is a key concept underlying next-generation of DW-mediated data storage devices without mechanically moving parts: a magnetic ratchet device allows linear or rotary motion in only one direction preventing it in the opposite one, and originates in the asymmetric energy barrier or pinning sites. Many fascinating prototypes for magnetic ratchet effects are attracting attention, from fundamental to engineering functionalities points of view. Magnetic quantum ratchets have been recently reported in artificially asymmetric graphene [4], or in superconducting systems where vortices are pinned at asymmetric substrates, or by designed antidot arrays [5].

Here we report the realization of a remagnetization ratchet in cylindrical FM/NM (FeCo/Cu) nanowires [6] by modifying the magnetic segment ($Fe_{35}Co_{65}$) length during the electrochemical synthesis. Our final objective is to manipulate the magnetization reversal in a way to provoke its stepped unidirectional propagation irrespective of the applied field direction.

The nanowires show a *bcc* (110) cubic symmetry, as determined by X-ray diffraction (XRD). Magnetic force microscopy (MFM) image taken at remanence indicates the overall axial magnetization in the nanowire. Moreover, the alternating dark-bright contrast observed along the nanowire reproduces its multisegmented character and denotes that magnetic charges accumulate at the FeCo interfaces with the Cu layers.

The magnetic configuration of individual NWs is presented by combined MFM imaging, PEEM-XMCD and micromagnetic simulations. The so-called 3D imaging MFM–based technique [7] has been used to study the magnetization process and to obtain a hysteresis loop. In this non-standard MFM mode the tip performs successive scans along the same region of the nanowire while the in-plane magnetic field varies between ± 700 Oe.

From these studies we conclude that the remagnetization of individual cylindrical FeCo/Cu nanowires with tailored increasing length segments proceed in few irreversible jumps at which magnetization reverses in the surface. Moreover, the reversal process propagates always unidirectionally, irrespectively of the external field direction, initiating at the end of segments with shorter length. Such ratchet effect originates in the broken symmetry induced by the increasing length of the FeCo segments and, like in a domino effect it is promoted by the magnetostatic coupling between adjacent segments.

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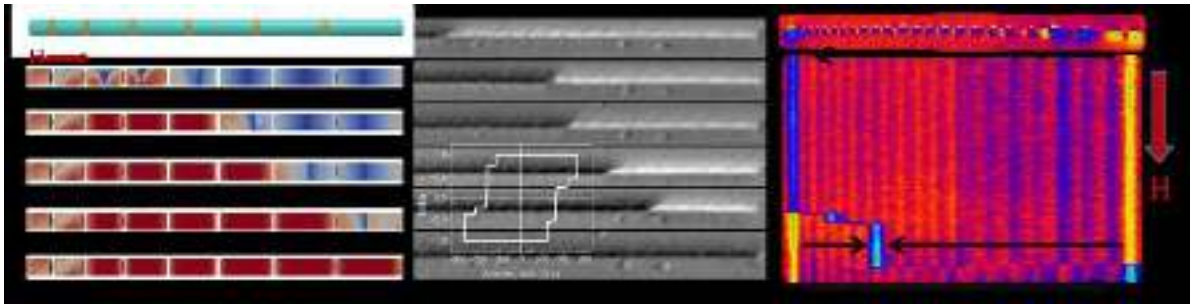

P285 - Magnetoresistive sensors with Superferromagnets

11. Nanomaterials, patterned films, nanoparticles and molecular magnetism

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Superferromagnets (SFMs), e.g., magnetic nano-crystal self-assemblies and/or arrays, represent promising candidates for Lab on a Chip (LoC) systems including many laboratory tasks. Such soft magnetic systems provide an opportunity to develop new materials with characteristics far beyond traditional solids. The randomly jumping interacting moments (RJIM) model, see [1] and refs. therein, gives useful framewok for studies of SFMs. In particular, it provides a basis for developing analytical tools employed in order to specify, quantify and analyse respective magnetic structures. Such tools explore correlations of magnetic noise amplitudes and allow for quantitative definition, description and study the SFM origin, as well as self-organized criticality in the response properties. In this contribution we briefly overview some results for a sensor mode of SFM reactivity associated with spatially local external fields, i.e., a detection of magnetic particles. Favorable designs of superferromagnetic systems for sensor implications are revealed.

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P286 - Micromagnetic simulations for modulated permaloy nanowires

11. Nanomaterials, patterned films, nanoparticles and molecular magnetism

Eugenio E. Vogel[1, 2] , *Guidobeth Sáez*[1], *Eduardo Cisternas*[1], *Pablo Díaz*[1], *Juan P. Burr*[3], *Eduardo Saavedra*[3], *Juan Escrig*[2, 3]

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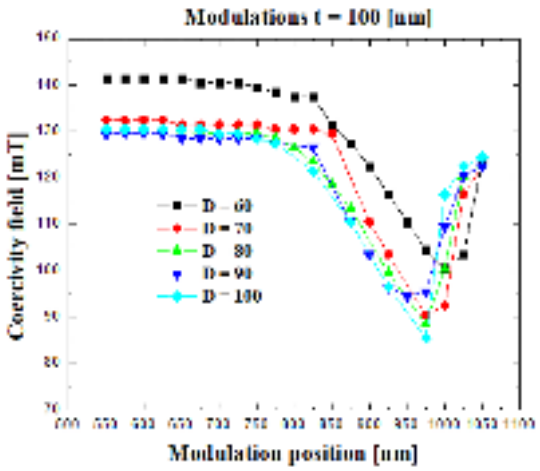
In this work we simulate the change in the coercive field for a cylindrical permaloy nanowire geometrically modulated by a zone of wider diameter (disk). The shape of the solid cylinder is kept fixed: length ***L***=1100 nm, diameter ***d***=50 nm, while the thickness of the disk ***t*** is varied in the range [50,150] nm, its diameter ***D*** is varied in the range [60,130] nm and the position ***z*** along the axis of the nanowire is varied from the center to the ends. The independent variables are discretized according to previous definitions. For each such point in the parameter space the Landau-Lifshitz-Gilbert equation is solved using OOMF, getting reproducible hysteresis curves to magnetically characterize the corresponding system. The competition of the easy axis anisotropy predominating in the wire and the easy plane anisotropy tending to prevail in the disk give rise to different non-trivial configurations. In particular the coercive field is found to minimize with the disk position along the wire (one example is shown in the figure), this behavior is modulated by D and t, thus providing the possibility of tuning the desired coercive field. The dipolar interaction plays here an important role which is discussed by a microscopic view of the spin orientations near the interphases. Towards the end of the presentation some fresh results including more than one modulation will be also presented.



P287 - Microstructure and magnetic properties in core/shell nanoparticles: (Co-, Ni-) ferrite/(CoFe, NiFe)

11. Nanomaterials, patterned films, nanoparticles and molecular magnetism

Daniel Casaleiz[1] , *Melek Villanueva[1], Ester M. Palmero[1], Sonia Estradé[2], Pau Torruella[2], Francesca Peiró[2], Yurena Luengo[1], Julio Camarero[1], Gorka Salas[1], Alberto Bollero[1]*

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Manipulation and control of the materials structure at the nanoscale allows for obtaining magnetic materials with tailored properties according to the requirements dictated by the final application. On this base we have studied the correlation between the microstructure and the magnetic properties in two types of nanostructured systems, ferrites and soft magnetic materials, with technological applications in energy, electronics and biomedical sectors [1,2].

In this study cobalt ferrite ($CoFe_2O_4$) and nickel ferrite ($NiFe_2O_4$) powders were synthesized by the coprecipitation method [3]. Nanostructuring of the crystallized ferrite powders was done through surfactant-assisted (oleic acid) ball milling for 24 min in order to reduce possible oxidation and avoid welding. A well-controlled reduction process under H_2 atmosphere has allowed going from pure ferrite ($CoFe_2O_4$; $NiFe_2O_4$) to metal (CoFe; NiFe) nanoparticles by producing intermediate core/shell nanostructures. Tailoring morphology and magnetic properties has been managed by nanostructuring and proper choice of the reducing temperature.

The effect of milling on homogenising and refining the microstructure was straightforward with a reduction of the average particle size in one order of magnitude by starting with coprecipitated particles of 100-200 nm grouped in the form of large micrometric clusters for $CoFe_2O_4$, and mainly micrometric particles for $NiFe_2O_4$. The accompanying reduction of the mean crystallite size and the microstrain induced during milling affect strongly the permanent magnet properties [1], with coercivity increasing from 0.7 to 4.5 kOe for the coprecipitated and milled $CoFe_2O_4$ powder, respectively.

The microstructural refinement produced during milling, i.e. the increase in the number of active surfaces to initiate the reduction process, allowed decreasing the optimum ferrite-to-metal transformation temperature by about 75-100 ºC. Room temperature hysteresis loops [Fig. 1(a)] show a gradual increase in the saturation magnetization, M_s, from 75 to 235 emu/g for milled $CoFe_2O_4$ and for CoFe particles (reducing process at 600ºC), respectively. Similar behaviour was observed for the reduction process applied to the as-milled $NiFe_2O_4$ powder with M_s=149 emu/g after complete reduction to NiFe [4]. The intermediate hysteresis loops shown in Fig. 1(a) correspond to $CoFe_2O_4$/CoFe nanostructures with an increased CoFe content with increasing temperature. This is in excellent agreement with the evolution of the X-ray diffraction patterns shown in Fig. 1(b). Inset of Fig. 1(a) shows a high-resolution transmission electron microscopy (HRTEM) image representative of one of these intermediate core/shell nanoparticles. Magnetometry and XRD results have been combined with a detailed morphological and microstructural study comprising HRTEM, HAADF imaging and EELS measurements, revealing successful synthesis of nanoparticles with a CoFe core and ending with an outer Fe_3O_4 layer of about 4 nm, which might open the possibility of using these high-saturation magnetization nanoparticles (M_s>200 emu/g) in bioengineering applications.

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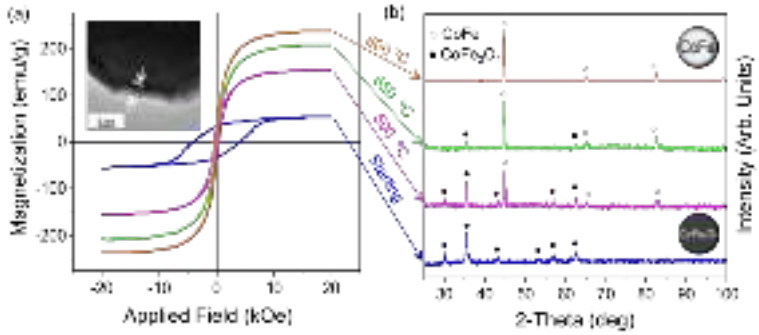

Figure 1. (a) Room temperature hysteresis loops and (b) XRD patterns of as-milled $CoFe_2O_4$ powder and milled+annealed particles at different temperatures under reducing atmosphere. Inset in (a) shows an illustrative HRTEM image of a core/shell nanoparticle obtained at intermediate reducing temperature (scale bar: 5 nm).

P288 - Probing magnetism of individual nano-structures using non-hysteretic Nb µ-SQUIDs

11. Nanomaterials, patterned films, nanoparticles and molecular magnetism

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Nano-magnetism offers intriguing physics and many applications. In order to investigate the quantum magnetism in individual nano-structures high bandwidth and sensitivity µ-SQUIDs operating at low temperatures are the most appropriate probes [1]. Our recent work [2] demonstrates that inductive shunting can eliminate the thermal bistability with good SQUID modulation in voltage resulting into large bandwidth and sensitivity. We use this idea and a newly made setup to study the anisotropic magnetization reversal in individual permalloy needles patterned by electron lithography close to Nb µ-SQUIDs. We compare the results obtained by operating the µ-SQUIDs in both hysteretic and non-hysteretic modes [Fig.1]. The obtained behaviour is well described by magnetization reversal through curling mode in an infinite cylinder under Néel-Brown model. We also compare our results with OOMMF [3] simulations on finite length needles. The latter also captures the vortex nucleation and annihilation and thus the observed minor hysteresis loops. Some preliminary measurements on switching statistics on these nano-needles and other nano-structures will also be presented.

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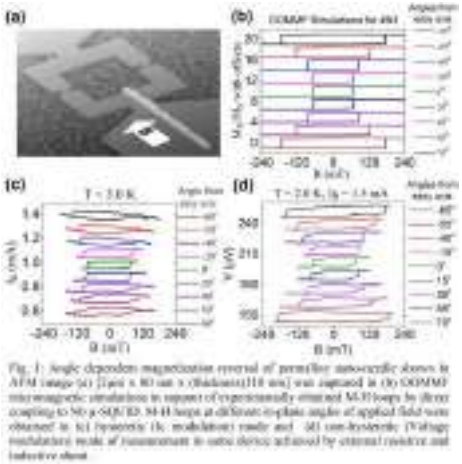

P289 - Processing and magnetoresistance-characterization of supersaturated nanostructured bulk materials

11. Nanomaterials, patterned films, nanoparticles and molecular magnetism

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Severe plastic deformation by high pressure torsion is used to consolidate and deform various binary and ternary powder mixtures. Different mixtures of diamagnetic (Cu or Ag) and ferromagnetic (Fe or Co) and their microstructural and physical properties will be presented in this contribution. Through high pressure torsion, large amounts of pressure (for consolidation) and strain (for deformation and alloying) are applied. During this top-down process, the initial powder mixture transforms to an ultrafine-grained or even nanocrystalline, fully dense bulk specimen. The elemental starting powders are alloyed – repeatedly supersaturated states can be observed, as some of the combinations of elements show a miscibility gap.

Microstructural and chemical investigations using scanning and transmission electron microscopy, as well as synchrotron X-ray diffraction and atom probe tomography are performed. Furthermore, the processed bulk materials are probed regarding their magnetoresistive behaviour. As expected, an influence of the starting composition of diamagnetic and ferromagnetic components on the magnetoresistance can be observed.

In addition, annealing treatments decompose the supersaturated states and lead to growth of nanoparticles, heterostructures are formed. The evolving segregated and enlarged phases influence the magnetoresistance. To disentangle resistive features, magnetoresistive measurements are carried out at room temperature and down to cryogenic temperatures.

This project has received funding from the European Research Council (ERC) under the European Union’s Horizon 2020 research and innovation programme (grant agreement No 757333).

P290 - Quantum fluctuations in magnetic nanostructures

11. Nanomaterials, patterned films, nanoparticles and molecular magnetism

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The problem of quantum fluctuations in magnetic nanostructures is discussed by considering a linear chain of a finite number of atoms with the exchange interaction of the electron spins of neighboring atoms, as in Heisenberg's theory of ferromagnetism. Electromagnetic magnetic dipole radiation from a spin flip wave is calculated. It is shown that including quantum field fluctuations in the radiation energy flux calculations gives much larger values than in the case of the averaged electromagnetic field. Radiation decay due to spin interaction with the quantized electromagnetic field is estimated. In particular, electromagnetic wave (EM) multiple scattering by a plane periodic array of magnetic microelements in free space is considered analytically by natural subdividing of the EM wave into the averaged and fluctuation components. Each magnetic element is characterized by magnetic susceptibility tensor and shape. An exact Dyson integral equation is derived for the magnetic field Floquet–Bloch amplitude in-plane averaged over an array unit cell. The mass operator of the Dyson equation is expressed via the T-scattering operator of the array unit cell that satisfies a type of the Lippmann–Schwinger equation. We showed that magnetic field fluctuations are generated by the Bragg–Laue diffraction of an averaged magnetic field on the periodic array and are described inside the array as waves propagating with the Laue wave vectors equal to the difference between the in-plane wave vector of the incident magnetic field and the reciprocal lattice wave vector. We derived, for the first time, an exact quadrature to calculate magnetic field fluctuations from their averaged value. These general results are illustrated by a simple Born approximation. In particular, we revealed a mechanism of discrete waveguide excitation by an incident plane EM wave via the averaged EM wave Brag–Laue diffraction on the magnetic microelement array in the quasi-static approach when the wavelength of incident EM is much larger than the sizes of magnetic elements and periods of the array. The mode energy excitation coefficient at normal incidence of the plane EM wave on the array is evaluated.

This work is supported by Russian Science Foundation, Project 19-19-00607 and by State of Russian Federation via Moscow Institute of Physics and Technology (assignment 074-02-2018-286).

P292 - Solvothermal synthesis of Fe3-δO4 nanorods and their magnetic-field-assisted assembly

11. Nanomaterials, patterned films, nanoparticles and molecular magnetism

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Anisotropic nanostructured materials have attracted attention due their unique electronic, magnetic and optical properties in various applications.Synthesis of size and shape controlled nanoparticles is of great importance and enable formation of ordered superlattices through a process called self-assembly. It is well known that fabrication of ordered assemblies from individual nanoparticles will provide unique collective properties compared to its constituent building blocks. In order to understand the fundamental principles that lead to collective magnetic properties, 1-D magnetite (Fe_3O_4) nanorods were synthesized by a solvothermal process using iron pentacarbonyl ($Fe(CO)_5$) as iron source. Oleic acid and hexadecylamine were used as capping ligands to prevent agglomeration and for size control of the nanoparticles. Immobilized needle-shaped nanorod arrays were formed by drop-casting on a Si-substrate applying a magnetic field in the plane of Si-substrate, which resulted in needle-shaped nanorod assemblies with widths of ~5−10 μm and typical lengths of ~1mm (see Figure (a) inset). Here, we have explored magnetic properties of needle-shaped magnetic particle arrays composed of magnetite nanorods and compared with the properties of the nanoparticle dispersion using SQUID magnetometry. Figure (a) shows the room temperature in-plane magnetization versus field results for the needle-shaped particle array together with the magnetization curve for the nanorod dispersion; the results reveal a significant in-plane magnetic anisotropy for the array. Moreover, the parabolic shape of the magnetization curve for the nanorod dispersion indicates that nanorod agglomerates form at low fields due to the magnetostatic (dipolar) interactions between nanorods. However, an applied magnetic field of approximately 30 mT is enough to align the nanorod magnetic moments along the magnetic field direction. Size and shape dispersity of the nanorods, given as average length and width, were determined using transmission electron microscopy as shown in Figure (b) and found to be 26.2 ± 8.6 nm and 4.8 ± 2.9 nm, respectively. Also, the crystallinity of the rods was verified by X-ray and selected area electron diffraction. The needle-shaped nanorod arrays will also be investigated in order to clarify the assembly formation. Therefore, future work will focus on structural information of the needle-shaped nanorod arrays by performing grazing incidence small angle scattering (GISAXS) studies. Further studies will also include use of templated substrates with nanofluidic channels to observe any confinement effects on the ordering besides other constraints like; slow evaporation rate of the solvent and magnetic field effects on the assembly process for the enhancement of magnetic properties.

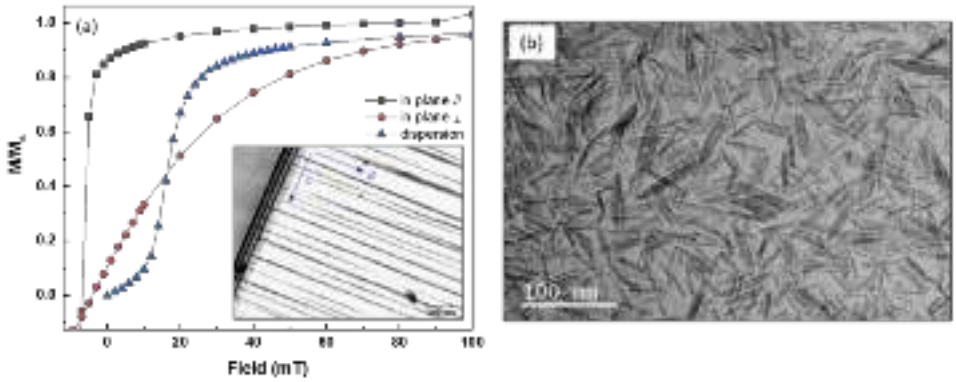

Figure: (a) Magnetization versus magnetic field for the nanoparticle array with the field applied parallel and perpendicular with respect to the nanoparticle needles together with the magnetization curve for the sintered dispersion. (b) TEM image of the rod-shaped iron oxide nanoparticles.

P293 - Structural and magnetic properties of ferromagnetic and exchange-biased Janus Particles

11. Nanomaterials, patterned films, nanoparticles and molecular magnetism

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In the field of three-dimensionally structured microscopic objects, the fabrication of magnetically anisotropic particles and the targeted tuning of their properties have become a substantial research task. Magnetic Janus particles are typically created by the deposition of a thin film system onto an array of self-assembled microspheres. Consequently, the thin film is structured into hemispherical caps which possess a size dependent curvature and are known to exhibit several types of magnetic textures, ranging from an in-plane texture called onion state, over a vortex to an out-of-plane state. It was shown that the type of emerging magnetic texture is strongly influenced by the film thickness, its magnetic properties and the particles' size, where, e.g., an onion state is energetically favourable only for particle diameters below 800 nm for soft magnetic caps.[1] However, when aiming for precise motion actuation in microfluidic transport experiments it is desired to deliberately tune the magnetic texture of the transported microspheres over a broad particle diameter range. In order to shift the phase transition between the onion and vortex state towards larger particle sizes, i.e., to the range of a few micrometers, a promising approach is to strengthen the ferromagnet's in-plane anisotropy by the choice of material composition. For this purpose, introducing an antiferromagnet at the ferromagnet's interface can add an additional unidirectional anisotropy to the curved film due to the presence of the exchange-bias (EB) effect which is expected to stabilize the formation of the onion texture for larger particle sizes. In this study, we present results from structural and magnetic characterization of both ferromagnetic and EB Janus particles in a direct comparison. Magneto-optic Kerr effect measurements and magnetic force micrographs revealed significant differences with respect to the caps' magnetization reversal and their magnetostatic charge contrast obtained in remanence which is due to an EB induced shift of the phase transition between onion and vortex texture towards larger particle diameters.

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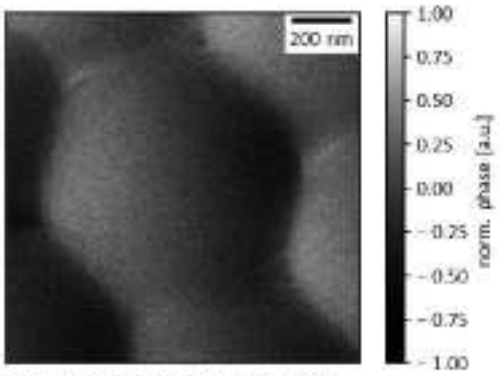

Figure: Magnetic charge contrast image from MFM measurement on an EB Janus particle (1 µm)

P294 - Study of magnetic properties of arrays of iron-based nanowires by FORC

11. Nanomaterials, patterned films, nanoparticles and molecular magnetism

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Magnetic nanowires arrays (MNA) until recently were considered as good candidates for information storage materials with high density. The magnetization of a single nanowire in this case plays the role of a bit of information. However, there are several significant factors preventing correct information recording and reading. The first one is intermittent magnetization reversal of a separate nanowire [1, 2] due to pinning of the domain wall on structure inhomogeneities. The second one is demagnetization fields created by long but narrow magnetized nanowires. Magnetostatic interactions between nanowires often lead to further complication of the magnetization reversal process [3].

In order to solve the problem of magnetization reversal, it is necessary to use a material with a low anisotropy of the crystal lattice (for example, cubic one), but with a sufficiently high magnetic moment. Iron is an excellent material for this purpose. However it is easily oxidizing, forming the phases, possessing less magnetic moment, than the pure material. Developed technology of synthesis has allowed to overcome this problem.

In the current work, iron-based MNA synthesized by template electro-deposition method are investigated. Porous anodic alumina (AOA) films of 35 μm thick were used as templates, obtained using two-step anodizing of aluminum. The electro-deposition of iron was carried out at room temperature in a three-electrode cell. The diameter of the nanowires is 30 ± 3 nm, while the distance between them is 100 ± 4 nm. The length of the filaments varies from 400 nm to 35 μm.

The study of magnetic properties of MNA was carried out by the method of first-order reverse curves (FORC) for the first time. Additionally, remagnetization curves have been measured with SQUID-magnetometry technique. The magnetic field up to 1.2 T was applied both along and across the long axis of the nanowires at room temperature.

Significant changing of hysteresis loop parameters as well as interaction and switching fields’ distributions depending on the nanowire length have been observed.

The work was supported by the Russian Science Foundation under grant 18-72-00011.

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P295 - Thermal traits of MNPs under high-frequency magnetic fields: effect of magnetic size and coating

11. Nanomaterials, patterned films, nanoparticles and molecular magnetism

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Over the last decade a lot of effort has been invested in the design of smart magnetic nanoparticles (MNPs) for biomedical applications, like drug delivery, tissue imaging and magnetic fluid hyperthermia (MFH)[1,2]. The MFH profits from heat generation achieved by the application of high frequency magnetic fields, in the range of tens to hundreds of kHz. The most relevant factor when studying the thermal response of MNPs is the specific power absorption (SPA), which is generally determined using the maximum slope of the heating curve as a function of time[3]. However, the evolution of the heat release is not linear with time, as can be ascertained from the SPA temperature evolution shown on the figure.

In our work we address the methodology of SPA analysis on different types of cobalt ferrite MNPs, different in terms of physical (5 - 6 nm) and magnetic (3.5 – 5 nm) size, and also in surface functionalization (oleic acid, 11-(furfurylureido)undecanoic acid, 11-maleimidoundecanoic acid). Dispersions with concentrations of MNPs adjusted from 1 mg/ml to 4.3 mg/ml were investigated in a large range of both frequency and amplitude of the magnetic field.

Our results are somewhat consistent with previous works [4,5] in which the increased physical size and/or concentration reflect a higher maximum SPA. When the particles are functionalized with large organic ligands, the maximum SPA and the temperature achieved are significantly reduced, which points, most likely, to the extra inertia of the particle that hinders the MNP movement through the fluid.

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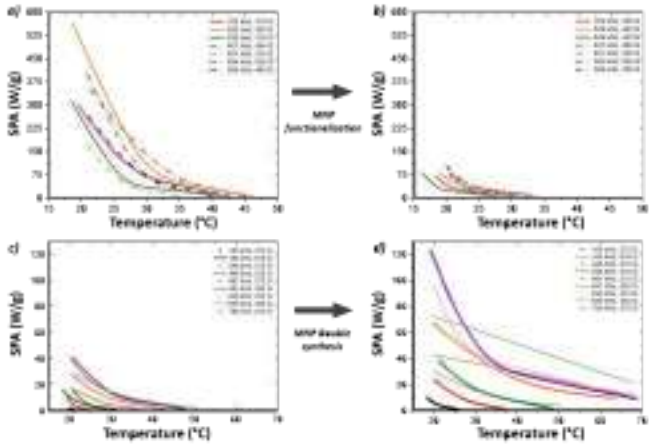

Figure 1 – Influence of surface functionalization (a,b) and add-growth of a shell (c,d) on SPA vs. temperature for two different samples of MNP: a) MNP1 - oleic acid; b) MNP1 - 11-maleimidoundecanoic acid; c) MNP2 - oleic acid; d) MNP1@shell - oleic acid.

P296 - Tuneable magnetic properties of nanocrystalline Fe-Cr alloys produced by severe plastic deformation

11. Nanomaterials, patterned films, nanoparticles and molecular magnetism

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Severe plastic deformation by high-pressure torsion (HPT) is an opportunity to evade the processing limits of binary systems that exhibit large miscibility gaps in their thermodynamical equilibrium and allows the production of binary alloys with non-equilibrium compositions below the melting point. HPT is a top-down approach, which offers the variation of processing parameters like applied pressure, strain and deformation temperature, effecting directly the mixing- and microstructure evolution process. The resulting bulk samples reveal grain sizes in the ultrafine or nanocrystalline regime. Furthermore, a proper concatenation of ball milling and arc melting prior to HPT helps to overcome HPT processing limitations, while still obtaining homogeneous supersaturated solid solutions.

In the Fe-Cr system the correlation between evolving microstructures and the magnetic properties of ferromagnetic Fe and antiferromagnetic Cr is in particular focus of this study. Functional tuneability of magnetic properties (e.g. the often mentioned giant magnetoresistance) is not only influenced by processing, but also by affecting the microstructure through subsequent annealing treatments[1]. Choosing a temperature range underneath the Curie-Temperature of Fe and above the Neel-Temperature of Cr induce interface coupling due to exchange anisotropy. The microstructural properties were examined including electron microscopy methods, X-ray diffraction techniques, atom probe tomography experiments and correlated to magnetic data obtained by SQUID magnetometry.

This project has received funding from the European Research Council (ERC) under the European Union’s Horizon 2020 research and innovation programme (grant agreement No 757333).

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12. Spin-orbit and topology driven phenomena

P297 - A general scheme to calculate the exchange interaction parameters of the extended Heisenberg model

12. Spin-orbit and topology driven phenomena

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We present an efficient and accurate approach for the calculation of the interatomic exchange interaction parameters of the extended Heisenberg model Hamiltonian based on the fully relativistic multiple scattering Korringa-Kohn-Rostoker (KKR) formalism. This approach gives access to bilinear isotropic exchange and Dzyaloshinskii-Moriya interactions, to biquadratic non-chiral and chiral two-site interactions as well as to all other multisite interaction terms entering the Heisenberg Hamiltonian accounting this way for higher-order terms beyond the classical version of the model. The computational scheme is based on the expansion of the free energy expression in terms of the electronic Green function when considering the formation of a spin spiral as a perturbation with respect to a ferromagnetic reference configuration. The approach gives also access to micromagnetic parameters as for example the exchange stiffness ($A_{\alpha\beta}$), the closely related spin-wave stiffness as well as the Dzyaloshinskii-Moriya ($D_{\alpha\beta}$) tensors. The temperature dependent behaviour of the exchange parameters is obtained accounting for thermal lattice vibrations treated by means of the CPA alloy theory within the alloy analogy model [1]. Results for pure elemental materials, for ordered compounds and for disordered alloys are compared with available experimental data demonstrating in general good agreement.

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P298 - Antiferromagnetic topological insulator MnBi2Te4

12. Spin-orbit and topology driven phenomena

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Using *ab initio* and Monte Carlo calculations we predict the van der Waals layered compound $MnBi_2Te_4$ to be antiferromagnetic (AFM) topological insulator [1], which is further confirmed experimentally [1]. $MnBi_2Te_4$ appears to be invariant with respect to the combination of the time-reversal and primitive-lattice translation symmetries, giving rise to the Z_2 topological classification of AFM insulators, and Z_2=1 for $MnBi_2Te_4$. Its (0001) surface, breaking the combined symmetry, shows a giant gap in the topological surface state thus representing a promising platform for the quantized magnetoelectric effect observation. In the 2D limit, $MnBi_2Te_4$ shows a unique set of thickness-dependent magnetic and topological transitions, which drive it through FM and (un)compensated AFM phases, as well as quantum anomalous Hall (QAH) and zero plateau QAH states [2]. Thus, $MnBi_2Te_4$ is the first stoichiometric material predicted to realize the zero plateau QAH state intrinsically. This state has been theoretically shown to host the exotic axion insulator phase.

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P299 - Charge and spin transport in monoaxial chiral magnets

12. Spin-orbit and topology driven phenomena

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Chiral magnets have attracted considerable attentions due to the topological characteristics associated with their peculiar spin textures, which originate from an asymmetric exchange interaction called the Dzyaloshinskii-Moriya interaction. The typical example is found in monoaxial chiral magnets, such as $CrNb_3S_6$ [1] and $Yb(Ni_{1-x}Cu_x)_3Al_9$ [2]. These compounds show a chiral helimagnetic state (CHM) at zero field [Fig. (a)], which turns into a chiral soliton lattice (CSL) in a magnetic field perpendicular to the helical axis [Fig. (b)]. As the magnetic field increases, the spatial period of the CSL increases. On the other hand, the CHM changes into a chiral conical magnetic state (CCM) in a magnetic field parallel to the helical axis [Fig. (c)]. These peculiar magnetic states bring about intriguing transport properties, such as the nonlinear negative magnetoresistance in the CSL [3] and a chirality-dependent nonreciprocal transport in the CCM [4]. In addition, a peculiar lock-in of the period of the CSL was discovered at a certain magnetic field [2]. Since these electric and magnetic properties have not been fully understood within the spin-only models, it would be crucial to explicitly take into account the coupling to itinerant electrons.

In this presentation, we report our theoretical studies on the peculiar electric and magnetic behaviors in the monoaxial chiral magnets, on the basis of a minimal itinerant electron model, a one-dimensional Kondo lattice model with the Dzyaloshinskii-Moriya interaction. By using Monte Carlo simulations at finite temperature, we show that the model explains well the nonlinear negative magnetoresistance in the CSL. We clarify the origin as the decrease of magnetic scattering from the chiral solitons while increasing the magnetic field [5]. Meanwhile, by variational calculations for the ground state, we find that the spatial period of the CSL can be locked at particular fields, as found in experiments. We clarify that this lock-in is a direct consequence of the coupling to itinerant electrons [6]. In addition, we study nonreciprocal spin transport in the CHM and CCM by using a Landauer-type formula based on a Green's function method following the previous study [7]. We show that the system exhibits a nonreciprocal spin current, which depends on the magnetic field, the chirality of the magnetic structures, and the polarized direction of the spin current. The result suggests that the monoaxial chiral magnets can be used as a spin-current diode [8].

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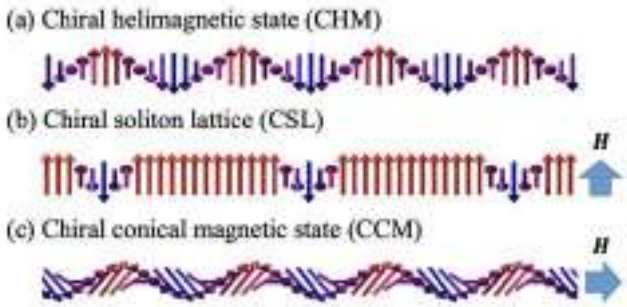

Figure: Schematic pictures of (a) the chiral helimagnetic state (CHM), (b) the chiral soliton lattice (CSL), and (c) the chiral conical magnetic state (CCM) in an applied magnetic filed $\boldsymbol{H}$.

P301 - Current-Induced Domain Wall Motion with Very High Velocity in Ferrimagnetic GdFeCo Wires

12. Spin-orbit and topology driven phenomena

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Ferrimagnetic rare-earth transition metal (RE-TM) materials have attracted great attention in recent years because of their fast dynamics of domain and high spin-orbit torque efficiency [1 -3], which are two crucial factors for realizing spintronic devices with low-energy consumption and fast operation. In the present study, we investigated current-induced domain wall motion (CIDWM) in ferrimagnetic GdFeCo wires at room temperature. For this work, Ferrimagnetic GdFeCo samples with structures of Pt(5)/GdFeCo(8)/SiN(10) and SiN(10)/GdFeCo(8)/ SiN (10) (thicknesses in nm) were prepared on the thermally oxidized silicon substrate by dc and rf magnetron sputtering. Ferrimagnetic GdFeCo wires with various widths (3 – 10 µm) were fabricated by using electron-beam lithography and lift-off technique. The magnetic properties of the GdFeCo wires were examined by anomalous Hall effect measurement. The motion of DWs in the wires was driven by pulse voltages and directly observed using polar Kerr microscopy in a differential mode. We found that very fast CIDWM with velocity up to over 1000 m/s was observed in the Pt/GdFeCo/SiN wires. The DWs were moved along the direction of the applied current-flow. However, CIDWM was not observed in the SiN/GdFeCo/SiN wires. It indicated that spin-orbit torques generated at the Pt/GdFeCo interface is mainly responsible for such fast CIDWM in these Pt/GdFeCo/SiN wires.

This research was partially supported by the Ministry of Education, Culture, Sport, Science and Technology, Japan - Supported Program for Strategic Research Foundation at Private University (2014-2020) and JSPS KAKENHI (Nos. 17H03240 and 18K14128).

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P302 - Database for spin Hall effect

12. Spin-orbit and topology driven phenomena

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Generation and detection of spin-polarized electrons in nanostructures is among the main challenges of spintronics. To this end, most frequently the spin Hall effect (SHE) is employed, whichallows for the conversion of charge current to spin current and vice versa. In non-magneticmaterials the SHE occurs as a consequence of the spin-orbit interaction and enables the control of spins without external magnetic field or magnetic materials. To identify materials with strong spin Hall effect, we performed high-precision, high-throughput ab-initio calculations of the intrinsic spin Hall conductivity (SHC) for over 20,000 existing non-magnetic crystals. From the new developed database, we identify seven materials with the SHC larger than that in Pt, which has so far been the most popular material among non-magnetic conductors as it can be readily integrated in spintronic nanostructures and exhibits a large value of the theoretical SHC of 2180 ($\bar{h}$/e)(S/cm) . The new record material is with the SHC of 2500 ($\bar{h}$/e)(S/cm). Our in-depth analysis of four representative materials with a large SHC reveals a prominent role of geometrical features in the band structure allowed by mirror symmetries in the lattice. We confirm this by a statistical analysis of the calculated SHCs for all the space- and point-groups of the 20,000 considered materials. Beyond these, our extensive open data collection also provides guidelines for the design of new spintronic materials with a large SHC.

P303 - Dissipative spin pumping into two-dimensional quantum spin Hall insulator

12. Spin-orbit and topology driven phenomena

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The two-dimensional quantum spin Hall insulator (2D QSHI) is the most primitive but quite important realization of topological insulator. It shows the helical edge states protected by time-reversal symmetry, whereas the quantized spin Hall conductivity in the bulk. While the quantum spin Hall state was traditionally realized in HgTe/CdTe quantum wells, recent calculations and experiments have verified that a monolayer of a transition metal dichalcogenide 1T'-WTe_2 serves as a 2D QSHI [1,2], which is expected to work as a good platform for quantum spin transport and spin-charge conversion.

When a spin current is pumped from a precessing magnet into the spin Hall system, it is converted to a charge current by the inverse spin Hall effect (see Figure (a)). In a 2D QSHI, the inverse spin Hall effect is understood as the topological charge pumping on the edge, which is quantized when the precession of the magnetization is slow enough (adiabatic) [3]. Although this adiabatic topological pumping scenario is well known, it is not exactly understood where this scenario works well, i.e. the conditions that should be satisfied by the physical parameters such as the exchange energy at the interface and the spin precession frequency.

In the present work, we theoretically investigate the spin pumping from a precessing ferromagnet into a 2D QSHI thoroughly from the adiabatic to nonadiabatic regimes, both analytically and numerically [4]. We analytically treat the dynamics of the edge-state electrons coupled to the precessing ferromagnet by the Floquet theory, and derive the pumped current as a function of the exchange energy and the precession frequency. We find that a heat bath for the edge electrons governs the transition between the adiabatic and nonadiabatic regime: when the edge electrons are coupled with a heat bath, their spin and energy can dissipate into the bath by a certain rate, eventually reaching a periodic steady state. The pumped current on the becomes quantized when the exchange energy exceeds the dissipation rate (see Figure (b)). We also calculate the edge current numerically on the 2D lattice model, and find that the bulk states in the QSHI effectively serves as the heat bath for the edge electrons.

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P304 - Electric field effect on domain wall velocity and Dzyaloshinskii-Moriya-Interaction in Co thin films

12. Spin-orbit and topology driven phenomena

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Electric control of magnetic properties of ferromagnetic materials has been the subject of intense research in recent years with the aim to reduce energy consumption in the next generation of magnetic memories. We investigate the influence of an electric field on the domain wall (DW) propagation in ultrathin Co films (0.5-1nm) in direct contact with an aqueous electrolyte. This approach allows for large uniform fields (>1V/nm) at the Co/electrolyte interface. It has been applied successfully to electrodeposited Co films, which show significant changes in DW velocity [1]. Here we focus on sputter deposited Pt/Co bilayers and Ta/Pt/Co trilayers capped by either AlO_x or MgO to prevent surface oxidation during transfer in air to the electrochemical cell. This protection layer is removed in-situ in electrolyte solution under potential control. Perpendicular magnetic anisotropy is established by carbon-monoxide adsorption at the film-electrolyte interface. We study the DW propagation with in-situ magneto optical Kerr effect (MOKE) microscopy after applying short magnetic field pulses perpendicular to the sample surface. Upon additional application of an in-plane magnetic field the domain propagation is asymmetric along the in-plane field direction (see figure) indicating the presence of Néel-type DW due to interfacial Dzyaloshinskii-Moriya (DMI) interaction [2]. We compare the influence of the electric field on DW velocity and DMI to recent results obtained in gated solid state devices [3]. Figure: Overlay of nucleation (brighter) and propagated domain at two potentials with an applied in-plane field $\mu_0 H_x$ = 135 mT and a propagation field pulse of $\mu_0 H_p$ = 11 mT and 20 ms (a) respectively 50 ms (b). The white scale bar corresponds to 100 µm. Potentials quoted against mercury-mercurous sulphate electrode (MSE).

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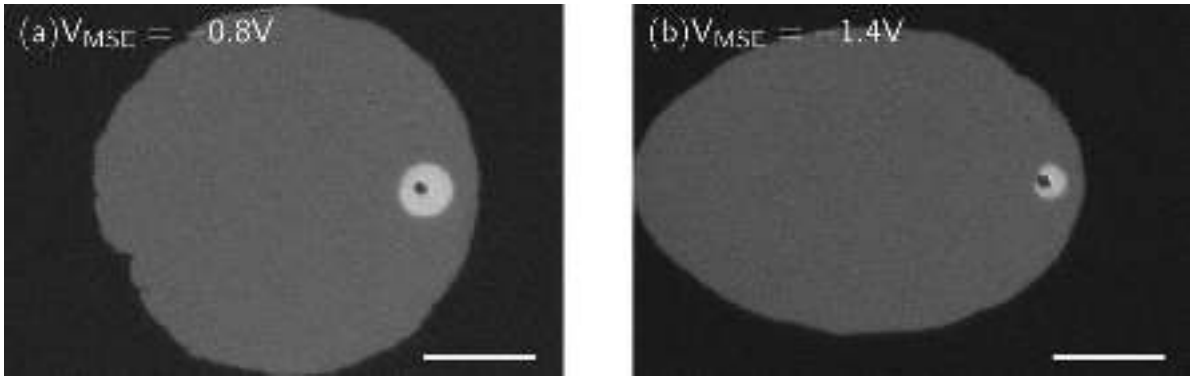

P305 - From Weiss-field to DM interaction for non-collinear magnets

12. Spin-orbit and topology driven phenomena

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We show for a simple non-collinear configuration of the atomistic spins (in particular, where one spin is rotated by a finite angle in a ferromagnetic background) that the pairwise energy (the electronic grand potential) variation computed in terms of multiple-scattering formalism cannot be fully mapped onto a bilinear Heisenberg spin model even in the absence of spin-orbit coupling (SOC). Three terms emerge: a bilinear (BL), a symmetric anisotropic (SA)-like and a Dzyaloshinskii-Moriya (DM)-like term depending on the underlying spin configuration.

We make a spin vs. charge as well as a density vs. current decompositions of the different terms showing that in the lack of SOC there is no DM-like term in trivial, collinear, spin systems. However, e.g., in the vicinity of the 3d metals surface, DM like term can be observed in non-collinear magnets even if the presence of SOC is neglected.

For the bulk case with cubic symmetry, like bcc Fe, the BL and SA term result a non-Heisenberg term, too, which is induced by the spin-polarized host and appears in leading orders in the expansion of the infinitesimal angle variations. However, an Eg-T2g symmetry analysis based on the orbital decomposition of the exchange parameters in bcc Fe leads to the conclusion that the nearest-neighbor exchange parameters related to the T2g orbitals are essentially Heisenberg-like: they do not depend on the spin configuration, and can, in this case, be mapped onto a Heisenberg spin model even in extreme non-collinear cases.

In addition, we show how the direct Weiss-field can be calculated for non-collinear systems besides the BL, SA and DM like terms.

P306 - Giant Spin Hall Effect in Weyl Semimetal at Room Temperature

12. Spin-orbit and topology driven phenomena

Bing Zhao , *Dmitrii Khokhriakov[1], Yang Zhang[2], Huixia Fu[3], Bogdan Karpiak[1], Anamul Md. Hoque[1], Xiaoguang Xu[4], Yong Jiang[4], Binghai Yan[3], Saroj P. Dash[1, 5]*

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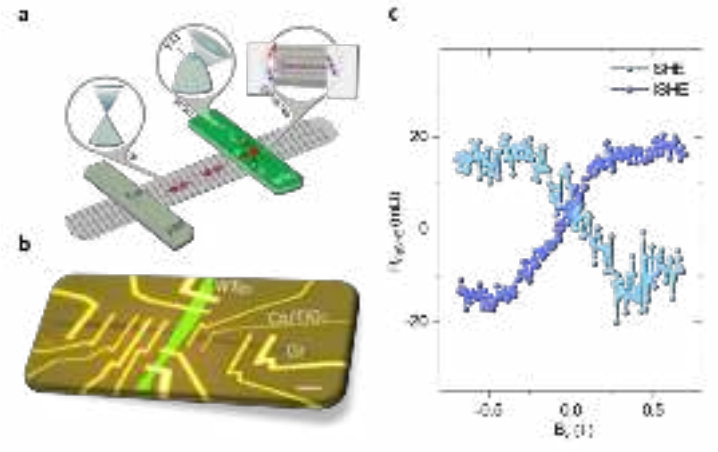
Discovery of two-dimensional (2D) topological semimetals has revealed the opportunities to realize several extraordinary physical phenomena in condensed matter physics. Specifically, these semimetals with strong spin-orbit coupling, novel spin texture and broken inversion symmetry are predicted to exhibit a large spin Hall effect that can efficiently convert the charge current to a spin current. Here for the first time, we report the direct experimental observation of a large and gate-controlled spin Hall and inverse spin Hall effects in a layered semimetal WTe_2 at room temperature obeying Onsager reciprocity relation. We demonstrate the creation and detection of the pure spin current generated by spin Hall phenomenon in WTe_2 by making van der Waals heterostructures with graphene, taking advantage of its long spin coherence length and a large spin transmission efficiency at the heterostructure interface. A large and gate-tunable spin Hall signal has been observed with a lower limit of spin Hall angle 0.37 and spin Hall resistivity ρ_{SH}= 3.29 x10^{-4} Ω□cm at room temperature, which is almost one to two orders of magnitude larger than that of the conventional heavy metals. These experimental findings well supported by ab initio calculations; pave the way for utilization of gate tunable spin-orbit induced phenomena in 2D material heterostructures for spin-based device architectures[1].

[1] B. Zhao, D. Khokhriakov, Y. Zhang, H. Fu, B. Karpiak, A.M. Hoque, X. Xu, Y. Jiang, B. Yan, S.P. Dash, Observation of Spin Hall Effect in Semimetal WTe2, (2018). doi:arXiv:1812.02113v1.



P307 - Impurity-induced topological phase transitions in Dirac semimetals

12. Spin-orbit and topology driven phenomena

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Weyl and Dirac topological semimetals (WSMs and DSMs) are remarkable materials, characterized by strong spin-orbit interaction, which provide a platform for realizing the axion electrodynamics and associated novel quantum phenomena such as the quantum anomalous Hall effect and the quantum topological magnetoelectric effect. Their robust topological quantum states may be utilized for creating spintronic devices featuring strong charge-spin interconversion, whose performance is protected against dissipation and decoherence. Despite considerable progress in the theoretical and experimental understanding of these materials, several fundamental issues are still outstanding. Of particular interest are the role impurities play in these materials. It is well known that the stability of a Dirac node in a DSM, in addition to the inversion and the time reversal symmetry, depends crucially on the presence of the special crystal symmetries, e.g. the rotational C_6 in hexagonal and the rotational C_4 in tetragonal systems. Breaking these symmetries in DSMs is expected to causes a phase transition to a WSM phase. In this work, using first-principles density functional theory combined with a topological analysis based on WannierTools, we have investigated the electronic properties of two prototypical DSMs, namely Cd_3As_2 and Na_3Bi, doped with magnetic and non-magnetic impurities. Specifically, our work shows that different realizations of doping and strain in the system lead to different topological phases, including the possibility of a mixed DSM and WSM phase.

P308 - Magnetic interactions within the metallic coplanar anti-ferromagnet weak ferromagnet Mn3Sn.

12. Spin-orbit and topology driven phenomena

Ramon Cardias[1, 2] , *Anders Bergman[1], Jonas Fransson[1], Attila Szilva[1], Yaroslav Kvashnin[1], Olle Eriksson[1], Angela Klautau[2],* ***Lars Nordström***[1]

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The metallic frustrated anti-ferromagnet Mn3Sn in a Kagome-like crystal structure, orders in a coplanar arrangement with 120 degrees in between moments at neigbouring Mn sites. This material possesses promising properties for antiferromagnetic spintronics applications, as it shows a large anomalous Hall effect and has a very weak ferromagnetic moment theat interact with an applied magnetic fields. This material is well studied both experimentally and theoretically and it is established that the true ground state have an opposite spin rotation compared to to the three fold rotation of the crystal structure. This fact that a certain chirality is favoured, is usually attributed to the Dzyaloshinskii-Moriya interaction (DMI). However the same interaction cannot explain the weak ferromagnetism observed, since the three DMI of the triangles perfectly balance each other. Rather an in-plane anisotropy has been invoked to explain the weak moment.

In this presentation we will argue that the DMI is responsible for both these effects, and that the earlier inconsistencies stem from the fact that the DMI cannot be mapped to a global spin model, but instead depend on the reference system in this metallic non-collinear system. In order to reach this conclusion we have generalised the Liechtenstein-Katsnelson-Antropov-Gubanov (LKAG) theory of calculating interatomic exchange interactions for collinear magnets to a general non-collinear order. In this way, we can identify both isotropic Heisenberg, anisotropic asymmeteric (DMI) and anisotropic and symmetric interactions. This generalisation reduces to the standard LKAG formalism in the collinear limit, including a DMI term. Our formalism also allows us to resolve the contributions from interatomic spin currents and charge currents to these spin interactions. Such currents can be induced by spin orbit coupling, as is exemplified by orbital moments, but in recent years it has been established that they can also originate directly from the non-collinear magnetic order.

We will present calculations of the total energy from the full-potential non-collinear Apw+lo method as implemented in the open source code ELK as well as calculations of interactomic exchange interations by means of a real-space LMTO-ASA method. Both results agree that the anti-rotated state possess a weak ferromagnetiic moments and is the ground state. In addition, the calculations show that the spin-currents give rise to large asymmetric interactions of DMI character even in absence

of spin orbit coupling. These non-relativistic DMI will have different properties than those induced
by spin orbit coupling as they are not dependent on the chirality.

P309 - Magnetic torque anomaly in Dirac semimetal Cd3As2

12. Spin-orbit and topology driven phenomena

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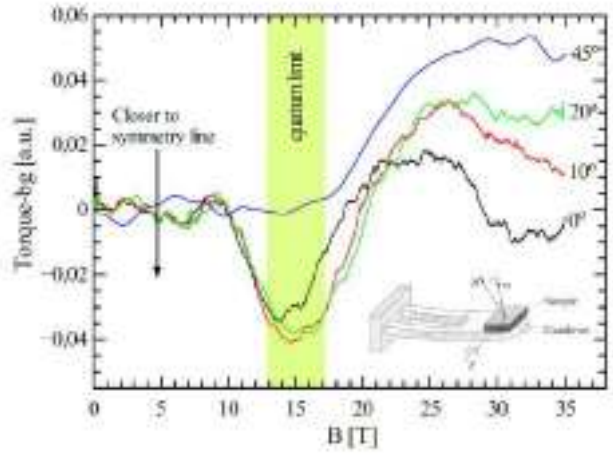
In Dirac and Weyl semimetals there are discrete touching points between valence and conduction band in the 3D Brillouin zone (Dirac and Weyl points). Linear energy dispersion in the vicinity of touching points leads to the non-trivial band topology and fundamentally interesting physics of Dirac and Weyl fermions. Cd_3As_2 is an intrinsic Dirac semimetal with a pair of Dirac points protected by rotational symmetry. By breaking the time reversal symmetry in Dirac semimetal, but preserving the protecting rotational symmetry, every fourfold degenerate Dirac point splits into the two twofold degenerate Weyl points. The magnetic response near the quantum limit depends on the bands topology and it differs for Dirac, Weyl or gaped semimetal. In the case of Weyl semimetal there is a change from diamagnetic to paramagnetic response when quantum limit is reached. In Dirac semimetal the magnetic response will strongly depend on the angle between magnetic field direction and rotational symmetry axis. If the field is directed in the direction of the rotational symmetry axis (rotational symmetry is preserved) we expect anomalous magnetic response around quantum limit (case of Weyl semimetal). This anomaly should be suppressed when the
magnetic field is rotated away from rotational symmetry axis.

By controlling the synthesis parameters we were able to grow monocrystal samples of Cd_3As_2 with different carrier concentrations. In the samples of low charge concentration (quantum oscillation frequency of 15 T) the magnetic torque was measured by piezoresistive cantilever technique (figure), in the magnetic field up to 35 T. Anomalous and angle dependent behaviour in the magnetic torque near the field of quantum limit has been found (figure). The observed anomaly in the magnetic response in Cd_3As_2 can be attributed to the magnetic field driven transition from Dirac to Weyl phase.



P310 - Magnetization states in ultrathin films with Dzyaloshinskii-Moriya interaction

12. Spin-orbit and topology driven phenomena

Jan Kisielewski[1] , *Marek Kisielewski*[1], *Anuj Dhiman*[1], *Vitalii Zablotskii*[2], *Andrzej Maziewski*[1]
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2 Institute of Physics CAS, Prague, Czech Republic

We use micromagnetic simulations to study ultrathin magnetic films with Dzyaloshinskii-Moriya interaction (DMI). We describe multiple magnetic states, like stripe domains, spin-spirals, and magnetic skrymions, which can be formed by playing on a wide range of a magnitude of DMI, magnetic anisotropy (represented by the quality factor Q), and externally applied magnetic field. The magnetic states are characterized by the periodicity of spatial distribution of magnetization and the mean value of the square of an out-of-plane normalized magnetization component $\langle m_z^2 \rangle$, and are mapped in (Q, D) diagrams for a broad range of Q and D parameters. The transitions between magnetic states can be explained in terms of vanishing domain wall energy.
The work was supported by National Science Centre in Poland, grant 2016/23/G/ST3/04196, and European Structural and Investment Funds and Czech Government, grant SOLID21-CZ.02.1.01/0.0/0.0/16 019/0000760.

P311 - New Topological Semimetal Candidate of Nonsymmorphic PdSb2 with Unique Six-fold Degenerate Point

12. Spin-orbit and topology driven phenomena

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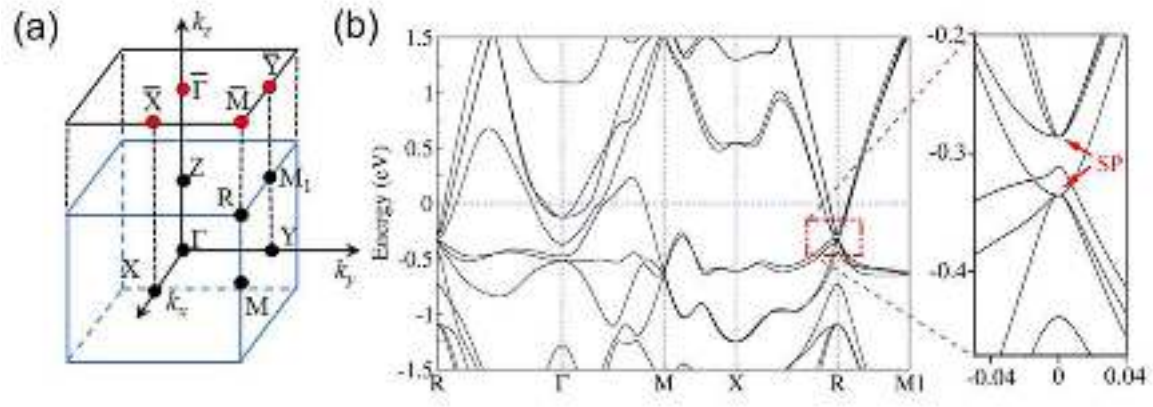
Since the discovery of *Majorana Fermions* in condensed matter systems, new quasiparticle predictions of novel Fermions have been predicted in solid state systems which exhibit three, six or eight fold degenerate band crossings protected by crystal symmetry in presence of spin orbit coupling and time reversal symmetry [1]. Here we note that Dirac and Weyl Fermions have already been observed in many solid state systems with unique properties. Dirac points are four-fold degenerate whereas Weyl points are two-fold degenerate, which always come in pairs. In contrast to the well-known Weyl and Dirac semimetals, which exhibit two- and four-fold degeneracies, respectively at the band crossing, a different type of Fermion has been realized recently in symmorphic MoP, which possess three fold degeneracy at the crossing point. Many pyrite compounds have been identified for their topological features in the band structure. For example, $PtBi_2$ is a Dirac semimetal and could also host triple point Fermions. The isoelectronic $PdSb_2$ is also a semimetal which is known to superconduct below 1.25 K. Based on *ab-initio* calculations, in this work, we predict new six-fold band crossing existing in the nonsymmorphic compound $PdSb_2$, completely distinct from other topological semimetals. The two sextuple points (SP) are formed at the corner of the Brillouin zone by three two-fold degenerate parabolic bands, which might provide a platform for exploring new topological materials with extremely large magnetoresistance (XMR) in noble metal compounds for spintronics.



P312 - Observation of Exchange Bias Effect in La2Cu0.9Cr0.1IrO6 compound

12. Spin-orbit and topology driven phenomena

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The author has chosen not to publicise the abstract.

Field 5

Field 6

P314 - Relativistic mechanism of magneto-transport in the type-II Weyl semimetals

12. Spin-orbit and topology driven phenomena

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[2] Dagestan State University, Makhachkala, Russia
[3] Joint Institute for High Temperatures, Russian Academy of Sciences, Moscow, Russia

The chiral anomaly induces an anomalous transport in the Weyl semimetal. This phenomena is the anomalous nonconservation of a chiral charge. In particular, this can be realized by parallel electromagnetic field. Using a simple theory (both a quasiclassical and Kubo approaches), we have shown, that in type-II Weyl metals another anomalous transport mechanism is possible. It is not associated with the chiral anomaly. The induced by this mechanism the electric current is proportional to the pseudoscalar product of the fields and directed along the magnetic field (see Figure), that differs it from the Hall current. At the same time, the conductivity corresponding to this transport chanel does not depend on the scattering time like the Hall conductivity. The new transport mechanism is based on the relativistic effect of the electric field on Landau levels. The electric eld changes the distance between the Landau levels, and also changes the effective velocity along magnetic field. At presence of a tilt in the spectrum, this velocity renormalization is differ for different Weyl points. This leads to a non-zero resulting drift velocity. As a consequence, an electrical current arises along the magnetic eld. Thus, we have proposed a new anomalous transport mechanism in the type-II Weyl semimetal, which is not associated with the chiral anomaly.

The research was supported by a grants of the RFBR (18-02-01022a, 18-32-00205 mol(a), 19-02-01000 A).

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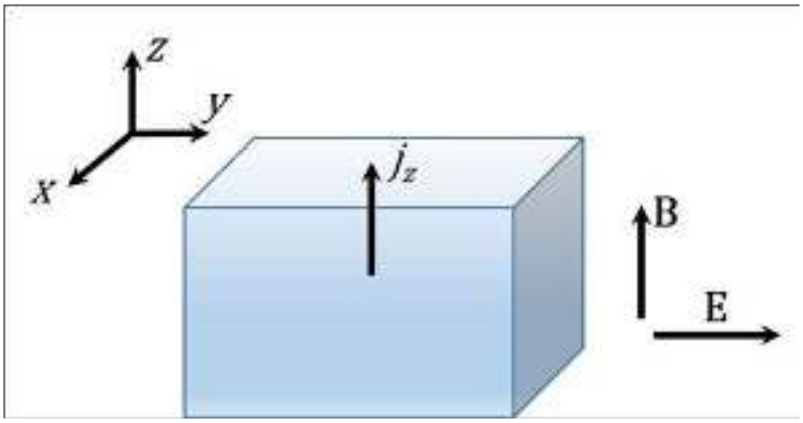

P316 - Spin Torque Ferromagnetic Resonance in Weyl Semimetal/Ferromagnet heterostructures

12. Spin-orbit and topology driven phenomena

Amilcar Bedoya Pinto[1] , ***Avanindra Pandeya***[1], *Stuart Parkin*[1]
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Weyl Semimetals, materials with three-dimensional topologically protected electronic states, show highly interesting physical properties including Fermi-arcs, the Adler-Jackiw (chiral) anomaly in magnetotransport and extremely high electron mobilities at the linear dispersion bands. Still, its potential for device applications needs to be addressed through the preparation of thin films, which would enable the design of functional heterostructures and new device paradigms. One promising application field of Weyl Semimetals is spin-orbitronics, as the Fermi-surface topology is expected to play an important role in spin-to-charge conversion efficiency, according to theoretical investigations [1,2].

In this work, we report the growth of epitaxial Weyl Semimetal thin films, namely NbP and TaP, by means of molecular beam epitaxy, and their successful integration in spin-torque devices. We use spin-torque ferromagnetic resonance (ST-FMR) to explore the spin-orbit torques produced by the topological Weyl semimetal, relying on the preparation of high-quality, in-situ TaP (NbP)/Permalloy interfaces. Preliminary ST-FMR results of TaP/Py/MgO device structures at room temperature show a very strong symmetric component of the voltage lineshape across the resonance (Fig. 1), as well as a change of the resonance linewidth by applying an external DC bias through the bilayer, both signatures of sizable spin-orbit torques induced by the WSM layer. The link between Fermi-surface topology and spin-to-charge conversion will be studied by performing photoemission experiments on the TaP (NbP) thin film surfaces prior to the deposition of the magnetic layers.

References

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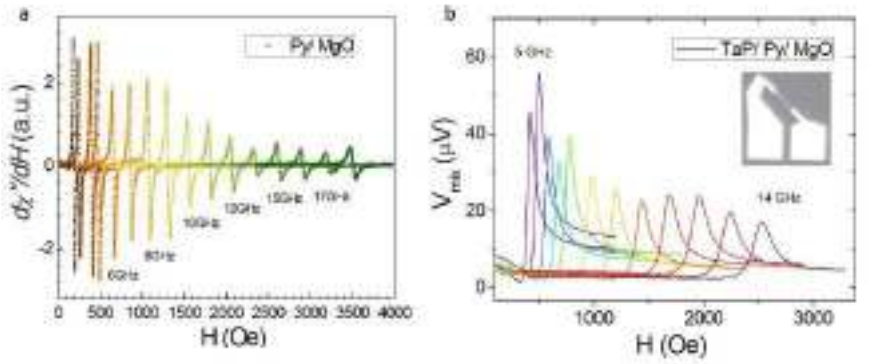

Figure 2. (a) Reference FMR response of a Py(6nm)/MgO(2nm) bilayer measured with a coplanar waveguide. (b) Frequency dependent ST-FMR signal of a TaP(6nm)/Py(6nm)/MgO(2nm) device structure, presenting a large symmetric component arising from damping-like torques.

P317 - Spin transfer from quantum spin Hall systems

12. Spin-orbit and topology driven phenomena

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The author has chosen not to publicise the abstract.

Field 5

Field 6

P318 - Spin-orbit torque magnetization switching in Pt/Co/NiO structure

12. Spin-orbit and topology driven phenomena

Maksim Stebliy[1] , *Alexander Kolesnikov*[1], *Alexander Samardak*[1], *Alexey Ognev*[1], *Mihail Bazrov*[1], *Mihail Letushev*[1], *Xiao Wang*[2], *Chi Fang*[2], *Chenyang Guo*[2], *Caihua Wan*[2], *Xiufeng Han*[2]

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The task of local magnetization control is a one of the crucial point of spintronics development. The spin-orbit torque (SOT) is a perspective method of such control [1]. Deterministic switching of the magnetization can be achieved under the action of spin current generated due to the spin Hall effect in a heavy metal layer and injected into a broken inversion symmetry ferromagnetic layer with perpendicular magnetic anisotropy (PMA). Broken inversion symmetry can be introduced using of adjacent layer of an antiferromagnet (AFM) [2]. In this work, the current induced switching of magnetization was investigated in a system containing NiO as AFM layer. This material combines the properties of a dielectric and an antiferromagnet making it suitable for the use as a capping layer.

The Pt/Co/NiO structures were deposited by magnetron sputtering on the Si/SiO_2 substrates. Effect of the Co and NiO layer thickness on the current-induced magnetization reversal process was investigated. A preliminary study of continuous films showed that antiferromagnetic ordering in NiO, which causes the exchange bias, is realized at the thickness of NiO larger than 10 nm and at the pressure of Ar during sputtering larger than 0.15 Pa, which is in an agreement with the previous study [3]. The maximum value of the induced exchange bias field was 25 mT. Increasing of the Co thickness in the range from 0.3 up to 0.9 nm leads to the enhancement of the PMA energy, Fig.1a. It was found that the possible mechanisms of the current-induced magnetization reversal depend on the Co layer thickness. In case of the minimal thickness and, consequently, the minimal anisotropy energy, the magnetization reversal occurs through the nucleation of domains, Fig.1c. At the maximum thickness, the magnetization reversal is realized through the domain wall motion, Fig. 1d. Current pulses with a duration of 7 us were applied to the 10-mm-wide Hall bar structure in the presence of a co-directed external magnetic field . The dependence of the reduced magnetization M_z on the current pulse amplitude was recorded for a quantitative assessment of the magnetization reversal process, Fig.1b. The plotted dependencies show that the magnetization reversal through the nucleation of domains occurs faster and requires less currents in comparison with the domain wall motion process.

This work was supported by Grant of the President of the Russian Federation (MK-2281.2019.2), Russian Foundation for Basic Research (#18-32-00867 and #18-52-53038) and the Russian Ministry of Science and Higher Education under the state tasks (#3.5178.2017/8.9 and #3.4956.2017).

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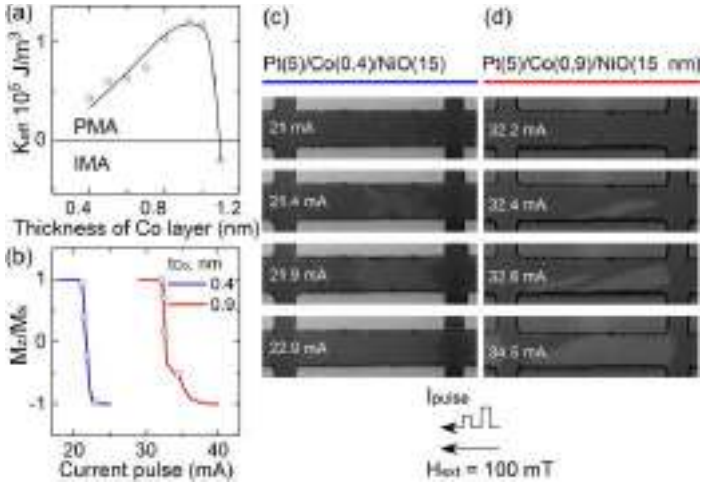
(a)
K_{eff} 10^5 J/m^3
1
0
PMA
IMA
0.4
0.8
1.2
Thickness of Co layer (nm)
(b)
M_z/M_s
1
0
-1
t_{Co}, nm
0.4
0.9
20
30
40
Current pulse (mA)
(c)
(d)
Pt(5)/Co(0.4)/NiO(15)
Pt(5)/Co(0.9)/NiO(15 nm)
29 mA
32.2 mA
29.4 mA
32.4 mA
29.9 mA
32.6 mA
32.9 mA
34.5 mA
Ipulse
H_{ext} = 100 mT

P319 - Stability of magnetic skyrmions in tilted magnetic field

12. Spin-orbit and topology driven phenomena

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Chiral topological magnetic skyrmions are localized non-collinear magnetic structures considered as promising candidates of information carriers in ultrafast and superdense magnetic memory, artificial neuron systems and other application. Stability of skyrmions with respect to thermal fluctuations is the key problem of their practical use. They have to be quite stable to keep magnetic information but at the same time they have to be manipulated by as small as possible external action to reach energy efficiency.

Stability of skyrmions and their lifetime in external magnetic field was estimated in [1] using transition state theory (TST) for magnetic degrees of freedom and harmonic (H) approximation for energy surface in the local minimuma and at the neighbourhood of transition state. The system was two-dimensional and magnetic field was directed perpendicular to the surface. However recently experimental observation of enhanced skyrmions stability in tilted magnetic field was reported [2]. Authors claimed that this effect is completely beyond the theoretical prediction in a conventional two-dimensional (2D) models but connected with competition between conical phase and skyrmions in three-dimensional (3D) systems.

In the report I will show that nonmonotonic dependence of stability (lifetimes) of skyrmions on the tilting angle of the field θ and on the value of magnetic field h takes place already in 2D system and even without dipole interaction. In tilted field the skyrmion is loosing circular symmetry as shown in fig.1 a. HTST predicts Arrhenius law for skyrmion lifetime: $\tau = \tau_0 \exp(\Delta E/k_B T)$, where ΔE is activation barrier, which is the difference between energy of the system at the saddle point and at the skyrmion local minimum, T is absolute temperature. Preexponential factor depends on the shape of the energy surface at the same points. Fig. 1b shows the logarithm of skyrmion lifetime in variables of a dimensionless magnetic field h ($h=HD^2/J$, H-magnetic field, D-Dzyaloshinskii-Moriya constant, J-exchange parameter, $\tau_{int}=\mu/(J\gamma)$) and its angle of inclination relatively the normal to the surface, θ. T he reason for the nonmonotonic dependence of lifetime on θ is the interplay between the pre-exponential factor τ_0 and value $\exp(\Delta E/k_B T)$. With an increase of θ, τ_0 decreases, while the barrier ΔE increases. There is a temperature range where the lifetime of the skyrmion has a maximum, as it is seen in fig. 1b (for T=4 K, J=2 meV), similar to maximum in density of skyrmions observed in [2] for definite tilting angle. Therefore, only taking into account the difference of entropy for saddle point and skyrmion minimum and the tilting angle dependence of activation barrier allows to explain observed in experiment enhanced skyrmion stability in 2D systems in tilted magnetic field.

This work was supported by RFBR grant 18-02-00267a and by Icelandic Research Fund Grant No. 185409-051.

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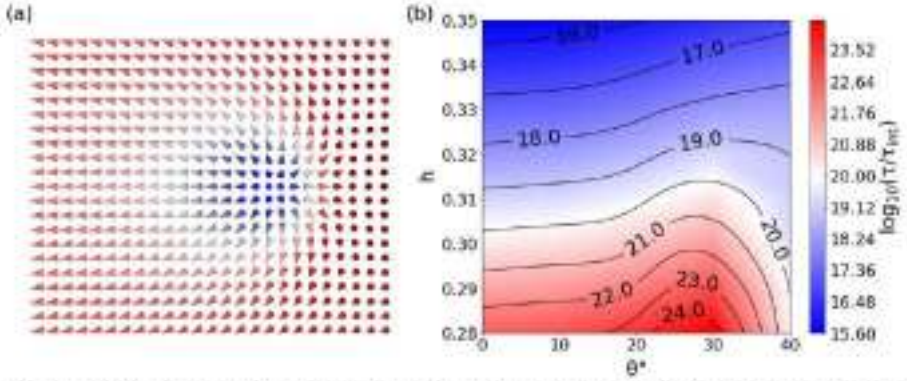

Figure 1. (a) Skyrmion configuration in tilted magnetic field h=0.7, θ = 60°. (b) Skyrmion lifetime as a function of tilting angle θ and magnetic field h. Anisotropy and Dzyaloshinskii-Moriya constants are K=0.1J, D=0.2J.

P320 - Stability of magnetic skyrmions in ultrathin films and dots

12. Spin-orbit and topology driven phenomena

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Magnetic skyrmions are topologically non-trivial inhomogeneous magnetization textures on the nanoscale. Skyrmions can be manipulated by spin polarized currents of extremely low density in comparison with the densities used in traditional spintronics [1]. Recently the individual skyrmions were experimentally observed at room temperature in Co/Pt, Ir/Co/Pt etc. ultrathin multilayer structures, including magnetic dots. To achieve efficient manipulation of the nanosized spin textures and implement skyrmion-based spintronic devices, it is essential to understand the skyrmion stability and dynamics in restricted geometries.

In this talk I focus on the skyrmion stability in ultrathin magnetic films and cylindrical magnetic dots. The skyrmions can be stabilized at room temperature and zero external magnetic field due to an interplay of the isotropic exchange, interface Dzyaloshinskii-Moriya (DMI), out-of-plane magnetic anisotropy and magnetostatic interactions. We consider the Neel´s skyrmions and calculate their stability phase diagrams within the micromagnetic approach. The chiral DMI induced on the interfaces of heavy metals with ultrathin ferromagnetic layers (0.5-1 nm) is crucial for the Neel skyrmion stabilization [2, 3].

The generalized DeBonte ansatz is used to describe the inhomogeneous skyrmion magnetization assuming its radial symmetry. The single skyrmion metastability/instability area, skyrmion radius, and skyrmion width are found analytically as a function of the DMI strength D in infinite magnetic films [2]. It is shown that the single chiral skyrmions are metastable below a critical value of DMI D_c, and do not exist at $D > D_c$. The calculated skyrmion radius increases as D increases and diverges at D approaching to D_c, whereas the skyrmion width increases monotonically as D increases up to the critical value without any singularities. The calculated skyrmion width is essentially smaller than the one calculated within the generalized domain wall model. It is shown that the criterion of skyrmion stability in an infinite film should be changed to describe the skyrmion stability in nanodots. The skyrmions can be the ground states for dots of a finite radius, whereas they can only be metastable in infinite films. The areas of the single-Néel skyrmion stability/metastability/instability and skyrmion radius in the cylindrical dots are found as functions of the uniaxial out-of-plane magnetic anisotropy and DMI strength [3]. The area of the skyrmion stability increases by decrease of the out-of-plane magnetic anisotropy constant. The calculated phase diagram allows optimizing the ultrathin dot magnetic parameters to stabilize the Néel skyrmions. Recent experiments and calculations of the magnetic skyrmion stabilization and dynamics in multilayer films with ultrathin ferromagnetic layers and ultrathin nanodots are discussed.

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P321 - Steering skyrmions with line defects: a Thiele's approach

12. Spin-orbit and topology driven phenomena

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Magnetic skyrmions are promising information carriers due to their small size, their topological quantization, and their efficient electric manipulation. In this context, controlling skyrmions is a key aspect to be developed, for example guiding along desired lines [1, 2] or trapping at desired positions [3]. Within Thiele's approximation, we present a model for guiding and trapping skyrmions, based on the use of several arrangements of Gaussian-like potential line defects. The skyrmion is driven by a spin-polarized current. A study of the resulting phase portrait of the trajectories leads to the analytical prediction of the steady positions. In the case of a grid of line defects a periodic array of steady positions is found, which could be interesting for many applications, such as using the skyrmion's stray field to trap tiny objects [4]. In some cases small driving current densities result in large velocities along desired lines. These results have been validated by solving Landau-Lifshitz-Gilbert equation and a rather good agreement is found.

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P322 - Structural and Magnetotransport Characterization of Co-doped Bi2Te3 Thin Films

12. Spin-orbit and topology driven phenomena

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The breaking of time reversal symmetry (TRS) in three-dimensional (3D) topological insulators (TIs), and thus the opening of a “Dirac-mass gap” in the linearly dispersed Dirac surface state is a prerequisite for unlocking exotic physical states [1]. Doping 3d transition metal impurities into TIs is a convenient approach to bring robust long-range ferromagnetic order that has been shown to break TRS and to enable novel topological phases [2].

Here we present a study of the structural and magneto-transport properties of Co-doped Bi_2Te_3 thin films. The films were prepared with the magnetron sputtering technique on $Si_{(111)}$ substrates with Co and composite Bi_2Te_3 targets. The substrate temperature was fixed at 300 ^{o}C while the Ar pressure at 3 mTorr. The doping was achieved by repeating ten times the Co-Bi_2Te_3 bilayer pattern with the high temperature allowing the mixing of the two materials. Thus the final structure is $Si_{(111)}/(Bi_{1-x}Co_x)_2Te_3$ with x= 0.04 - 0.4. Structural characterization with the X-Ray Diffraction (XRD) technique revealed a preferential (00*l*) texture. The surface morphology was also observed with Field Emission Scanning Electron Microscopy (FESEM). Magnetoresistance (MR) and Hall measurements were performed for the Co-doped Bi_2Te_3 samples and two reference films of Bi_2Te_3 and Co, all with Hall bar configuration. For the Hall bar configuration a stencil mask was used on a 7x7mm^2 substrate, while a second mask was aligned to make pads of Cr/Au for the electric contacts. The electric contacts were of aluminum wire and made with a wire-bonder. The magnetotransport measurements were performed for magnetic field from -5 T to 5 T and for temperature ranging from 3 to 300 K. Weak antilocalization phenomena (WAL) were observed and the data were fitted to Hikami-Larkin-Nagaoka equation, for instance, the fit yielded α=1 and l_φ=12.83 nm for pure Bi_2Te_3 at 3 K. With the onset of ferromagnetism in Co-doped Bi_2Te_3 samples the WAL phenomena disappeared. The carrier density and mobility of thin films were determined by magneto-transport measurements using Hall bars channels. The undoped Bi_2Te_3 film is n-type with a 2D carrier density of 8.9x10^{15} cm^{-2} at 3K. Doping with cobalt results in p-type charge carriers, at temperatures below 50 K, with a calculated density of 1.4x10^{18} cm^{-2} at 3K for x=0.2 cobalt composition. We also present magnetoresistivity (R_{xx}) data with the field rotating in-plane (xy-plane), for magnetic fields 0.1 – 0.5 T at low temperatures.

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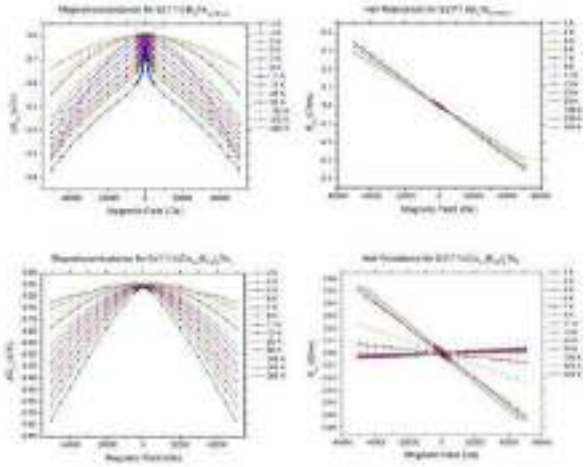

P323 - Structural and Magnetotransport Characterization of Sm-Doped Bi2Te3 Thin Films

12. Spin-orbit and topology driven phenomena

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Topological insulators (TIs) feature among the most significant contemporary discoveries in condensed matter physics, since they have a gapless topological surface state (TSS) which exhibits robust spin-momentum locking protected by time-reversal symmetry (TRS)[1]. Recent studies have shed light to various approaches in breaking TRS and thus opening a gap in the linearly dispersed Dirac surface state with the aim of unlocking exotic physical states[2]. Among these approaches doping either with 3d transition metals or with rare-earth elements are ways to achieve the breaking of TRS.

In this study we present our results on structural characterization and magnetotransport properties of Sm-doped Bi_2Te_3 thin films. The films were prepared with magnetron sputtering technique on Si(111) substrates with Sm and composite Bi_2Te_3 targets. During the deposition substrate temperature was stabilized at 300 ^{o}C and Ar pressure at 3 mtorr. The doping was achieved by repeating five times the Bi_2Te_3/Sm bilayer pattern with the two phases mixing due to the high deposition temperature. Finally, the samples had the structure: Si(111)/$(Bi_{1-x}Sm_x)_2Te_3$ with x=0.02-0.10. The samples were structurally characterized with X-Ray Diffraction (XRD) that revealed a predominant (00*l*) texture and Scherrer crystallite size from 13 nm for x=0.02 to 20 nm for x=0.1. The surface morphology was also observed with Field Emission Scanning Electron Microscopy (FESEM) that revealed pyramid shaped crystal structures with size of the order of 10^2 nm. Magnetoresistance (MR) and Hall measurements were performed on 4x4 mm^2 square samples with contacts of copper wire pressed at their edges on the sample with indium. The magnetotransport measurements refer to magnetic fields in the range of -9 T to 9 T and for temperatures from 2.5 to 300 K. Low field magnetoresistance is cusp-shaped at low temperatures indicative of weak antilocalization phenomena. The corresponding fitting to Hikami-Larkin-Nagaoka yielded a phase coherence length of 225.6 nm for the Sm-doped sample with x=0.1. Hall measurements showed that Sm-doped sample with x=0.1 is p-type with 2D carrier density of 1.4x10^{16} cm^{-2} at 3 K, in contrast to pure Bi_2Te_3 that is n-type with carrier density of 8.9x10^{15} cm^{-2}. Magnetoresistance data were also acquired as a function of the angle of the magnetic field with film's plane, for magnetic fields up to 0.5 T and at low temperatures.

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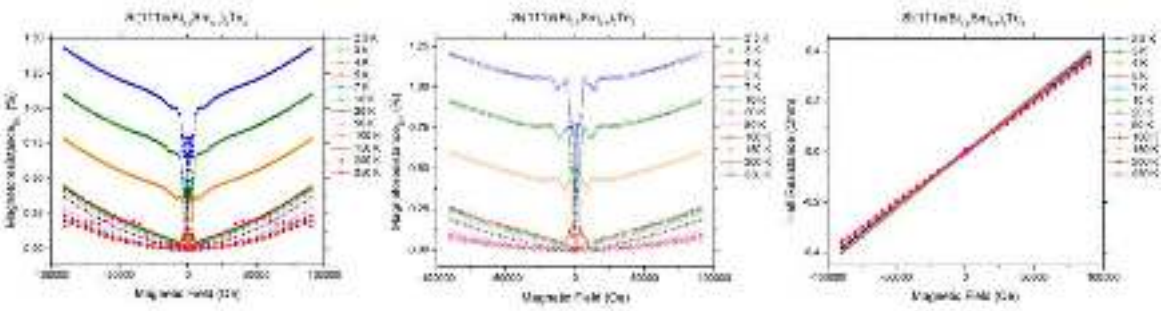

P324 - Theory of Dzyaloshinskii-Moriya Interaction and Antiferromagnetic and Ferromagnetic metals

12. Spin-orbit and topology driven phenomena

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In magnetic thin films, broken inversion symmetry or coupling to adjacent heavy metals can induce Dzyaloshinskii-Moriya (DM) interactions. Knowledge of the DM parameters is essential for understanding and designing exotic spin structures, such as hedgehog Skyrmions and chiral Néel walls, which are attractive for use in novel information storage technologies. We introduce a framework for computing the DM interaction in two-dimensional Rashba ferromagnets and antiferromagnets. Unlike in Rashba ferromagnets, the DM interaction in antiferromagnets is not suppressed even at low temperatures. The material parameters control both the strength and the sign of the interfacial DM interaction. Our results suggest a route toward controlling the DM interaction in magnetic materials by means of doping and electric fields.

P325 - Topological magnetoelectric effect vs QAHE in magnetic TI thin-film trilayers

12. Spin-orbit and topology driven phenomena

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The quantum anomalous Hall effect (QAHE) and the topological magnetoelectric effect (TME) are quantum phenomena that emerge when time-reversal symmetry (TRS) is broken at the surfaces of topological insulator (TI) thin films. The common origin of these effects is the axion electrodynamics θ-term, which is directly related to the Z_2 topological index of the TI. To study these effects, we investigate theoretically a four-terminal device consisting of a Bi_2Se_3 TI nanoribbon and two antiferromagnetic metal layers positioned at the top and bottom surfaces, which break TRS at the surface by proximity effect and act as conducting leads for vertical transport. By using a combination of tight-binding models and non-equilibrium Green's function methods, we show that quantum transport along both longitudinal and vertical direction of the heterostructure is strongly influenced by whether the exchange fields on the top and bottom surfaces of the TI are parallel or antiparallel. In the first case, the system is in the QAH phase characterized by conducting chiral edge states on the sidewall surfaces; the second case leads to an axion-insulator phase where all surface states are gapped. For transport in the vertical direction, we focus in particular on the axion-insulator phase. By computing different magneto-electric coefficients, we discuss the conditions for the TME to be quantized, or what it is that limits fundamentally the accuracy of its quantization, in comparison with the case of the QAHE.

13. Magneto-optics and magnetoplasmonics

P327 - All-Optical Magnetic Switching in Compensated Ferrimagnetic Mn2RuxGa by Single Pulse Excitation

13. Magneto-optics and magnetoplasmonics

Chandrima Banerjee[1] , *Gwenael Atcheson[1], Niclas Teichert[1], Zsolt Gercsi[1], John Michael David Coey[1], Plamen Stamenov[1], Karsten Rode[1], Jean Besbas[1]*

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The growing demand for data recording and fast information processing through magnetic reversal of magnetic materials is a key goal of spintronics. Antiferromagnetic (AFM) materials are particularly promising, as they are insensitive to magnetic fields and exhibit spin dynamics in the terahertz range [1]. Measuring magnetic effects in AFMs is difficult due to the absence of coupling with external magnetic fields. An alternative set of materials is the compensated ferrimagnets (CFM).

Mn_2Ru_xGa (MRG) is such a material. It is an inverse Heusler alloy, where Mn atoms occupy two antiferromagnetically coupled inequivalent sub-lattices at Wychoff positions 4a and 4c. MRG associate a low magnetization (50 $kA.m^{-1}$) with a high spin polarization of ~ 60%. It shows a high anomalous Hall effect; diverging coercivity close to the compensation temperature; and an intrisic spin-orbit torque, which can be studied using standard techniques.

The magneto-optical Kerr effect (MOKE) is an efficient way to characterise MRG as it is sensitive mainly to the 4c sublattice. This allows imaging of magnetic domains even in the absence of net magnetisation. Furthermore, excitation with femtosecond pulses allows studying its temperature behaviour as one pulse can heat up the electronic bath in times as short as a few tens of femtoseconds. For example, picosecond reversal of magnetization triggered by femtosecond laser light pulses has been demonstrated in amorphous ferrimagnet GdFeCo[2].

In this work, we show the behaviour of $Mn_2Ru_{0.8}Ga$ film in response to single femtosecond pulse without an external magnetic field [3]. Figure 1a-b depicts MOKE micrographs of a saturated MRG film after excited by a single laser pulse of wavelength 800 nm and fluence 8.1 mJ/cm^2 (1a) and 12.2 mJ/cm^2 (1b). In 1a, the area irradiated by the pulse is identifiable as the white contrast in the centre of the picture. Upon increasing fluence (Fig. 1b), three regions of different contrast appear: i) the surrounding saturated region which has not been affected by the pulse, ii) the white contrast area present at lower fluence, and iii) a central multidomain region. In this central region, the intensity was sufficient to heat the sample above the Curie temperature and thus form a multidomain state after cooling. The contrast of the white area (ii) is opposite to both the saturated (i) and the multidomain (iii) areas. We tentatively attribute the origin of our single-pulse switching to light-induced heating, and will discuss all-optical switching in a non-rare-earth-containing CFM.

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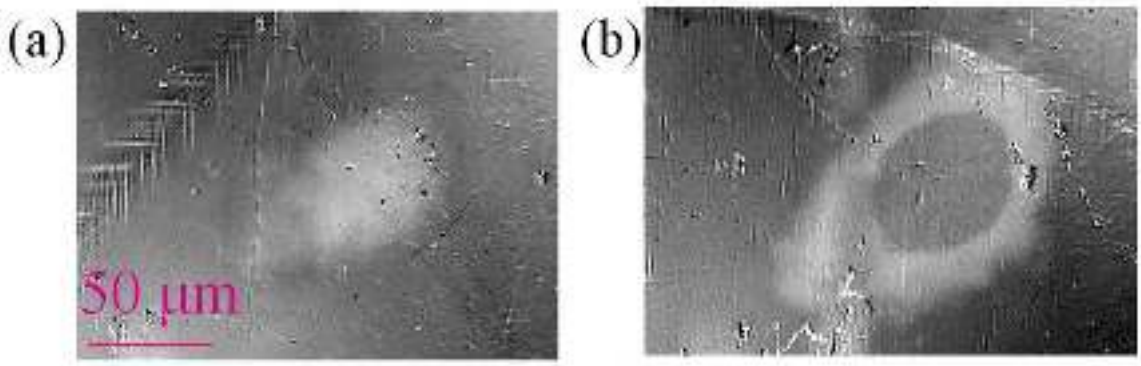

Figure 1: Kerr micrographs of MRG after excitation with single laser pulse of fluence (a) 8.1 mJ/cm² and (b) 12.2 mJ/cm² respectively. The dark grey and white regions indicate down and up orientation of 4c sublattice respectively.

P328 - Characterization of Magnetic Domains Using MOKE Microscope with Rotating Analyzer

13. Magneto-optics and magnetoplasmonics

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Magneto-optical (MO) methods are often used as highly sensitive non-destructive techniques to probe physical properties of various magnetic materials down to the nanometre scale. Spatially resolved MO experiments are suited for visualization of magnetic domains larger than 150 nanometres. There are many further advantages of magneto-optical microscopy, such as non-destructiveness, possible high time resolution or low requirements on samples and easy manipulation with them, which enables great way to analyse wide variety of nanostructured magnetic materials. As disadvantage of the MO microscopy, the obtained results represent only optical contrast and for advanced investigation a comparison with additional methods, e.g. magnetometry or anisotropy measurements, must be used.

We report on the development of a magneto-optical Kerr effect (MOKE) microscope that employs the rotating analyser method. This technique is usually used in spectroscopic measurements and allows for obtaining the Kerr rotation of the studied system directly form the captured pictures with the accuracy of several millidegrees resolution. Spatial imaging of the Kerr rotation, combined with sub-pixel domain wall detection and image post-processing techniques, is useful for detailed characterization of magnetic properties. e.g. stability of magnetic domains, pinning, etc. Combined in a setup with a high-speed camera, capable of capturing 100 fps, dynamics of magnetic domains can be captured as well. To demonstrate the setup capabilities, we present exemplary measurements and characterization of several samples, such as NiFe permalloy gratings and domain structures of Bi:YIG garnets.

P329 - Individual contributions to magnetooptical permittivity: model system bcc Fe

13. Magneto-optics and magnetoplasmonics

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We present analysis of individual contributions to the optical transitions to outgoing magnetooptic (MO) permittivity, i.e. anomalous transport at optical frequencies. The magneto-optical transitions are visualized in the Brillouin zone and the key transitions contributing to the MO response are identified. As a model material, we made those studies on bcc Fe. The electronic structure and the dipole matrix elements were calculated using the WIEN2k code [1]. The outgoing spectra are compared to the experiment.
All major MO contributions are classified into two contributions, denoted parallel and perpendicular contributions, providing about 2/3 and 1/3 of the total MO permittivity, respectively. First, the parallel contributions, originates from the transitions only from few k-points of the reciprocal space, where 3d-bands crosses each other and where the *k*-vector direction has parallel contribution to the magnetization direction. This is demonstrated in Fig. 1(a), showing the bandstructure of bcc Fe, with two dominant magnetooptic transitions, whose positions in the reciprocal space are denoted CΣ and CΔ. Fig. 1(b) shows magnetooptic transitions on isosurface energy difference between bands 14 and 17, demonstrating that nonzero contributions to magnetooptic transitions appear only at a limited number of *k*-points (in this example at CΣ points), being basically a point feature of the electronic structure. This contribution has form of a dipole, meaning two strong contributions with opposite signs for MO transitions to split bands, however, not completely canceling each other. In our example, it corresponds to transitions between bands 14-17 and 14-18.
The second contribution, called perpendicular, originates from the k-points having non-zero perpendicular projection to the magnetization direction. This contribution is much weaker compared to the parallel one for a single k-point, however it originates from larger areas of the isosurface of the k-points and for a given spin direction, it provides single sign contribution. Therefore, its overall contribution is of the similar order as the first one.

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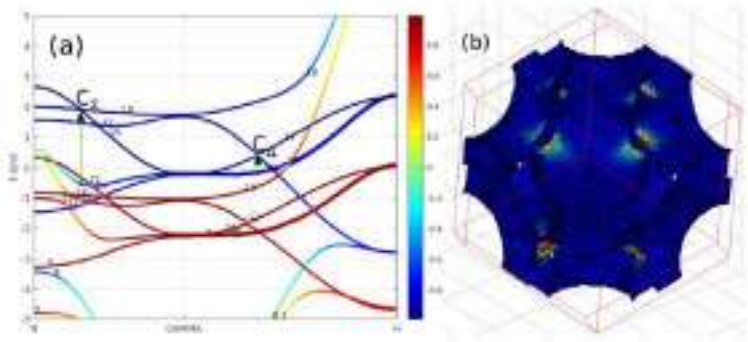

Fig 1: (a) Bandstructure of bcc Fe on k-path N-Gamma-H, where the segment Gamma-H is parallel with the magnetization. Two points of interest are marked, C_Σ and C_Δ. The color denotes projection to 3d-states, red=3d-electrons, spin-up, blue=3d-electrons, spin-down. (b) surface in the reciprocal space of bcc Fe defined by constant energy difference of 2.4 eV between bands 14 and 17. The color shows magnetooptic transition probability (blue=0). The only non-vanishing transitions are in the vicinity of C_Σ points.

P330 - Magnetic domains in amorphous ferrimagnetic Tb:Co: Order in disordered thin films

13. Magneto-optics and magnetoplasmonics

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In the search of optimal materials and structures for the efficient and fast magnetic writing and reading for the magnetic memory elements, rear Earth (RE)- transition metal (TM) alloys have become a material class of interest. As a candidate for all-optical light-induced magnetization switching (AOS), without any external magnetic field(1,2), ferrimagnetic amorphous alloys containing terbium and cobalt (Tb:Co) have attracted attention due to their strong out-of-plane magnetic anisotropy(3). This alloy provides a possibility of tuning the magnetic and magneto-optical properties via adjustment of the Tb:Co ratio.

In this work, we investigate the relation between the alloy's composition and coercive field, as well as the resulting magnetic domains' size. A range of *Tb:Co* thin films were prepared by magnetron co-sputtering. Magneto-optical Kerr effect (MOKE) was employed to measure a coercive field, H_C, while the magnetic domain structure of films in a remanent state was resolved using MOKE microscopy. AOS experiments were carried out using a femtosecond pump-probe setup. It was determined that the samples with a Tb content higher than the compensation point, between 24 and 29 at. %, and thickness of 30(2) nm exhibit thermally assisted, light induced AOS with 10 thousand shots in a laser pulse burst. MOKE microscopy revealed that magnetic domains in TbCo films form arbitrary patterns, and are of random sizes (Inset in Figure 1(a)). However, we show that they can exhibit a certain ordering. We applied a pair correlation function (PCF) analysis, in order to evaluate MOKE microscopy images and determine the average domain size (See Figure 1(a)). The domain width (DW) was extracted as the first minimum in the PCF plot and DW versus H_c plot is shown in Figure 1(b). It can be observed that the stronger coercive field, the larger the magnetic domain. The results of our research show that (1) the size of a magnetic domain and coercive field can be controlled by changing the composition; and that (2) AOS can occur for a variety of films with compositions above the compensation point and magnetic domain sizes in a wide length range from less than 1 to 15 µm. Even though the domains appear to be random, the PCF shows that films exhibit a correlation length which corresponds to the average width of the magnetic domain as approximated by a first minimum in a PCF plot. This hints about ordering of the random magnetic domains at a certain length-scale .

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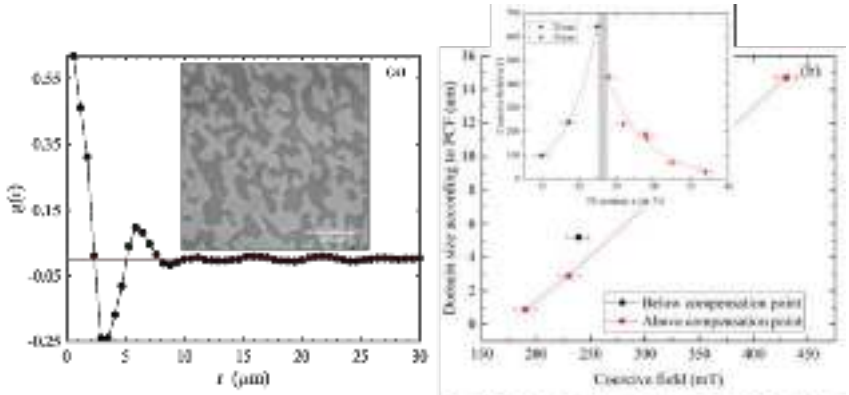
(a)
g(r)
r (μm)
(b)
Domain size according to PCF (μm)
Coercive field (mT)
Before compensation point
Above compensation point

P331 - Observation of interfacial effects at Pt/GdFeCo interface using magneto-optical Kerr effect

13. Magneto-optics and magnetoplasmonics

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Interfacial effects such as the spin Hall effect (SHE), the Dzyaloshinskii-Moriya interaction (DMI), and the interfacial Rasba effect [1-3], which are induced by strong spin-orbit coupling at the magnetic/heavy metal interface have been of great interest because they promote fast current-induced domain wall motion at low current density [4-5], which is indispensable for realizing low-energy consumption and high-speed operation memory and logic devices. Magneto-optical Kerr effect (MOKE) is well known as a useful method for detecting the magnetization direction of magnetic materials. Furthermore, it has been widely used recently to probe interfacial information such as spin-orbit torques, chiral magnetism, and related effects. Recently, we reported contributions of the interfacial effects to MOKE in TbCo thin films [6]. In the present work, we investigated MOKE spectra in GdFeCo thin films with various seed layers and showed contributions of the interfacial effects to magneto-optical properties in these GdFeCo thin films.

Thin films with structures of Pt(5 nm)/GdFeCo(6 nm)/SiN_x(10 nm), Cu(5 nm)/GdFeCo(6 nm)/SiN_x (10 nm) and SiN_x (10 nm)/GdFeCo(6 nm)/SiN_x (10 nm) were deposited on silicon substrates with thermally oxidized SiO_2 layer (100 nm).

Polar MOKE rotation and ellipticity spectra of the samples were measured in an energy range of 1.77 – 4.13 eV (wavelength range of 300-700 nm) by a home-made MOKE spectroscopy using a Xenon light source and a photo-elastic modulator [7] and were simulated based on the effective refractive index method [8].

As shown in Fig. 1, the measured MOKE spectra are consistent with the simulated ones for the Cu/GdFeCo/SiN_x and SiN_x/GdFeCo/SiN_x samples. However, there are some differences between the measured and simulated MOKE spectra for Pt/GdFeCo/SiN_x at low energy region. Such differences are attributable to the interfacial effects of the spin-orbit interaction at the Pt/GdFeCo interface.

This research was partially supported by the Ministry of Education, Culture, Sport, Science and Technology, Japan - Supported Program for Strategic Research Foundation at Private University (2014-2020) and JSPS KAKENHI (Nos. 17H03240 and 18K14128).

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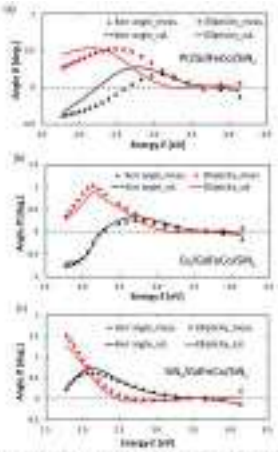

Fig. 1 Polar MOKE rotation and ellipticity spectra for Pt/GdFeCo/SiN_x (a), Cu/GdFeCo/SiN_x (b) and SiN_x/GdFeCa/SiN_x (c). solid and dot lines represent simulated and experimental data, respectively.

P332 - Observations of a large magnetic domain wall in thin magnetic cylinders

13. Magneto-optics and magnetoplasmonics

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The author has chosen not to publicise the abstract.

Field 5

Field 6

P333 - Optical and magneto-optical properties of Bi and Tb substituted Yttrium Iron Garnets on Si substrate

13. Magneto-optics and magnetoplasmonics

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Monolithic integration of non-reciprocal photonic devices requires high quality thin films of materials with strong magneto-optical (MO) effect. So far most research on integrated optical isolators has been based on Ce-substituted Yttrium Iron Garnet (Ce:YIG) as the MO material [1]. However, Ce:YIG has an absorption peak at 1 eV making it unsuitable for use in optical isolators operating at the lowest dispersion wavelength of 1300 nm. To overcome this limit Bi and Tb-substituted Yttrium Iron Garnet (Bi:YIG, Tb:YIG) gained a considerable attention due to its high MO response and low optical absorption.

In this work we report about spectrally dependent optical and MO properties of epitaxial and polycrystalline thin films of Bi:YIG and Tb:YIG with various Bi and Tb content on GGG and Si substrates grown by pulsed laser deposition. The effect of growth temperatures and O_2 pressure on the film optical and MO properties was studied. On Si substrates, bottom-up and top-down crystallization of Bi:YIG using YIG seed layers below or above the Bi:YIG was investigated in order to enable integration of garnets on photonic substrates. In-depth optical and MO characterizations of the bilayer films were performed by MO Faraday spectroscopy along with spectroscopic ellipsometry in wide spectral range from 0.7 to 6 eV. Utilizing the absorption coefficients together with Faraday rotations we deduced spectrally dependent figure of merit for all investigated samples.

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P334 - Three dimensional MO imaging using bismuth-substituted iron garnet films on glass substrates

13. Magneto-optics and magnetoplasmonics

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Measuring three dimensional magnetic field distribution is essential for the nondestructive measurement. The magneto-optical (MO) imaging technique was carried out to visualize the magnetic field distributions. In this study, a 3inch-size bismuth-substituted neodymium iron garnet film prepared on a glass substrate by the metal-organic decomposition method [1] was used as an MO imaging plate. A disc-shaped permanent magnet was chosen as a sample generating the magnetic field distribution. The MO imaging plate was put on the magnet, and an LED panel with a wavelength of 610 nm illuminated through a polarizing film and a plate-type beam splitter. Then, MO images were captured by a CCD camera placed after an quarter wave plate and an analyzer. Magnetic field values were calibrated by the polarization modulation method [2]. To obtain three dimensional magnetic field distribution, the distance between the magnet and the MO imaging plate was varied from 0 to 15 mm with 0.5 mm-steps. Figure 1 shows the z-component of magnetic field distribution in the x-z plane, which was reconstructed from 30 MO images. It was clearly observed that the magnetic field decreased with the distance from the magnet and it has negative values at outside of the edges of the magnet with z = 0 mm, which was consistent with the simulated one.

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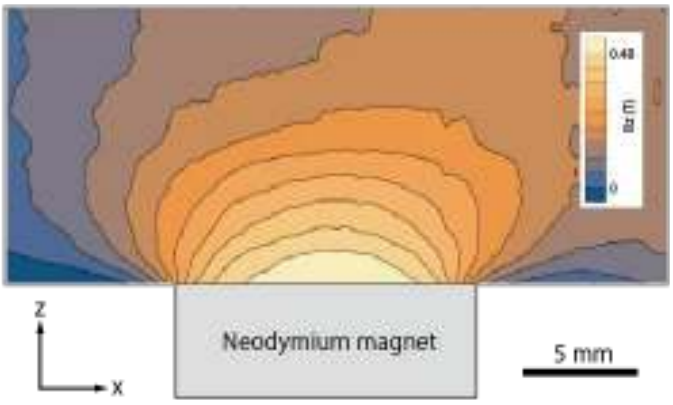

Fig.1 Z-component of the magnetic field distribution of the neodymium permanent magnet.

14. Multifunctional magnetic materials: magnetic shape memory materials, multiferroics including artificial/composite multiferroics, and perovskites

P335 - Broadband transverse magnetic susceptibility in multiferroic Y-type hexaferrite Ba0.5Sr1.5Zn2Fe2O22

14. Multifunctional magnetic materials: magnetic shape memory materials, multiferroics including artificial/composite multiferroics, and perovskites

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Noncollinear spin systems have attracted significant interest in recent research activities, especially the compounds with magnetically induced ferroelectricity from changes in spiral magnetic ordering within the crystal, because they can present unusual physical phenomena like remarkable magnetoelectric effects, with potential applications in ultra-dense magnetic storage devices as well as low power spintronic devices [1,2]. Single phase multiferroics are of great interest for this new multifunctional devices, being Y-type hexaferrites good candidates, and among them the ZnY compounds due to their ordered magnetic behaviour over room temperature, prior to their paramagnetic transition near 330 K. Polycrystalline Y type hexaferrites with composition $Ba_{0.5}Sr_{1.5}Zn_2Fe_2O_{22}$ (BSZFO) i.e the optimal composition to exhibit multiferroic properties, were sintered in 1050º C-1250º C temperature range by means of standard ceramic techniques.

Transverse magnetic susceptibility is obtained when applying a bias DC magnetic field, while AC applied field and response is measured in a transverse direction. It has been proved to be a versatile tool to study singular properties of bulk and nanoparticle magnetic systems, especially to obtain their anisotropy and switching fields. We have developed a fully automated, broadband system based on a LCR, that allows this measurement in varying ranges of DC and AC applied fields, temperature and frequency with enhanced sensitivity. Transverse susceptibility measurements (TS) have been carried out on BSZFO polycrystalline samples, in the temperature range 80-350 K with DC fields up to ±0.5 T, revealing different behaviour depending on the sintering temperature. The relative amplitude of TS decreases with the increase in sintering temperature. Sample sintered at 1250 ºC is qualitatively different, suggesting a mixed Y and Z phase like CoY hexaferrites. Sintering at lower temperatures single phase Y-type compounds are obtained, but the TS behaviour of the sample sintered at 1150 ºC is shifted at temperatures 15 K higher. Regarding the DC field sweeps the observed behaviour is a peak that shifts to lower values with increasing temperature. However, the samples corresponding to single Y phase exhibit several maxima and minima in the 250 K – 330 K range at low DC applied field, which is a clear signature of the magnetic field induced spin transitions in this compound. The sintering temperature then also play a key role in the temperature range in which the compound undergoes spin transitions.

This work was supported by the Spanish Ministerio de Ciencia Innovación y Universidades, (AEI with FEDER), project id. MAT2016-80784-P.

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P336 - Charge ordering of multiferroic LuFe2O4

14. Multifunctional magnetic materials: magnetic shape memory materials, multiferroics including artificial/composite multiferroics, and perovskites

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Multiferroic $LuFe_2O_4$ is a hexagonal layered compound with variable valence of iron ions Fe^{2+}/Fe^{3+} [1], so a mean valence is +2.5. Due to this feature ferroelectricity of this substance is given rise by charge ordering in contrast to common ferroelectrics where lattice distortion takes place. All iron sites are crystallographically equivalent and form triangular bilayers (W layers).
Charge order of stoichiometric and nonstoichiometric substances were investigated theoretically in our previous works [2,3]. It is shown that a high-temperature ordered phase on a triangular bilayer is a dimer partially disordered antiferroelectric (DPDA) state. It is also shown that 3D-CO can be stabilized by interbilayer interaction. Several ferrielectric phases can be realized as low-temperature state and different partial disordered states occur in nonstoichiometric systems.
From the experiment phase transition to high-pressure multiferroic phase (HP) can be observed at 8 GPa [4]. Thermodynamic model described in previous works can be used to estimate influence of pressure in this system (Fig. 1) by varying interlayer distance *h* in bilayer. Ferroelectric phase should be stabilized when *h* decreases. But a distortion of crystal lattice occurs due to Yahn-Teller effect. Electronic structure calculations yield to dimerisation in iron ion sublattice [4] with nonsymmetrical dimer formation.
Biased dielectric response in $LuFe_2O_4$ low-pressure phase can be described in terms of domain wall motion when pinning effect occurs [5]. The weak DC bias applied to the electric domain wall causes its partial detachment from pinning centers.

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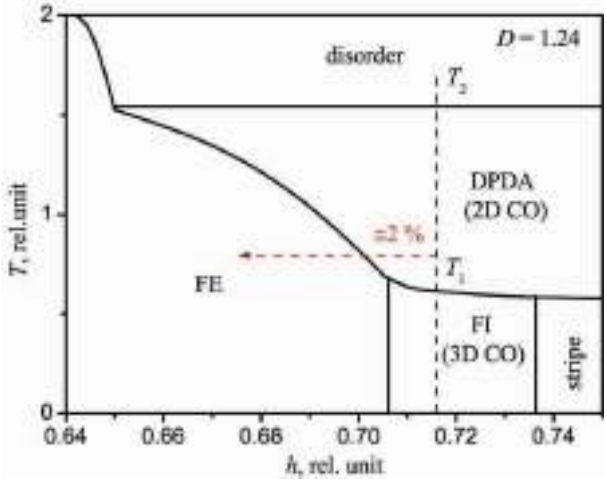

P337 - CRYSTAL AND MAGNETIC STRUCTURE OF BaFe12-xGaxO19 (x≤ 2) INVESTIGATED IN THE WIDE TEMPERATURE RANGE

14. Multifunctional magnetic materials: magnetic shape memory materials, multiferroics including artificial/composite multiferroics, and perovskites

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Barium hexaferrites and their solid solutions doped by Ga^{3+} ions are of interest due to their distinctive physical characteristics. Hexaferrites possess large magnetocrystalline anisotropy, high Curie temperature, large magnetization, in addition to its excellent chemical stability as well as corrosion resistivity. They provide an extensive selection of feasible applications, for instance, multiple-state storage components, novel storage media, transducers as well as new functional sensors.

The analysis of experimental data of doped barium hexaferrites shows that their physical properties directly depend on the concentration of diamagnetic substitution, type of crystal structure, crystalline size and even anion stoichiometry.

The crystal structure and magnetic properties of $BaFe_{12-x}Ga_xO_{19}$ (x≤ 2) solid solutions were studied by high-resolution neutron powder diffraction (NPD). Ga^{3+} ions were chosen due to similar ionic radii and significant difference in electronic shell configuration in comparison with Fe^{3+} ions. Isovalent diamagnetic substitution (replacement of the Fe^{3+} ion with D^{3+} ion with the same oxidation state) leads to serious destruction of the magnetic ordering without destruction of the charge ordering. Magnetic long-range ordering destruction in $BaFe_{12-x}Ga_xO_{19}$ solid solutions is caused by frustration of magnetic structure (Fe^{3+}-O-Fe^{3+} bonds breaking). Precisions investigations with NPD let us to establish true atomic coordinates and accurately calculate magnetic moments for each Fe^{3+} ions in different oxygen coordination in the wide temperature range. We concluded that decrease in total magnetization of the $BaFe_{12-x}Ga_xO_{19}$ solid solutions with Ga ions concentration is a result of two competition factors. First is weakening of the inerlattice and intralattice Fe^{3+}-O-Fe^{3+} exchange interactions. Second is structural relaxation (decrease of microstraine values with Ga content increasing) that can be a result of complex hybridization of the electronic shells for 3d-fully filled Ga^{3+} ions. When the concentration of gallium ions increases in the crystallites the microstrain increases that can be attributed to the increasing of the system disorder because of the statistical distribution of the gallium ions of the magnetic sublattices, having a greater ionic radius unlike iron ions. This result will be critically important for explanation of the presence of magnetically ordered state and ferroelectric properties that opens new opportunity for extensive practical application of hexaferrites.

P338 - Development of magnetic order in series of anisidine tetrachlorocuprate layered hybrid perovskites

14. Multifunctional magnetic materials: magnetic shape memory materials, multiferroics including artificial/composite multiferroics, and perovskites

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Metal-organic compounds with perovskite crystal structure provide a fertile playground for design of the multifunctional materials. Due to wide possibilities of combining the building blocks in such crystals, different physical properties can be tuned, such as elastic, conducting, optical, polar, magnetic. Some properties can be mutually dependent, and some orders mutually coupled, paving the way to design of the magnetoelectric multiferroics.

One interesting example of the hybrid layered perovskite multiferroic is the ethylammonium tetrachlorocuprate, which consists of the ferromagnetic layers of corner sharing $[CuCl_4]^{2-}$ octahedra connected by two layers of polarizable organic ions of $C_2H_5NH_3^+$. Motivated by its ferroelectricity and rich magnetic behaviour below 10.5 K, including magnetic anisotropy and transitions between different magnetic states, as well as recently observed change of magnetization with the structural changes above 300 K, we changed the composition of this metal-organic perovskite and studied the accompanied changes of the crystal structure and magnetic properties.

Here we explored the novel series of the solid-state architectures consisting of the tetrachlorocuprate units and different anisidine isomers. Ortho-anisidinium, meta-anisidinium and para-anisidinium tetrachlorocuprates were prepared by crystallization from the mixed organic-aqueous solutions. In the crystal structure considerable change of geometry was observed: from the discrete square planar tetrachlorocuprate anions in the ortho-anisidinium compound to the Ruddlesden-Popper perovskite phase with slightly distorted layers built from $CuCl_6$ octahedra in the para-anisidinium compound. It seems that in the meta-anisidine compound structure resembles the para-compound, but with more distorted anionic layers.

Up to now, we studied the temperature dependence of magnetization of the pure powder samples using SQUID magnetometer in temperature range 2–300 K at different magnetic fields and magnetic hysteresis loops in the ordered state. Large impact of geometric and electronic changes of the organic cation structure on magnetic properties was observed.

Magnetic susceptibility in the paramagnetic state as well as the saturation magnetization are in agreement with spin 1/2 per Cu^{2+} ion. These spins remain in the paramagnetic state down to the lowest temperatures in the ortho-anisidinium tetrachlorocuprate showing that there are no magnetic interactions between the discrete planar $[CuCl_4]^{2-}$ units. However, there are transitions to the ferromagnetic state measured at 4.2 K and 9.5 K for the meta-anisidinium and para-anisidinium tetrachlorocuprates, respectively. Their ferromagnetic-like hysteresis loops are very soft, without the observable coercivity, gaining very easily the saturation. Higher transition temperature is observed for larger separation between the cuprate plains, showing that packing of the isomers play an important role in transfering the interaction between the planes. Moreover, in the meta-compound magnetic transition is not so clearly ferromagnetic, that might be influenced with bigger canting of the tetrachlorocuprate octahedra and higher possibility for disorder in interlayer packing.

This research showed that a small change in structure of the cation connecting the magnetic layers has drastic influence on the geometry and magnetism of the cuprate units within the structure, thus motivating us for further studies of such compounds with similar composition and structure.

Authors acknowledge financial support of Croatian Science Foundation under the installation research project Multiferroic and Magnetoelectric Systems UIP-2014-09-8276.

P339 - Dynamic magnetic and dielectric behavior of single crystal lead substituted barium hexaferrite

14. Multifunctional magnetic materials: magnetic shape memory materials, multiferroics including artificial/composite multiferroics, and perovskites

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M-type barium hexaferrites from the (Ba,Pb)$Fe_{12}O_{19}$ family show a dramatic influence of lead-doping on dielectric, magnetic, as well as optical properties. The parent compound $BaFe_{12}O_{19}$ is a well-known semiconducting ferrimagnet with broad range of application. On the other hand, the $PbFe_{12}O_{19}$ material shows both ferromagnetic and ferroelectric properties above the room temperature. Spin and charge of iron ions within the structure of this system suggest there might a coupling between magnetic and dielectric excitations.

We report on our investigation of dynamic magnetic and dielectric properties on single-crystalline lead-substituted hexaferrite (Ba,Pb)$Fe_{12}O_{19}$. On the basis of ac magnetic susceptibility and dielectric spectroscopy in radio-frequency range and low temperatures we show that the presence of lead in (Ba,Pb)$Fe_{12}O_{19}$, as compared to pristine $BaFe_{12}O_{19}$, leads to emergence of pronounced relaxations both in dielectric and magnetic sector. Their characteristic relaxation times and activation energies are similar which suggests a bi-relaxor nature of the chosen composition of (Ba,Pb)$Fe_{12}O_{19}$. We discuss the dispersion of these relaxations and their origin in the context of magnetic domains walls and the influence of doping on the crystal lattice dynamics of the M-type barium hexaferrite.

This work was supported by the Russian Ministry of Education and Science Project 5-100 and Croatian Science Foundation projects IP-2013-11-1011 and IP-2018-01-2730.

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P340 - Effects of contacts and substituents for manganese on current-voltage characteristics of manganites

14. Multifunctional magnetic materials: magnetic shape memory materials, multiferroics including artificial/composite multiferroics, and perovskites

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The aim of this work is to establish the regularities and mechanisms of the influence of manganese-substituting divalent and quadrivalent ions combinations together with contacting electrodes materials on the formation of switching current-voltage (I-V) characteristics of various types in manganites, which is important for understanding the nature of nonlinear phenomena in highly correlated systems, as well as for obtaining the required properties of manganites as promising functional materials for magnetic and spin electronics.

Polycrystalline samples of $La_{0.65}Sr_{0.35}Mn_{0.85}(Me^{2+}_{0.5}Ge^{4+}_{0.5})_{0.15}O_3$ (Me^{2+} = Zn^{2+}, Ni^{2+}, Mg^{2+}) compositions were prepared by traditional ceramic processing. The final sintering step was performed at 1200°C for 10 h, and the samples were cooled together with the furnace. I-V characteristics of manganites were measured using sputter-deposited electrodes made of Ni, Au and Ag at different temperatures in the 80-280 K range.
It was found that I-V characteristic of (Zn,Ge)-substituted manganite with gold contacts at 260 K brightly exhibits multiple S-type regions (Fig. 1), which in the sample with Ni contacts are expressed poorly.
At the same time, (Ni,Ge)-containing sample with gold contacts does not reveal negative differential resistance, but its I-V characteristic with silver electrodes has two S-shaped sections at 260 K (Fig. 1). At low temperatures (80-140 K) dependences I(V) of all samples are close to linear.
(Mg,Ge)-substituted manganite show the following interesting peculiarities. At the temperatures of 190-240 K and relatively high voltages they have the property of voltage stabilization, that is, I-V characteristics exhibit sharp, vertical increase in current at almost constant voltage. Moreover, behavior of current-voltage characteristics practically does not depend on the type of contacts (only some quantitative parameters change). It should be noted that the samples of (Mg,Ge)-containing manganites have the smallest grain diameter and the highest porosity [1].
Possible approaches to the interpretation of obtained experimental data are discussed allowing for the mechanism of insulator-metal transition in phase separation model, self-heating effect, charge tunneling limited transport between competing coexisting phases and grains, jumps of oxygen ions in the transitional layer “metal-manganite”, ratio of the work of exit from manganite and metal, chemical interaction of contacting metal with manganite, mechanical stresses resulting from the difference in thermal expansion coefficients of manganite and the metal [2-5].

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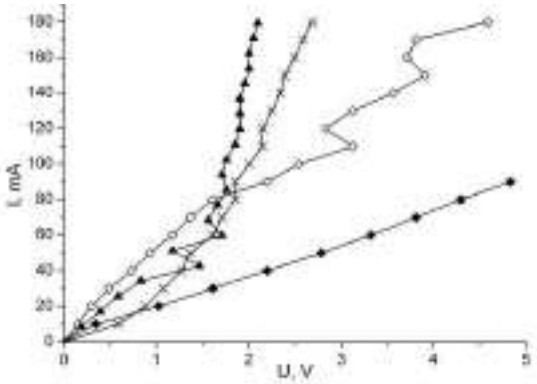

Figure 1. Current-voltage characteristics of manganites with various contacts at 260 K:
$La_{0.68}Sr_{0.32}Mn_{0.85}(Zn_{0.5}Ge_{0.5})_{0.15}O_3$ – ▲ (Au), × (Ni);
$La_{0.65}Sr_{0.35}Mn_{0.85}(Ni_{0.5}Ge_{0.5})_{0.15}O_3$ – ◆ (Au), ◇ (Ag)

P341 - Electrical and magnetic properties of Ba hexaferrite with iso- and heterovalent cation substitutions

14. Multifunctional magnetic materials: magnetic shape memory materials, multiferroics including artificial/composite multiferroics, and perovskites

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Two main methods (based on changing of chemical composition) for control of the magnetic and absorbing properties can be distinguished: replacement of Fe3+ iron ions by ions with the same oxidation state (D3+) or isovalent substitution [16-18] and replacement by ions with the different oxidation state (D2+, D4+) or heterovalent substitution. Both types of substitution lead to the magnetic structure frustration and a weakening of the exchange interactions (due to decrease the number of Fe-O bonds). Our idea is in observation quantum effects (spin crossover and charge state disproportionation) for heterovalent substitution. It should be noted that in hexaferrites with a mixed valence state of iron the anomalous effects of charge and spin ordering should be observed theoretically. Thus, for Fe^{4+} ions, effects of charge disproportionation can be observed. And crossover of spin states can be detected for the Fe^{2+} ions. The abstract presents the study of Sc-, Ti- and Zn-substituted samples of barium hexaferrite obtained by ceramic technology from high-purity powders of barium carbonate and iron (III) oxides, titanium (IV) and scandium, in particular, BaFe12 – xZnxO19 at x = (0.25-1), BaFe12 – xTixO19 with x = (0.25 - 1) and BaFe12 – xScxO19 with x = (0.1 - 1.2). Electrophysical measurements were carried out in the temperature and frequency ranges of 300–373 K and 1 kHz – 1 GHz, respectively. In the study of dielectric and electrical properties, we used the methods of complex impedance spectroscopy. As a result, it was revealed that Sc-, Ti- substitutions lead to a decrease in specific resistivity compared to pure BaFe12O19. In the case of heterovalent substitution, the dielectric constant ε´ turned out to be an order of magnitude higher, possibly due to the appearance of Fe2 + cations in the material of the grains and their localization near the phase boundaries, as well as the presence of low electrical conductivity oxide in the grain boundary phase. For Sc-substituted hexaferrite, a sharp decrease in ε´ with increasing T was established, which may be due to the higher contribution of thermal activation processes. In addition, it is noted that with increasing Sc concentration, the dielectric losses in the sample decrease. Zn substitution leads to phase separation for concentrations >0.25. Correlation between chemical substitution, crystal structure, charge and spin ordering, magnetic and electrical properties were discussed in abstract.

P343 - Ferromagnetic FeNiCoAl Cold-Drawn Rapidly Quenched Microwires for Medical Applications

14. Multifunctional magnetic materials: magnetic shape memory materials, multiferroics including artificial/composite multiferroics, and perovskites

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Superelasticity is the shape memory property that has been most explored for commercial use. Its application is guided by the ability of SMAs to sustain large elastic strains at certain temperatures during use. To improve the maneuverability, reliability, and safety of these devices as well as to improve advantages over the NiTi alloy system through increase in superelastic properties [1], Fe-based shape memory alloys have been developed since they offer relatively cheap alloying constituents and ease of fabrication [2]. In the attempt to reduce the steps involved in the thermo-mechanical processing of these materials rapid quenching from the melt has been reported by our group for the fabrication of wire-shaped materials [3]. In this work we report up to 5% superelasticity in rapidly quenched $Fe_{43.5}Ni_{28}Co_{17}Al_{11.5}$ microwires cold drawn 50 µm in diameter and subsequently annealed at 800°C for one hour. Microwires with the diameter of about 200 µm have been prepared by in rotating water quenching technique followed by cold-drawing down to 50 µm. The SE and elongation were examined by cyclic loading/unloading tensile test with increasing applied strain at room temperature. SEM, TEM, thermomagnetic, and magnetic measurements (PPMS and VSM.) have been performed to assess the structural and magnetic samples. The amorphous-like structure observed by SEM in the as-cast microwires transforms into a polycrystalline structure with some elongated grains after cold-drawing, the grains increasing in number and size after annealing. HR-TEM studies indicates the presence of α-Fe structures and Fe-Co-rich structures dispersed in a Ni-Al matrix. The Fe-Co (dhkl = 2,04nm) structures are predominant. Thermomagnetic curve of as-cast microwire measured at low fields of 20 Oe present a maximum at 325°C which is abruptly decreasing until 370°C, the Curie temperature of austenite phase. Within this temperature range the martensitic transformation takes place and it is also accompanied by a relaxation of the stresses induced during cold drawing. When cooling, the curve does not follow the same path, showing irreversible transformation. An increase in magnetization can be observed. In the case of annealed microwires, a more definite Curie temperature has been observed indicating that the stresses have been released through annealing and the martensitic transformation took place. Superelastic tensile stresses of up 5 % have been achieved in the annealed FeNiCoAl cold-drawn microwires, as well as high values of strain and very good repeatability under successive loading and unloading. Potential uses of superelastic alloys also include miniature stents, catheters or guide wires in minimally invasive medicine due to their small dimensions.

Acknowledgements: This work was supported by the Romanian Ministry of Research and Innovation, NUCLEU Programme (Project PN 19 28 01 01).

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P344 - Investigation of structural, electrical and magnetic properties of La0.55Sr0.45MnO3 perovskite.

14. Multifunctional magnetic materials: magnetic shape memory materials, multiferroics including artificial/composite multiferroics, and perovskites

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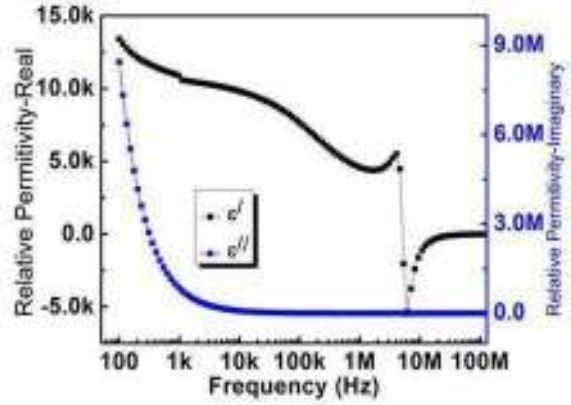
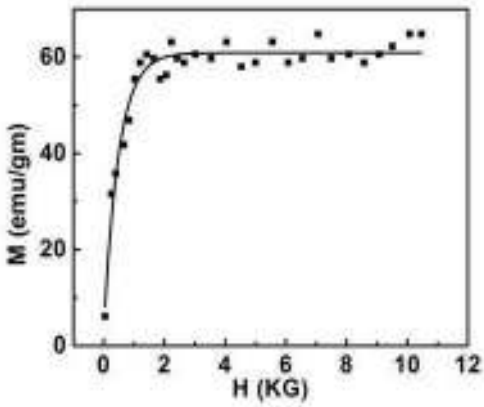
Abstract:

Polycrystalline $La_{0.55}Sr_{0.45}MnO_3$ perovskite samples have been synthesized by conventional solid-state reaction technique. The structural, electrical and magnetic properties of the samples have been investigated. It is found that the bulk density of $La_{0.55}Sr_{0.45}MnO_3$ increases with increasing sintering temperatures up to 1300 °C. All the samples have rhombohedral structure as confirmed by room temperature XRD investigation. A pronounced increase in capacitance is observed from 77K to room temperature .The electrical resistivity decreases as the temperature increases indicating a semiconductor-like behavior from liquid nitrogen (77K) temperature upto room temperature. The dielectric constant ε´ is observed to be strongly dependent on the frequency. The imaginary part of the dielectric constant (ε´´) is found to decrease rapidly with the increase of frequency up to 10 KHz which then flattens out at higher frequency regime. The frequency dependent real part (μ′) remains almost constant in the frequency range 100Hz to 50 MHz, which is attributed to only the spins. The negative value of real part of ac permeability signifies the diamagnetic behavior of the sample in the frequency range 55-90 MHz. This behavior is assumed to have been originated from the presence of Mn^{3+} ions on the B site resulting in magnetic dipole alignment opposite to the applied field. A significant decrease of ac permeability has occurred around 25°C indicating a magnetic phase transition. The room temperature dc magnetization shows a strong ferromagnetic ordering for $La_{0.55}Sr_{0.45}MnO_3$ and saturation magnetization is found to be equal to 61 emu/gm.





P346 - Magnetic and dielectric properties of double perovskite La3Ni2TaO9

14. Multifunctional magnetic materials: magnetic shape memory materials, multiferroics including artificial/composite multiferroics, and perovskites

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The author has chosen not to publicise the abstract.

Field 5

Field 6

P347 - Magnetic and transport properties of La0.7Sr0.3MnO3/Nd0.5Ca0.5MnO3 epitaxial bilayer thin film

14. Multifunctional magnetic materials: magnetic shape memory materials, multiferroics including artificial/composite multiferroics, and perovskites

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The manganese based perovskite oxides of the type $Ln_{1-x}A_xMnO_3$ (Ln-trivalent rare earth ion, A-divalent alkaline earth ion) are known to show interesting structural, magnetic and transport properties [1]. $La_{0.7}Sr_{0.3}MnO_3$ (LSMO) with a maximum Curie temperature of T_C = 369 K shows metallic behaviour below the Curie temperature. With half metallicity and ~100% spin polarization of the conduction-electrons, this material is considered to be an ideal candidate for spintronic devices and magnetic tunnel junctions. On the other hand, $Nd_{0.5}Ca_{0.5}MnO_3$ (NCMO) has a charge ordered insulating phase below T_{CO} = 250 K with an antiferromagnetic transition at T_N =160K [2]. In a recent study on the thickness variation of LSMO ultrathin films deposited on STO substrates, it was concluded that a nonmetallic nonferromagnetic state can be created at the interface if the thickness was controlled at the unit cell scale [3]. We have deposited $La_{0.7}Sr_{0.3}MnO_3$ epitaxial thin films of various thickness on a $Nd_{0.5}Ca_{0.5}MnO_3$ thin film layer grown on $SrTiO_3$ (STO) (001) substrate using pulsed laser deposition (PLD) technique. We have investigated the proximity effect between the ferromagnetic and charge ordered antiferromagnetic bilayer samples. As the thickness of the LSMO layer is decreased below 5 nm, the bilayer films exhibit insulating/magnetic behaviour up to 50 kOe and a metallic/magnetic phase for higher applied magnetic fields with a clear metal to insulator transition.

References:

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P348 - Magnetic behaviour of multiferroic [C(NH2)3][Cu(HCOO)3]

14. Multifunctional magnetic materials: magnetic shape memory materials, multiferroics including artificial/composite multiferroics, and perovskites

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Guanidinium copper(II) formate, $[C(NH_2)_3][Cu(HCOO)_3]$ belongs to the family of metal-organic perovskites with the formula ABX_3. It crystallizes in the orthorhombic space group *Pna21.* Copper ions are octahedrally coordinated and mutually connected with anti-anti formate bridges forming a framework with nearly cubic cavities in which the guanidinium ions are located. Due to the Jahn-Teller effect of Cu(II) cation, the octahedral coordination is elongated. The framework consists of the Cu-formate chains in the crystallographic c-axis, where Cu ions inside the chain are linked with short bonds and Cu ions between the chains with the long bonds.

In this work we have studied magnetic properties of $[C(NH_2)_3][Cu(HCOO)_3]$ using MPMS5 SQUID magnetometer. Temperature dependence of magnetization showed a broad peak centered at 45 K which can be ascribed to antiferromagnetic order within the Cu-formate chains. Below 5 K the sharp rise of magnetization indicated a formation of complex 3D spin long range order. Hysteresis loops at the temperatures below 5 K showed a sharp increase of magnetization for the fields even lower than 50 Oe. Anisotropy could be seen in both M(T) and M(H) measurements. Measurement of transverse magnetic moment showed that if the field is lower than 1000 Oe in *a*-direction, the magnetization in *c*-direction is still bigger than the magnetization in *a*-direction, indicating large anisotropy and the c-axis as an easy axis. The effect of electric field (E~1kV/mm) on the magnetization could be seen in M(T) curves at temperatures below 5 K in a way that the magnetization curves with and without the electric field did not overlap.

Search for the explanations of observed magnetic behaviour is in process considering the interesting crystal structure of this compound.

P350 - Magnetoelectric Response In Honeycomb Antiferromagnet Fe4NbTaO9

14. Multifunctional magnetic materials: magnetic shape memory materials, multiferroics including artificial/composite multiferroics, and perovskites

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1. Introduction

The materials with $A_4B_2O_9$ (A= Co, Mn, Mg, Fe; and B= Nb, Ta) formula, have received a great attention for their rich interplay among charge, spin, and lattice. These compounds show many fascinating properties, such as linear magnetoelectric coupling, multiferroic behaviors, microwave dielectric properties. $Fe_4B_2O_9$ (B=Nb, Ta) have been recently studied for their magnetoelectric and multiferroic properties. Both materials crystallize in α-Al_2O_3 type structure and contains two different crystallographic positions occupied with magnetic ions. Both of the two materials are stacked in a hexagonal crystal structure corresponding to the space group P-3c1. The magnetic and magnetoelectric properties of $Fe_4Ta_2O_9$ strongly differ from that of $Fe_4Nb_2O_9$. The main purpose of this work is to investigate magnetoelectric response arising from honeycomb based antiferromagnet Fe_4NbTaO_9 prepared using two synthesis methods.

2. Experimental

Polycrystalline Fe_4NbTaO_9 samples were synthesized by vacuum sealed solid state method (S1) and novel arc melting method (S2). The DC magnetization measurements were done in a Cryogenic make Physical Property Measurement System (PPMS). Dielectric measurements were carried out by LCR meter Agilent E4890A. The polarization was obtained by integrating the pyroelectric current performed using a Keithley 6514 electrometer.

3. Results

The structural, magnetic, dielectric and pyroelectric properties of a Fe_4NbTaO_9 polycrystalline samples have been characterized. The powder x-ray-diffraction (XRD) profiles indicate that both samples prepared in this study have single phase and crystallizes in the P-3c1 space group. The temperature dependent magnetization measurements show antiferromagnetic ordering around 88 K for both the samples. The dielectric and pyroelectric data reveal two broad transitions under zero magnetic field in contrast to all the other members of its corundum-related family of materials. Both samples show positive and negative magnetodielectric behavior. Reduction in the dimensionality of the magnetic lattice is considered to be response for the magnetoelectric effect observed in this compound.

4. Conclusions

In summary, we have synthesized polycrystalline Fe_4NbTaO_9 to investigate its crystal structure, magnetic, electric properties and the coupling effect between electric and magnetic properties. It is found that magnetoelectric coupling in Fe_4NbTaO_9 still work when partial Nb ions are replaced by Ta ions.

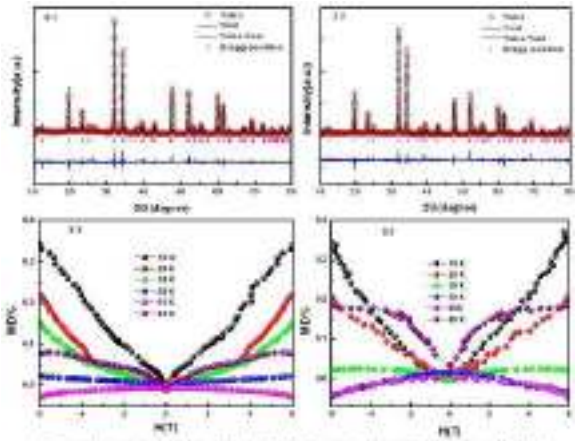

Figure shows room temperature XRD patterns and magnetodielectric effect of solid state (S1) and sol gel method (S2) synthesized FSTO samples.

P352 - Ni-substitution effect on the properties of Ba1.5Sr0.5Zn2-xNixFe12O22 powders

14. Multifunctional magnetic materials: magnetic shape memory materials, multiferroics including artificial/composite multiferroics, and perovskites

Borislava Georgieva[1] , *Svetoslav Kolev[1], Kiril Krezhov[1], Chavdar Ghelev[1], Daniela Kovacheva[2], Benedicte Vertruyen[3], Raphael Closset[3], Lan Maria Tran[4], Michal Babij[4], Andrzej J. Zaleski[4], Tatyana Koutzarova[1]*

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Multiferroic materials in which long-range magnetic and ferroelectric orders coexist have been of great interest in the fields of both basic and applied sciences. The Y-type hexagonal ferrite $Ba_{1.5}Sr_{0.5}Zn_2Fe_{12}O_{22}$ is a multiferroic material at room temperature in a low magnetic field of 0.1 T. We considered the influence of the magnetic cation (Ni^{2+}) substitution on the structural and magnetic properties of $Ba_{1.5}Sr_{0.5}Zn_{2-x}Ni_xFe_{12}O_{22}$ powders. The powders were synthesized by using the citric-acid sol-gel auto-combustion method. During auto-combustion, the burning gel expanded rapidly in volume. The auto-combusted powders were annealed at 1170 ^{o}C in air.

The XRD spectra of the powders showed the characteristic peaks corresponding to the Y-type hexaferrite structure as a main phase and a second phase $(ZnNi)Fe_2O_4$.

The SEM image of a $Ba_{1.5}Sr_{0.5}Zn_{2-x}Ni_xFe_{12}O_{22}$ sample showed that the particles were well agglomerated to form clusters of different sizes and shapes. The powders consisted almost entirely of large hexaferrite-phase particles with a size of a few microns and clusters of particles with different submicron size and various shapes. Small spinel ferrite particles were also observed.

The hysteresis measurements were carried out on a SQUID Quantum Design magnetometer at 4.2 K and at room temperature. The *ac*-magnetization was measured in an *ac*-magnetic field with an amplitude of 10 Oe and a frequency of 1000 Hz to determine the magnetic phase transition. A strong influence of the Ni-substitution on the magnetic properties was observed. A magnetic phase transition from a helicoidal to a ferrimagnetic spin order at 283 K was observed for the sample $Ba_{1.5}Sr_{0.5}Zn_{0.5}Ni_{1.5}Fe_{12}O_{22}$.

P353 - OPTICAL AND MAGNETO-OPTICAL SPECTROSCOPY OF CO DOPED NI-MN-GA FILMS

14. Multifunctional magnetic materials: magnetic shape memory materials, multiferroics including artificial/composite multiferroics, and perovskites

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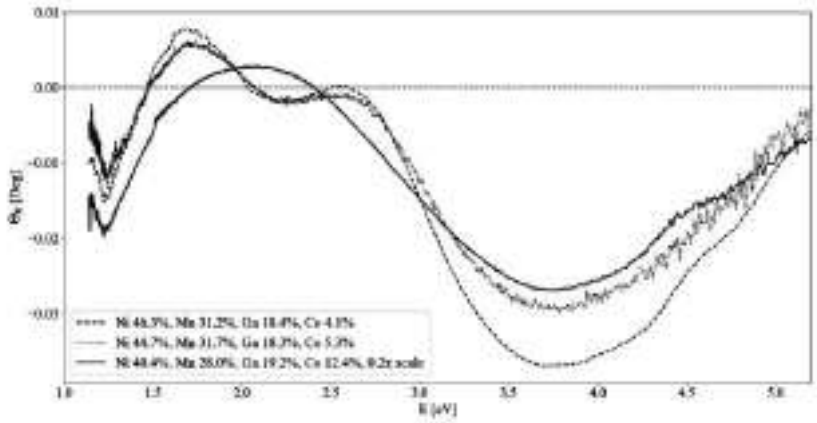
Heusler compounds that undergo martensitic transformation are of scientific interest due to their potential for future applications [1]. The most known alloy of this class is Ni-Mn-Ga, which has been intensively studied during the last decade as it exhibits magnetically induced reorientation [2]. The martensitic transformation to low symmetry phase, which is the key to this behavior, can be tailored by proper doping. Detailed understanding of changes in the electronic structure induced by doping is therefore necessary for future applications of these compounds.

Here we present optical and magneto-optical (MO) investigations of Co doped Ni-Mn-Ga films on MgO substrates grown by dc sputtering. The amount of Co doping was set from 3 to 12 atomic percent. MO experiments were performed in polar configuration using rotating analyzer technique in the spectral energy range from 1.2 to 5 eV. The MO spectra exhibited two prominent spectral bands around 1.4 and 3.8 eV (see Fig. 1), respectively. The first band originates from the crystal field transition of Ni, while the latter one originates from the charge transfer transition between Ni and Mn 3d states [3]. Changes in the low energy spectral band with different Co doping were observed. This indicates modification in the electronic structure of Co doped Ni-Mn-Ga due to the replacement of Ni by Co.

In addition, temperature dependency was studied in order to examine expected hysteresis when undergoing the martensitic transformation. The measurements was performed for the whole spectrum as well as for one of the prominent energy value at which a phenomenon occurs.



P354 - Phonon thermal transport and phonon-magnon coupling in polycrystalline $BiFeO_3$ systems

14. Multifunctional magnetic materials: magnetic shape memory materials, multiferroics including artificial/composite multiferroics, and perovskites

Yung-Kang Kuo[1] , *B. Ramachandran[1], K. K. Wu[1], M S Ramachandra Rao[2]*
[1] National Dong Hwa University
[2] Indian Institute of Technology Madras

Temperature-dependent thermal conductivity of polycrystalline $BiFeO_3$, $Bi_{0.9}Ba_{0.05}Ca_{0.05}FeO_{2.95}$ and $Bi_{0.9}Ca_{0.1}FeO_{2.95}$ materials was measured using a direct heat pulse technique. Thermal conductivity of the $BiFeO_3$-based materials is analyzed using a phonon model to probe the thermal transport mechanisms in these ferrites. It is found that the calculated thermal conductivity of the $BiFeO_3$-based compounds is in good agreement with the experimental data. The suppression of low-temperature phonon peak in thermal conductivity of the doped $BiFeO_3$ materials is mainly attributed to the phonon-point-defect scattering. In addition, the contribution of optical phonon-magnon resonance scattering to optical phonon thermal transport reveals the presence of phonon-magnon coupling in these $BiFeO_3$ materials. Finally, magneto-thermal conductivity measurements show the magnon thermal transport in pure and doped $BiFeO_3$ systems.

P355 - Reversible patterning of magnetic properties

14. Multifunctional magnetic materials: magnetic shape memory materials, multiferroics including artificial/composite multiferroics, and perovskites

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In the framework of piezoelectric/ferromagnetic patterned heterostructures, purpose of this work is to investigate the electrical control of magnetization by modifying the magnetic shape anisotropy through local strain. We recently observed differences between 50 nm thick Ni pristine full film and patterned stripes for surface acoustic wave resonators, showing how shape anisotropy plays a primary role [1].
Here, we propose to exploit the piezoelectric properties of (0001) ZnO to locally and reversibly induce shape anisotropy on $Co_{60}Fe_{20}B_{20}$ thin films, which possess an intrinsic low magnetic anisotropy. Indeed, the same concept of changes of magnetic behavior between full film and patterned one can be applied on piezoelectric/ferromagnetic system where patterned stripes can be tuned and transferred via an electrical bias applied through the thickness of the piezoelectric material. We plan to exploit the stripes geometry as bottom electrodes of the heterostructure to locally modify the strain and therefore selectively modify the magnetic shape anisotropy. It will gives a reorientation of magnetization along the stripe. Such concept can firstly be done using a simple pattern, and possibly later transferred with more complicated geometries such as the artificial Kagome structure.
In order to choose our device geometry, preliminary results obtained with magnetostatic calculations of the demagnetizing field energy and Comsol simulations were done. Key parameters are the distance between electrodes and the electrode width, whose dimension must be larger than ZnO thickness in order to get the electric field lines mostly top-down. Experimentally, we plan to deposit 10 nm of Ag, as well as 5 nm of Ti to avoid oxidization close to ZnO film on top of an insulating MgO (001) substrate. A stripe pattern will be performed by using interference lithography technique. Different stripe width and spacing will be processed; 0.5 and 1 µm. In a next step, 300 nm thick ZnO layer and a additional 10 nm thick SiO_2 will be performed on all over the surface, exept on a small spot ideally hidden thanks a Ta band. It will allows to keep a spot for the wire bonding connection on bottom electrodes. Such amorphous interlayer will be inserted to further decouple the classical interfacial magnetoelectric contributions such as strain effects and also to reduce the RMS before magnetic deposition. On top of the amorphous film, 5 nm thick ferromagnetic layer will thus deposited. Finally, a MgO capping layer of 3 nm will be used.
Once structures realized, all samples will be characterized with and without an applied bias by XAS and XMCD measurements at room temperature. In order to apply the voltage through the thickness of the samples, a set of specifically designed sample holders will be used [2]. In addition, measurements will be performed in different directions, along and perpendicular to the stripes, *i.e.* expected easy and hard magnetic axis.

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[2] F. Motti *et al.*, Phys. Rev. B. **97**, 094423, (2018).

P356 - Room temperature ferrimagnetism in Yb-doped relaxor ferroelectric PbFe2/3W1/3O3

14. Multifunctional magnetic materials: magnetic shape memory materials, multiferroics including artificial/composite multiferroics, and perovskites

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Multiferroic materials have gained enormous attention due to their potential applications in novel multifunctional devices such as sensors, transducers, memories, and spintronics [1]. In this context, Pb-based double perovskites are particularly interesting multiferroic materials which can exhibit relaxor dielectric behavior together with high (antiferro) magnetic ordering temperatures [2–4]. In the present work, we study the effect of Yb^{3+} substitution on the structural, dielectric and magnetic properties of polycrystalline samples of the $Pb(Fe_{1-x}Yb_x)_{2/3}W_{1/3}O_3$ (PFYWO) perovskite, with a special emphasis on a selected composition $x = 0.1$ (PFYWO01). Coexistence of relaxor ferroelectric state and room temperature ferrimagnetic ordering was observed and related to the cationic ordering between Fe(Yb) and W cations.

The structural analysis reveals the presence of a single cubic perovskite phase, with *Fm-3m* space group, and partial *B*-site ordering. The lattice parameter was found to increase linearly (7.95 Å to 8.2 Å) with increasing Yb (0 to 50%) concentration. Above 50% Yb doping concentration, not all the samples are in a single phase. The temperature dependence of dielectric permittivity ε(T) of PFYWO01 exhibits a broad maximum ε_m at $T_m \sim 210$ K ($f = 25$ Hz), which is shifted towards higher temperature side (from 210 K to 236.5 K) with increasing frequency f (from 25 Hz to 1 MHz), while the magnitude of ε_m decreases (from 3800 to 3270). The dispersive behavior of T_m follows the Vogel-Fulcher law with activation energy $E_a \sim 0.03$ eV, characteristic relaxation time $\tau_0 \sim 1.36\times10^{-12}$ s, and freezing temperature of polarization $T_{VF} \sim 190.7$ K, suggesting the existence a ferroelectric relaxor behavior similar to that of undoped $PbFe_{2/3}W_{1/3}O_3$ [4]. The temperature and field dependence of the magnetization M(T,H) reveal the presence of ferrimagnetic ordering with ordering temperature T~ 300 K in PFYWO01. The observed ferrimagnetism mainly originates due to the unbalanced magnetic sub-lattices (excess magnetization $M \sim 0.63\mu_B$ at H = 50 kOe) below the ordering temperature caused by the incorporation of 10% Yb at *B*-site of PFYWO. The global dielectric and magnetic behavior of PFYWO and undoped $PbFe_{2/3}W_{1/3}O_3$ will be discussed in the light of cationic ordering.

We thank the Stiftelsen Olle Engkvist Byggmästare, the Swedish Research Council (VR) and Russian Foundation for Basic Research for financially supporting this work.

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P357 - Room temperature ferromagnetism and ferroelectricity in double perovskite Y2NiMnO6 thin film

14. Multifunctional magnetic materials: magnetic shape memory materials, multiferroics including artificial/composite multiferroics, and perovskites

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Double perovskites multiferroic have attracted increasing interest because of coexistence and enhanced coupling between the ferroelectric and magnetic orders in same phase. Herein, this work reports successful fabrication of nanostructured Y_2NiMnO_6 thin films by pulse laser deposition method in oxygen and argon gas atmosphere. These epitaxial films exhibit unexpected above room temperature ferromagnetism and ferroelectricity, indicating the coexistence of more than one ferroic interaction in nanostructured Y_2NiMnO_6. The size of the nanostructures and the surface roughness of the thin films are found to control both the ferroelectric and magnetic order. Study indicates that the room temperature ferromagnetism and ferroelectricity have similar origin and attributed to the unsaturated surface spins and surface charge polarization, respectively. Magnetic force microscopy and piezoelectric force microscopy studies confirm the existence of the ferromagnetic and ferroelectric domains in the films, respectively. This study demonstrates that tailoring of morphology of nanostructures provides ample opportunity to tune the inherent ferroelectric and magnetic orders of the Y_2NiMnO_6 thin films.

P358 - SMART magnetic shape memory microwires for mechanical applications

14. Multifunctional magnetic materials: magnetic shape memory materials, multiferroics including artificial/composite multiferroics, and perovskites

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Nowadays, SMART shape memory materials attract a lot of interest due to their multifunctional nature, playing the role of actuators and sensors simultaneously. However, their practical application requires possibility of reproducible production on a large scale. Here it is shown how kilometres of monocrystalline wires exhibiting reasonable amplitude of two - way shape memory effect can easily be produced in a short time (minutes). Being magnetic in nature, such a wire exhibits 1600% variation of magnetic permeability due to a 2% strain in axial direction, as a result of well-developed anisotropy in the wire. The transformation temperature can be played with using small variation of chemical composition within the range from 100-300K. These properties give to the wire function of very sensitive SMART actuators that can be easily produced in a large amount.

P359 - Structure and multiferroic properties of BiFeO3 films with ferromagnetic Co100-xPtx underlayer

14. Multifunctional magnetic materials: magnetic shape memory materials, multiferroics including artificial/composite multiferroics, and perovskites

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$BiFeO_3$ (BFO) with a perovskite structure, showing ferroelectric (FE) and magnetic orderings at room temperature at the same time, has attracted much attention for potential applications in advanced spintronic and memory devices based on the electric-magnetic couplings. [1-3] Considering that the electric-magnetic coupling is the fundamental mechanism to function the related spintronic devices, development of ferromagnetic (FM) electrode that can induce specific texture of BFO is thus one of the most effective ways to facilitate this coupling. In this work, $Co_{100-x}Pt_x$ underlayers with x = 0-75 are sputtered onto glass substrates as a bottom electrode, and structural as well as multiferroic properties of the studied BFO films on the glass substrates with various FM $Co_{100-x}Pt_x$ bottom electrodes are reported. At reduced T_d = 450 ^oC, all studied BFO films show a pure perovskite structure. For Co underlayers, BFO films show isotropic orientation. For x = 0.25-0.5, BFO films exhibit (110) texture. For x = 75, the texture of BFO films is transformed into (001).

Besides, BFO films $Co_{100-x}Pt_x$ underlayers at T_d = 350-500 ^oC also show densely packed grains with size of 30-80 nm and flatly crack-free surface. Low formation temperature of perovskite BFO due to the adoption of $Co_{100-x}Pt_x$ underlayers results in dense microstructure, fine grains, and smooth surface morphology, which are favorable for applications. Besides, the BFO films on $Co_{100-x}Pt_x$ underlayers exhibit desired ferroelectric and magnetic properties. Good ferroelectric properties with the electrical polarization ($2P_r$) of 78-144 $\mu C/cm^2$ and coercive field of 401-455 kV/cm obtained for studied BFO films on $Co_{100-x}Pt_x$ underlayers are comparable to those grown on single crystal substrates. The ferroelectric properties are sensitive to the texture of BFO films with $Co_{100-x}Pt_x$ underlayers. Moreover, exchange bias between BFO and $Co_{100-x}Pt_x$ is observed after a field cooling from 370 ^oC to RT at 2 kOe. Large exchange bias field of 90-183 Oe at RT with coercivity of 552-1631 Oe obtained is larger than the epitaxial FM/BFO bilayers (~15-150 Oe). The presented results provide useful information for the applications based on electric-magnetic interactions.

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P360 - The challenges in realizing an exchange coupled BiFeO3 – Ferrimagnet Bilayer

14. Multifunctional magnetic materials: magnetic shape memory materials, multiferroics including artificial/composite multiferroics, and perovskites

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One approach to realize a new generation of data storage device is to use an array of magnetic tunnel junction (MTJ) as bits. To efficiently manipulate the state of the MTJ one ferromagnetic (FM) layer is exchange coupled to a multiferroic (MF) antiferromagnet (AF). It has been shown that the magnetization manipulation of CoFe deposited on BiFeO3 (BFO) is indeed possible upon application of voltage at the BFO layer [1]. However, due to oxidization of the CoFe layer at the BFO interface the realization of a reliable device was not possible. Moving to an oxide FM layer the coupling to BFO was only observed up to a temperature of around 50K [2]. We propose to use a ferrimagnetic electrode on top of the MF layer to achieve large coupling strength. We choose the double perovskite Sr2FeMoO6 as conducting ferrimagnetic material (Tc > 410 K [3]) and Barium doped BFO (BBFO) as MF layer both deposited in-situ by pulsed laser deposition (PLD). Both BBFO and SFMO single layers deposited on SrTiO3 (STO) substrates show high crystalline quality. BBFO layers have smooth surfaces and exhibit ferroelectric properties in piezoresponse force microscopy measurements. SFMO grows fully epitaxial on STO up to a thickness of around 20 nm. The B-site disorder is calculated from the intensity of X-ray reflexes. We achieve a disorder as low as around 11%. We point out the challenges in the realization of such a material stack due to the different growth conditions. Depositing SFMO as a first layer in pure argon background pressure, the layer decomposes due to the formation of a SrMoO3 phase [4] during the deposition of BBFO in pure oxygen pressure. When depositing BBFO as a first layer we observe melting of the BBFO layer at the high deposition temperature of SFMO.

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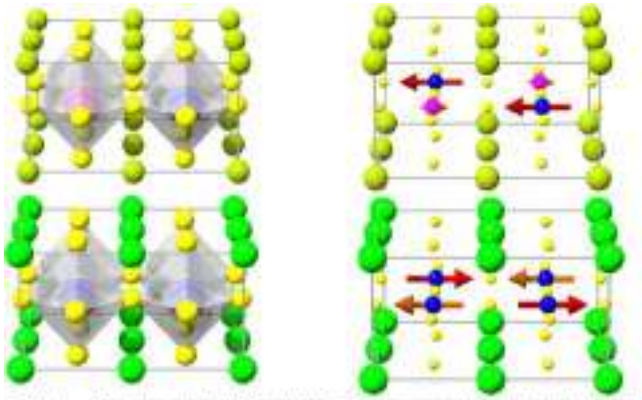

Figure 1: Crystal structures of BFO (bottom) and SFMO (top) demonstrating the structural (left) and magnetic (right) similarity. Spin directions and ionic sizes are not to scale. All right pointing spins from Fe^{3+} of the G-type antiferromagnet BFO are expected to show an antiferromagnetic superexchange coupling to the Fe^{3+} ions of the SFMO. The left pointing spins from Fe^{3+} of BFO have only the negligible magnetic moment at the Mo^{5+} ions as superexchange partner.

P361 - The polar distortion and its relation to magnetic order in multiferroic HoMnO3

14. Multifunctional magnetic materials: magnetic shape memory materials, multiferroics including artificial/composite multiferroics, and perovskites

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The orthorhombic (Pbnm) $HoMnO_3$ is of particular interest due to its high magnetically-induced polarization values (*P*) and magnetoelectric coupling strength. The mechanism behind this involves high magnetic frustration, which results in a magnetic order that creates a distortion in the crystal lattice. This distortion breaks inversion symmetry and creates a macroscopic electric polarization P along the a-axis.

We investigated the atomic distortion to identify the broken symmetry of Pbnm in thin films of HoMnO3 at low temperature and the relation between the magnetic order of Ho and the structural distortion. Forbidden reflections for Pbnm has been observed showing that the distortion does not exclusively affect to the atomic position along the polar axis, it also moves atoms along other directions. Moreover, studying reflections with component along the polar axis we observe the polar distortion directly, visualized by the difference diffraction intensity from opposite domains.

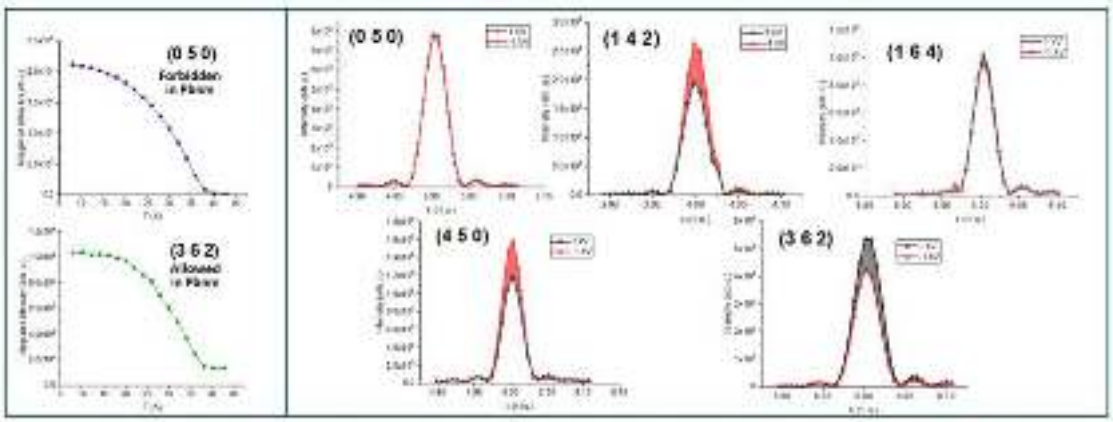

Figure 1. (a) Temperature dependence for a forbidden reflection (050) and an allowed reflection (362). (b) κ-scans of S reflections for 2 opposite E-fields (+1 kV and -1 kV).

P362 - Two-step phase transition and nonlinear off-diagonal magnetic susceptibility in nickel olivine

14. Multifunctional magnetic materials: magnetic shape memory materials, multiferroics including artificial/composite multiferroics, and perovskites

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$LiNiPO_4$ is one of orthorhombic (*Pnma*) olivines promising for application as cathodes in Li-ion batteries. Among this group, nickel olivine is the unique one, because it orders magnetically in two steps, i.e., at 21.8 K - the 2^{nd} order transition to an incommensurate phase, *IC*, and then, at 20.9 K - the 1^{st} order transition to an antiferromagnetic, commensurate phase *C*. The magnetic structure of these phases is complicated and it is not fully understood till now, though a few models were proposed. In our research, we focused on: (i) magnetic properties of the ordered phases, (ii) the phase diagram, and (iii) search for uncommon macroscopic magnetic properties of this compound. The high quality single crystal of $LiNiPO_4$ was used as the sample. Studies of the specific heat were chosen as the main tool for studying the ordered phases and clarification of the low-field part of the phase diagram. For realizing the latter task, we measured angular dependences of torque and magnetic moment (for magnetic field, **B**, rotating within the *a*-*c* and *b*-*c* planes, for several |**B**| values and fixed temperatures).

The specific heat studies revealed a splitting of the specific heat anomaly related to the phase transition between the *IC* and the low temperature *C* phases. Here, we propose the possible nature of this phenomenon. Furthermore, based on the specific heat studies, the low-filed part of the phase diagram was clarified and the parameters of parabolic dependences of the phase transitions points on the value of magnetic field directed along the *c* axis were determined.

The measured angular dependences of magnetic torque and magnetization were found to have atypical shapes. To explain this observation, the hypothesis that the magnetic moment induced by **B** along the *a*, *b*, and *c* axes depends not only on the **B**-component parallel to the considered main axis but also on the square of the **B**-component perpendicular to this axis was put forward. We confirmed validity of the proposed model by the very good agreement between the theoretical and the measured dependences. The effect was named the "nonlinear, off-diagonal magnetic susceptibility". We suppose that complex exchange interactions, layered crystalline structure, strong magnetic anisotropy and a quasi - two-dimensional character of the magnetic structure, manifesting themselves simultaneously in $LiNiPO_4$ are the basis of this phenomenon.

P363 - X-ray magnetic scattering, diffraction and reflectivity at XMaS

14. Multifunctional magnetic materials: magnetic shape memory materials, multiferroics including artificial/composite multiferroics, and perovskites

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XMaS[1] is the EPSRC funded UK National Facility for Materials Science at the European Synchrotron Radiation Facility (ESRF) in Grenoble, France. Initially dedicated to magnetic materials, it now offers a wide range of techniques and sample environments, facilitating studies of soft and hard condensed matter, physical chemistry, and solid and liquid interfaces. The beamline is currently being upgrade[2] to align to the new ESRF Extremely Brilliant Source (EBS) lattice. This will necessitate a new source (0.86 T short bending magnet) with a concomitant enhanced energy range (2.1 to 33 keV, and even 41 keV with non-optimal performances) and significantly smaller focal spot (down to 30 (H) x 80 (V) µm[2]) at the sample position. With upgraded beam conditioning/defining components and sample environments, we expect a step change in capabilities when operations resume in mid-2020.

In this presentation, I will show our current and anticipated capabilities across the fields of magnetic scattering, diffraction and reflectivity. The different types of magnetic scattering techniques available at XMaS in the current energy range between 2.4 and 15 keV will be presented, namely resonant magnetic scattering[3-6], charge-magnetic interference scattering[7-9] and resonant magnetic reflectivity[10-13]. Recent published work will illustrate each technique.

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15. Spin waves, magnonics, ultrafast magnetization dynamics and optically driven spin excitations

P364 - Ab initio theory of spin-wave stiffness: Exchange interactions meet electron transport

15. Spin waves, magnonics, ultrafast magnetization dynamics and optically driven spin excitations

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Spin stiffness (exchange stiffness, spin-wave stiffness) represents an important ground-state quantity of ferromagnets. This quantity controls, e.g., the temperature dependence of magnetization, or the width of magnetic domain walls. In this contribution, we present an ab initio theory of the spin-wave stiffness D for itinerant ferromagnets with effective exchange interactions derived from the magnetic force theorem [1]. The resulting formula involves spin-dependent one-particle propagators (Green's functions) and spin-independent effective velocity (current) operators appearing in a recent theory of electron transport [2]. Application of this approach to pure metals and ordered alloys allows one to overcome the problem of nonconvergent lattice summations [3]; application to random alloys enables one - in combination with the coherent potential approximation (CPA) - to include the disorder-induced vertex corrections, often neglected in evaluation of interatomic pair exchange interactions.

Numerical implementation of the developed formalism was done in the tight-binding linear muffin-tin orbital (TB-LMTO) method. The calculated D for bcc iron and fcc nickel agree reasonably well with previous values obtained from the pair exchange interactions [3]. The calculated spin stiffness for random fcc Ni-Fe alloys exhibits a concentration trend in qualitative agreement with experiment; the variation of D correlates strongly with that of the reciprocal value of alloy magnetization. For iron-rich bcc Fe-Al random alloys, the calculations indicate an increase of D due to Al alloying, which contradicts existing experimental data. This disagreement can be partly explained by general disorder-induced softening of spin waves [4] and by effects of atomic ordering present in this alloy system.

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P365 - Angle-dependent spin relaxation in multilayers with synthetic ferrimagnets

15. Spin waves, magnonics, ultrafast magnetization dynamics and optically driven spin excitations

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Spin pumping, when a ferromagnetic layer undergoing ferromagnetic resonance (FMR) pumps spin-polarized electrons into an adjacent nonmagnetic layer [Phys. Rev. Lett. **88**, 117601 (2002)], leads to a number of interesting effects in magnetic multilayers and can be used for tuning spin relaxation. Complementarily, FMR-driven spin pumping can be used for characterizing spin transmission across interfaces of ferromagnetic (F) and antiferromagnetic (AF) layers with nonmagnetic (N) layers – the spin-mixing conductance [Rev. Mod. Phys. **77**, 1375 (2005)]. For this, the materials are commonly incorporated into spin-valves of type F/N/F(AF), where first F is resonantly excited and becomes the source and at the same time the probe of the spin current pumped into N. With typically negligible spin dissipation in thin N, the spin mixing conductance of the N/F(AF) interface can be obtained from the spin-pumping contribution to the FMR linewidth of the probing F-layer.

The spin conductance is a function of the angle between the spin-current polarization and the magnetization vector of F (or Néel vector of AF). To date, however, little has been reported in the way of a systematic *angle-resolved* study of the spin conductance. For F/N/F systems, the problem is that a conventional FMR measurement, performed in a relatively strong magnetic field, aligns both ferromagnetic layers rather firmly in parallel. As a result, there is at best a small and often unknown angle between the current polarization and the magnetization of the static F-layer [J. Appl. Phys. **103**, 07B505 (2008); Phys. Rev. Lett. **116**, 047201 (2016)]. F/N/AF systems do not have the same difficulty, since AF is almost insensitive to the external magnetic field, so the spin-current polarization can be easily varied with respect to the AF's Néel vector by re-orienting the F's magnetization. We have used this relative field-insensitivity typical for AFs to study the spin-conductance angular properties of the N/F interface in a multilayer system Py/Cu/[Fe/Cr/Fe], where a synthetic ferrimagnet (SFM) Fe/Cr/Fe performs the exchange-biasing function of AF [Phys. Rev. B **98**, 144401 (2018)]. Varying the strength of the antiferromagnetic exchange coupling in the SFM allowed us to compare the spin-pumping contribution to the magnetization dynamics of the Py for parallel, antiparallel, and non-collinear mutual alignment of the resonating and static ferromagnetic layers. Using our recent findings that the spin pumping-mediated damping in spin-valves is generally anisotropic and tensorial, containing the widely used Gilbert- and the often-disregarded Bloch-like terms [Phys. Rev. Lett. **122**, 147201 (2019)], the nonmonotonous dependence of the spin relaxation in Py we observe can be explained in terms of relaxation of the transverse angular momentum in the static layer as well as of angular modulation of the longitudinal spin transport. This work analyzes in-detail the mechanism for in-situ tuning the free layer damping via its magnetic orientation with respect to the fixed layer in spin-valve type structures.

P366 - Atomistic spin-lattice dynamics: methodology and applications

15. Spin waves, magnonics, ultrafast magnetization dynamics and optically driven spin excitations

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In this talk I will present a computationally efficient and general first-principles based method for spin-lattice simulations for solids and clusters [1]. The method is based on a coupling of atomistic spin dynamics and molecular dynamics simulations, expressed through a spin-lattice Hamiltonian, where the bilinear magnetic term is expanded up to second order in displacement. For bcc Fe, for example, we observe good agreement of the magnon and phonon dispersions with previous simulations. We also illustrate the coupled spin-lattice dynamics method on a more conceptual level, by exploring dissipation-free spin and lattice motion of small magnetic clusters (a dimer, trimer, and tetramer). This method opens the door for a quantitative description and understanding of the microscopic origin of many fundamental phenomena of contemporary interest, such as ultrafast demagnetization, magnetocalorics, and spincaloritronics.

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P367 - Conical Mirror XUV Polarimeter for complete ultrafast magnetic sampling at M-edges of Fe, Co & Ni

15. Spin waves, magnonics, ultrafast magnetization dynamics and optically driven spin excitations

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Free electron lasers and lab-based high harmonic radiation sources providing bright femtosecond extreme ultraviolet (XUV) pulses allow to perform ultrafast magnetic spectroscopy at 3p to 3d transitions (M-edges). Transient XUV absorption experiments have revealed fast demagnetization dynamics at the M-edges of thin Fe, Ni and Co samples by probing changes to the XUV magnetic dichroism initiated by a visible/NIR pump pulse. A challenge in these measurements is to generate high-flux circularly polarized XUV pulses at high stability to resolve changes to the absorptive part of the magneto-optical functions that are typical 3 orders of magnitude smaller than the non-magnetic absorption background. In a complemetary technique the Faraday rotation of linear XUV pulses transmitted through thin magnetic layers is observed with an XUV polarization analyzer[1]. This gives access to the refractive part of the magneto-optical functions. A disadvantage of current setups is that the polarization detector needs to be rotated which slows down acquisition speed.

We present a conical mirror XUV (COMIX) polarimeter that can be employed to characterize the polarization state of XUV sources and perform ultrafast magnetic investigations that access the full complex dichroic index of refraction. It contains a conical gold mirror pair that acts as a polarization analyzer and a CCD behind the mirror pair that detects the reflected XUV photons. Two reflections off the conical mirror pair at the Brewster angle result in an extinction ratio of approx. 500 in the spectral range of the M-edges of Fe, Co and Ni. Hence, only the linear polarization component orthogonal to the mirror surfaces is efficiently reflected. Due to the rotational symmetry of the device the COMIX polarimeter samples all rotation angles simultaneously. Thus, the COMIX polarimeter permits a full determination of the ellipticity ε and orientation θ of the polarization ellipse within a single acquisition. At sufficient fluences, as provided by free electron lasers, this even allows for single shot determination of the polarization state. By observing the magnetically dependent changes in ellipticity Δε and orientation Δθ of the polarization state after transmitting through thin magnetic samples the full complex magneto-optical functions are measured.

In a first demonstration of the COMIX polarimeter's capabilities, we characterize the polarization state of the XUV radiation emitted from our HHG source directly. Secondly, we evaluate the performance of an all reflective phase shifter for generating circularly polarized light[2] and compare it with a MAZLE-TOV[3] implementation of our setup. In femtosecond VIS/NIR pump - XUV probe experiments at a lab-base HHG source we then monitor femtosecond demagnetization dynamics at the M-edges of thin CoPt samples.

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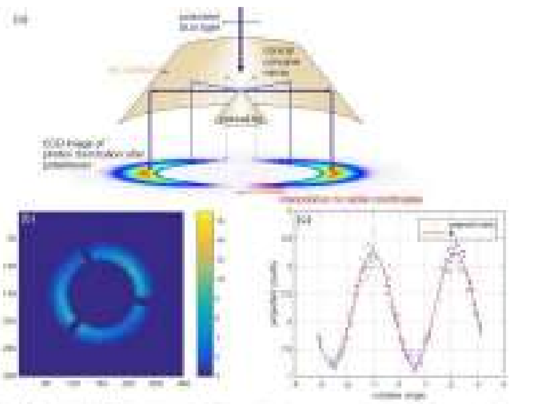

Fig. (a) Principle of CDSX polarimeter. Only the polarization component orthogonal to the conical mirror surface is efficiently reflected and forms a pattern on a CCD detector. (b) Simulated CDSX CCD signal: total photon counts N=[illegible], polarization orientation was ψ=67.48°, visibility ν=0.784. (c) simulated CCD signal compared on rotation axis and fit with sinusoidal ψ=67.41°, ν=0.781 [illegible]

P368 - Direct imaging of higher order modes in magnonic waveguides

15. Spin waves, magnonics, ultrafast magnetization dynamics and optically driven spin excitations

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Nowadays, miniaturization of CMOS technologies is limited by physical restrictions of the manufacturing process. These limits may be overcome by data processing with magnons within magnonic waveguides. Guiding a path towards smaller elements and miniaturization of various devices at technologically relevant radio frequencies [1, 2].

Here, we use scanning transmission x-ray microscopy (STXM) with magnetic contrast and spatial and temporal resolution of 18 nm and 35 ps respectively to investigate the fundamental dynamics of spin-wave propagation in magnonic Py and Co/Fe waveguides. Via a global continuous wave or burst RF excitation, short wavelength spin-waves can be excited from the edges forming a standing spin-wave pattern. Due to the physical constriction of the width of the waveguide, standing spin-waves also exist in lateral dimension. Therefore, the dispersion relation exhibits higher order modes in backward volume (BV) configuration (*cf.* Fig 1(a)) [3].

We directly observe corresponding mode profiles of higher order modes at one single excitation frequency revealing characteristic nodes with a phase shift of standing spin-waves for Py exemplarily shown in Fig 1(b) and (c). Additionally, excitation frequencies up to 18 GHz show similar behaviour within Co/Fe waveguides paving the way for high frequency spin-wave excitation beyond the fundamental BV mode.

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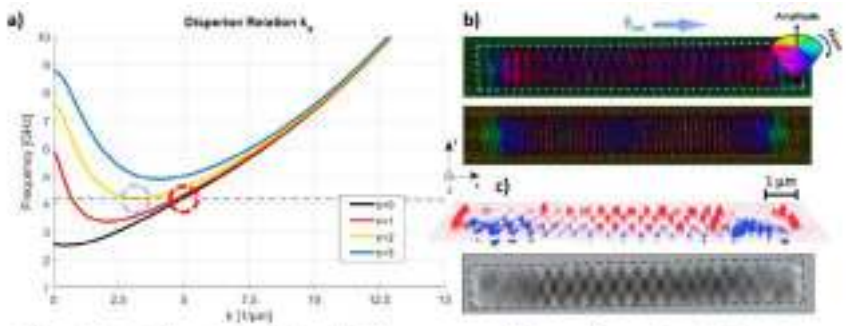

Figure 1: (a) Dispersion relation in BV geometry. Higher order modes (n=1,2,...) are depicted which intersect the excitation frequency. (b) Corresponding mode profiles reveal node behaviour with a phase shift in the upper mode profile (n=2). The lower one shows the mode profile of the fundamental and the first higher order. (c) Exemplary STXM mode profile of a third order mode (n=3) with two nodes across the Py waveguide.

P369 - Direct Optical Measurement of the Magnon Chemical Potential in YIG/Pt Systems

15. Spin waves, magnonics, ultrafast magnetization dynamics and optically driven spin excitations

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The influences of the Spin-Seebeck-Effect (SSE) as well as Spin-Transfer-Torques (STT) on the spin system of magnetically ordered insulators have been extensively studied in the field of magnon spintronics [1,2]. These influences can be interpreted using a description of the magnonic system outside its state of equilibrium by means of the magnon chemical potential [3,4].

The most widely used approach to investigate these phenomena is to use currents in an adjacent metallic injector structure to excite spin waves through SSE by Joule Heating induced thermal gradients and by STT via the Spin Hall Effect (SHE). Subsequent detection of the spin waves is commonly done nonlocally by taking advantage of Spin Pumping and the Inverse Spin Hall Effect (ISHE) in a metallic detector structure in a certain distance to the injector. This method is very sensitive to the overall magnon population in the system, but it cannot distinguish between different magnon modes. Nevertheless, the direct access to the spectral magnon distribution is crucial for an understanding of the underlying effects. In addition, it is necessary for the direct measurement of the chemical potential.

In this work, we studied the influence of SSE and SHE-STT on the spatial distribution of the magnon chemical potential of structured YIG/Pt thin film systems by Micro-focused Brillouin Light Scattering (μBLS) Spectroscopy. By using this technique, we are able to extract the intensities of different spin wave modes in the GHz regime, from which the chemical potential is deduced making use of the Bose-Einstein distribution in the Rayleigh-Jeans limit. We are able to measure the chemical potential with spatial resolution, even below the Pt injector as well as close to it. It is probed in dependence of the applied current and the relative orientation of this current to an external magnetic field. The chemical potential is observed to increase due to the SSE, with values up to 1.5 GHz at injector temperatures of around 100 °C. This approach is of special interest for the possible generation of magnon Bose-Einstein-Condensates (BEC) as well as the investigation of spin transport phenomena.

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P370 - Directional magnonic ring coupler as a basic unit for neuromorphic magnonic network

15. Spin waves, magnonics, ultrafast magnetization dynamics and optically driven spin excitations

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In recent years, there has been a strong interest in taking the advantage of spin waves[1-2] for data transfer and wave-based computation, and this interest is powered mainly by the high potential of a beyond-CMOS [3], energy efficient new technology. The properties of spin waves depend on the wide spectrum of ultra-compact magnonic devices and large-scale integration magnonic circuits have been introduced. The magnonic coupler elements have recently been introduced to be the unit of integrated magnonic network and several experiments have been performed with coupler-based reconfigurable magnonic circuits which can act as interconnection and frequency spatial division demultiplexing magnonic devices[4]. Since the even state exhibits an odd symmetric property with respect to the mirror plane parallel to the waveguides, the transfer occurs along the backward direction of the drop waveguideThe principle of the proposed directional magnonic ring coupler in lateral configuration is schematically pictured in Fig. 1. The coupler based on a parallel-couples a narrow YIG waveguide S_1 to adjacent waveguide Z_1 with a coupling length of L.

The internal magnonic ring structure was formed from L-type junction of four magnonic waveguides Z_i of equal width si = 500 μm (i = 1..4) in order to maintain the spin-wave phase matching. Magnonic ring was placed between two parallel magnonic buses S_1 and S_2 of width w_1 = 500 μm and w_2 = 500 μm, respectively. Since the even state exhibits an odd symmetric property with respect to the mirror plane parallel to the waveguides, the transfer occurs along the backward direction of the drop waveguide

The geometry of internal magnonic rectangular ring is defined by the simple rules. In x-direction along the long side of the ring the variation of sizes will significantly affect the spin-wave coupling regime. Thus, the length of the DC should also be properly designed. The value of coupling region is determined by the phase matching condition between spin waves which are propagated along S_1 and Z_1. The reduction of coupling region can destroy the full spin-wave transfer between stripe otherwise with the enlargement of the long side of Z_1 waveguide the spin wave power will be coupled back to the S1 stripe.

We report that in this structure can be obtained special regimes of SW coupling. Thanks to usage of ring resonator SW can propogates forward and backward without changing direction of internal magnetic field. Our results are relevant to the development of the advanced integrated magnonic couplers and offer a range of further opportunities in planar magnonics for high frequency signal processing in neuromorphic computation.

This work was supported by the grant from Russian Foundation for Basic Research (No.18-37-20005, №. 18-29-27026).

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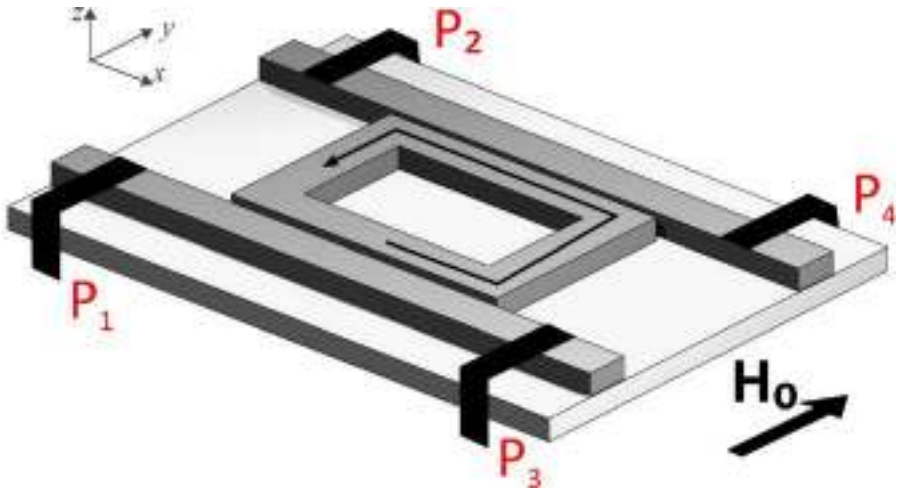
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P371 - Double pump THz spectroscopy of multiscale kinetics of the magnetic phase transition in FeRh

15. Spin waves, magnonics, ultrafast magnetization dynamics and optically driven spin excitations

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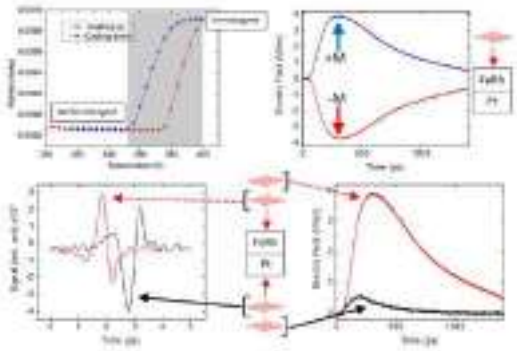
We used the technique of double pump THz emission spectroscopy to explore laser-induced sub-picosecond and nanosecond magnetization dynamics in the vicinity of phase transition between antiferromagnetic and ferromagnetic states in the FeRh/Pt heterostructure. The magnetic phase transition in FeRh is shown in Fig. 1a. The range where both ferromagnetic and antiferromagnetic phases co-exist is seen, in particular, in the hysteresis in temperature dependence of the net magnetization of FeRh. Previous publications showed a possibility to trigger this phase transition with a femtosecond laser excitation. However, although some groups claimed that the phase transition occurs at the sub-picosecond timescale [1, 2], others did not agree with those statements and insisted that the characteristic time-scale of the phase transition is in the range from 10 to a few 100 ps. It is well known that kinetics of any first order phase transition must contain two stages: nucleation of new phases and growth of the nuclei. Aiming to resolve the controversy and learn about ultrafast different stages in the kinetics of the phase transition, we performed the double pump THz emission experiment. While the first pump was meant to generate nuclei of the ferromagnetic phase, the second pump not only generated nuclei of the ferromagnetic phase, but also could cause an ultrafast expansion of the nuclei generated by the first pump. Changing the delay between the two pump pulses we were able to reveal that THz emission from the second pulse increases upon increasing the delay between the first and the second pump pulses (see Fig. 1b). The THz emission changes sign upon magnetization reversal. Hence the emission must be assigned to photo-magnetization and the dynamics must be assigned to the growth of the nuclei generated by the first pump. While the first pump pulse causes the ultrafast nucleation of the ferromagnetic phase, the second pump pulse causes an explosive growth of the nuclei. Our studies as a function of temperature and magnetic field show that although femtosecond laser pulse is able to generate nuclei of the ferromagnetic phase in FeRh on a sub-picosecond time scale, the magnetization in these nuclei is not aligned along the applied magnetic field. Preforming experiments with different orientations of the FeRh/Pt heterostructure (see Fig. 1c and 1d). we were able to distinguish electric dipole and magnetic dipole THz emission which must be assigned to photo-induced magnetization at FeRh/Pt interface and in FeRh bulk, respectively. Using these measurements, we conclude that the first nuclei are predominantly generated at the FeRh surface opposite to the FeRh/Pt interface. Afterwards the nuclei with the magnetization along the applied magnetic field grow and propagate to the FeRh/Pt interface on a timescale of 100 ps.



P372 - Field controlled patterns of spin wave emission by a GHz rep-rate laser

15. Spin waves, magnonics, ultrafast magnetization dynamics and optically driven spin excitations

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Ultrafast optical excitations of spinwaves in thin magnetic films was first observed nearly two decades ago [1]. Typically, low rep-rate lasers are used in which the second pulse arrives much after the emitted spinwave is damped. This has changed in recent years with availability of high rep-rate lasers, where two consecutive pulses are spaced just 1 ns apart. This allows the excitation of high amplitude sustained emission of SWs.

In contrast to experiments conducted previously on dielectric samples [2], we here present results using a metallic thin film which is easily integrable with the existing silicon technology. Coherent excitation of spinwaves in NiFe thin films have been achieved using GHz repetition rate laser. A μ-focused Brillouin light scattering (BLS) technique is used as a probe to detect the spatial as well as spectral extent of the emitted spinwaves.

The result using a 20 nm NiFe thin film shows a strong enhancement of the broadband ferromagnetic resonance frequencies, at multiple harmonics of the repetition rate as shown in Fig. 1. To observe the spatial extent, we acquired area maps and plotted them at different frequencies of the spin waves. The 7 GHz mode is localized to the pump region, while the 8 and 9 GHz modes show propagation along the direction perpendicular to the applied magnetic field (H_{app}). We also observe appearance of a caustic propagating spinwave beam which forms an X-pattern. By changing the strength of the external magnetic field slightly, we can change the propagation pattern at a particular frequency from localized to elliptical and to a caustic shape.

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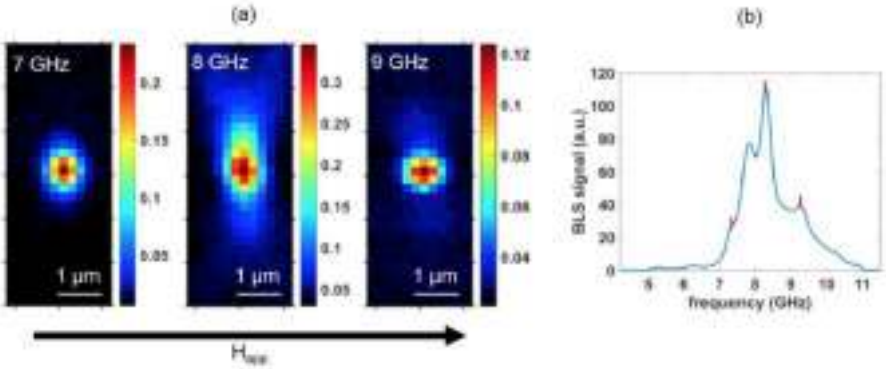

Figure 1: (a) Spatial maps of spinwaves emitted in a 20 nm thick permalloy film on sapphire substrate at oblique external magnetic field. (b) BLS spectra showing integrated counts.

P373 - Impact of the interface on ultrafast spin-to-charge conversion in metallic bilayers

15. Spin waves, magnonics, ultrafast magnetization dynamics and optically driven spin excitations

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The efficient conversion of spin to charge currents by spin-orbit interaction (SOI) is of great relevance for the detection and generation of spin currents in future spin-based electronics [1] and the development of efficient emitters of terahertz electromagnetic pulses [2,3]. Thus, understanding and optimization of spin-to-charge conversion (S2C) is highly desirable. Current research has started taking the role of interfaces into consideration. For example, recent works demonstrated ultrafast S2C by the inverse Rashba-Edelstein effect at interfaces of metallic heterostructures [4,5]. Here, we analyze S2C in an important model system: F|N bilayers consisting of ferromagnetic (F) and nonmagnetic (N) metal thin films. To measure S2C, we employ femtosecond optical pulses to trigger ultrafast spin transport from the F into the N layer (see figure) [2-5]. Through S2C, the spin current is partially converted into a transverse charge current that is monitored by detecting the concomitantly emitted THz electromagnetic radiation. To simplify the separation of interfacial S2C, we minimize S2C in the N bulk by using the common low-SOI materials Al and Cu. Our measurements indicate that S2C at Co|Al and Py|Cu interfaces can, respectively, even become comparable to the overall S2C in Co|Pt and Py|Pt reference bilayers. We show that S2C is drastically affected by modification of the interface and discuss our results in terms of possible extrinsic S2C mechanisms.

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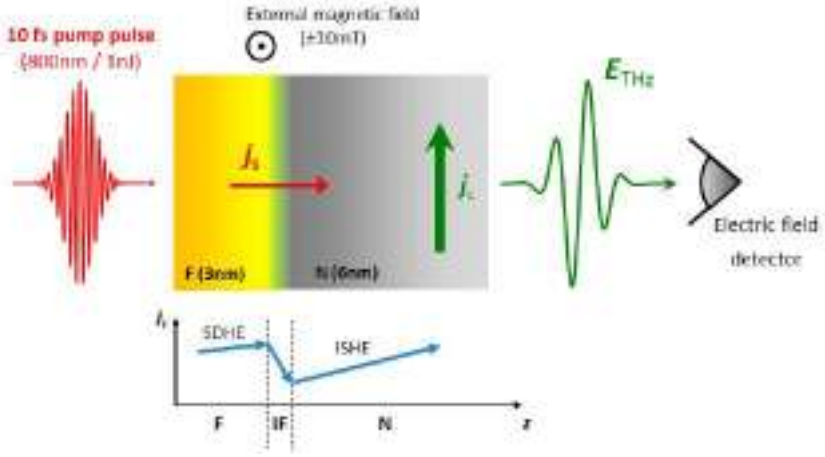

P374 - Implementation of the Stimulated Raman Adiabatic Passage Mechanism in Magnonics

15. Spin waves, magnonics, ultrafast magnetization dynamics and optically driven spin excitations

Qi Wang[1] , ***Anna Maria Friedel***[1], *Thomas Brächer*[1], *Andrii Chumak*[1], *Burkard Hillebrands*[1], *Philipp Pirro*[1]

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Magnonics is the field of spin waves and their quanta, magnons. Spin waves are the dynamic excitations of a magnetically ordered body and bring the potential to implement innovative ways of data processing due to their wave-based nature. One example is the concept of “quantum-classical analogies” such as the **Sti**mulated **R**aman **A**diabatic **P**assage (STIRAP). This process describes the population transfer between two states, where direct transitions are dipole forbidden, using a specific coupling scheme to a third state. The STIRAP process has found various applications in many fields of physics [1] and has already been implemented in the field of waveguide optics [2].

We present first results of the magnonic realisation of the STIRAP process. Our demonstrator consists of three, partially curved magnonic waveguides, which are locally coupled to each other via the dipolar stray fields of magnons in well-defined regions of small separation between two neighbouring waveguides. This design is equivalent to two magnonic directional coupler devices [3] arranged in series and with coherent coupling between them, as shown in Fig. 1(a). Using micromagnetic simulations, we show that the population of magnons can be transferred between the outer waveguides via the intermediate waveguide. If the “counterintuitive” coupling scheme is used, the intermediate waveguide is not excited during the transfer, as shown in Fig. 1(b).

This implementation of a mechanism known from the field of quantum control and coherent control into magnonic functionalities is not the only quantum-classical analogy phenomenon that could be transferred to magnonics. Other examples could be the waveguide realisation of electromagnetically induced transparency or Bloch oscillations. Thus, our results bear high potential for future magnonic device functionalities and designs by bringing together the wealth of quantum-classical analogy phenomena with the benefits of means to control wave propagation in magnonic systems.

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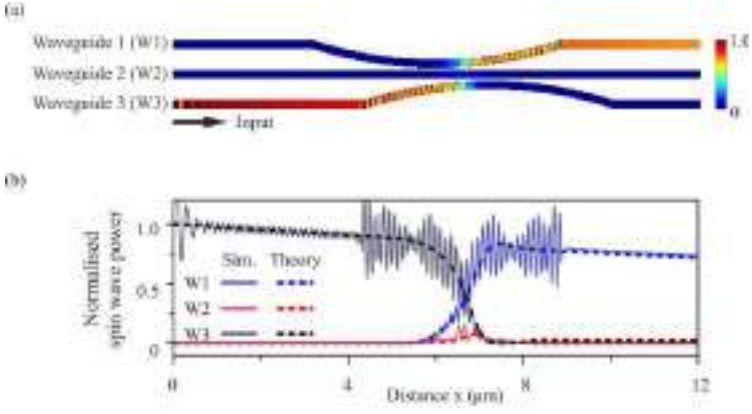

Fig. 1 (a) The two-dimensional spin wave power distribution for the “counterintuitive” coupling scheme. (b) The normalised spin wave power for different coupled waveguides.

P375 - Investigation of ultrafast two-step demagnetization in Ni-Mn-Sn Heusler alloy film

15. Spin waves, magnonics, ultrafast magnetization dynamics and optically driven spin excitations

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Laser-induced ultrafast magnetization dynamics in $Ni_{54.3}Mn_{31.9}Sn_{13.8}$ Heusler alloy film was investigated using time-resolved magneto-optical Kerr rotation dual color technique as a function of laser pump fluence within long-range delay times. Two-step demagnetization process consisting of sub-picosecond and sub-nanosecond component was observed. Simultaneous existence of both components have been explained in the frame of extended microscopic three-temperature model. It was found that in contrast to the fast component, the demagnetization time of the slow component strongly depends on the fluence. The model parameters changes with the fluence were explained by the Curie temperature proximity effect.

P376 - Laser-induced helicity-dependent domain wall motion studied by advanced micromagnetic modelling

15. Spin waves, magnonics, ultrafast magnetization dynamics and optically driven spin excitations

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Understanding and controlling the magnetic state of thin ferromagnetic multilayers with ultrashort laser pulses is nowadays attracting great interest, as it promises faster and less dissipative magnetic recording devices. However, the mechanisms allowing optical control of the magnetization are still under debate. Recently, domain wall motion in Pt/Co stacks by ultrashort laser pulses below the switching threshold have been demonstrated experimentally to be helicity dependent [1].

Here we present the results of a micromagnetic self-consistent solver that couples the Landau-Lifshitz-Bloch equation to the three temperatures model 3TM (and/or the two temperatures model, 2TM), and it takes into account the laser helicity by means of an magneto-optical effective field as due to the inverse Faraday effect (IFE). Examples of these processes are shown in Fig. 1. A down-up domain wall (DW) is initially placed in the middle of a Co/Pt thin film. The laser is focused slightly displaced from the center of the DW (see Fig. 1 for both locations of the laser spot), and both circular (right σ+, left σ-) and linear polarizations were evaluated. After a train of 100 laser pulses, a clear DW motion is observed for only one circular polarization (σ+ or σ-), and this depends on the laser location (Fig. 1). A marginal DW motion is achieved under laser pulses with linear polarization. These micromagnetic results, which are in agreement with recent experimental observations [1], allow us to elucidate the role of several effects which cannot be isolated in experimental setups. Indeed, the laser generates the helicity-dependent magneto-optical effective field due to the IFE, but it also induces thermal gradients [2], which are polarization independent. On the other hand, our extended micromagnetic solver allows us to also evaluate the influence of the magnetic circular dichroism (MCD) in these processes, which is the differential absorption of left and right circularly polarized light depending on the local state of the magnetization. Our results constitute a major step towards a deeper understanding of the ultrafast and all optical control of the ferromagnetic order.

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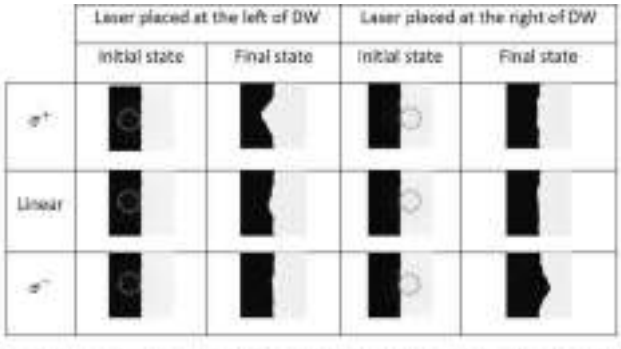

Fig. 1. Domain wall motion before (Initial state) and after (Final state) a train of 100 laser pulses in a Co/Pt sample. The size and the location of the laser spot are indicated by the grey circle in the snapshots at the initial state. Left (σ^+), linear and right (σ^-) polarizations are evaluated. White and black indicate up and down out-of-plane magnetization.

P378 - Levitating antennas for spin wave excitation and detection

15. Spin waves, magnonics, ultrafast magnetization dynamics and optically driven spin excitations

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The excitation and the detection of spin waves is crucial for all experiments dealing with magnetization dynamics and spin wave propagation. The most common and straightforward excitation technique is via a microwave antenna (e.g. [1–5]). The electric current passing through the antenna is then used to produce high frequency magnetic field necessary to excite spin waves.

The main disadvantage of the spin wave investigation techniques using microwave antennas is the fact, that the excitation (and/or detection) antenna is typically fabricated on the sample itself and thus cannot change its position on the substrate. As it is often required to measure for multiple positions of the antennas (multiple positions on the magnetic sample or multiple spacings between antennas in case of SW propagation detection), a series of samples is then necessary to fabricate in order to measure desired number of points. This fact is not only limiting the number of possible measurement points but also lowers consistency as each sample can have different defects affecting the results.

We present an approach where the antenna is separated from the sample. It is fabricated on a glass substrate that is fastened onto a coupler with a SMA connector going either to RF source or vector network analyzer (VNA). This device is then attached to a x-y-z-tilt micromanipulator (Fig. 1[a]) allowing for positioning over the sample while accurate navigation is provided by an optical microscope. Moreover, the transparent substrate allows not only for easy navigation but also for optical detection, especially the Brillouin Light Scattering (BLS [6]) which is one of the main techniques for spin waves. For BLS measurement, this method needs less z-clearance below the objective lens when compared to antennas contacted with probes. Lower possible working distance allows for higher numerical aperture and also for the aberration correction of added glass thickness leading to higher lateral resolution of the method.

First results have been measured showing that our devices can be used for spin wave excitation which was captured on a Permalloy layer by BLS (Fig. 1[b]). The device was also successfully used with VNA in order to measure the broadband ferromagnetic resonance (by one port reflection) and spin wave propagation in a Permalloy stripe (by two port transmission) where one antenna was fixed on the sample and contacted with a probe while second antenna was levitating above the sample surface.

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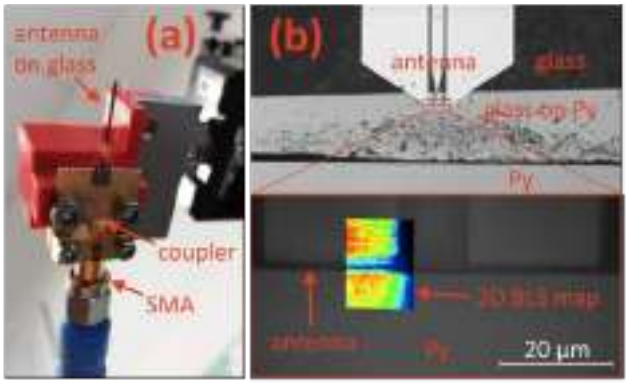

Fig. 1: (a) photograph of the levitating antenna device. (b) optical micrograph of the antenna landed on Permalloy layer. The bottom cutout shows a 2D BLS measurement of spin wave intensity on the Permalloy layer which was excited by the antenna.

P379 - Magnetic anisotropy and spin wave propagation in sinusoidally modulated thin films

15. Spin waves, magnonics, ultrafast magnetization dynamics and optically driven spin excitations

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Magnonic circuits are potential candidates for future information transfer and computing technologies. However, the technical realization of such devices is extremely challenging with conventional approaches. They rely on planar structures, where the magnetic properties are exclusively given by the intrinsic parameters of used materials and by the shape of desired structures. Therefore, properties like uniaxial magnetic anisotropy cannot be directly controlled. To achieve this directional control, we exploited recently presented approach of inducing the effective magnetic interaction by the introduction of curvature to the system [1].

Recent advances in 3D nanofabrication [2] allow to prepare structures with properties unobtainable by standard lithography approaches. One of the possibilities of 3D nanofabrication is nanoscale control of magnetic anisotropy magnitude and direction. We studied spin wave propagation in waveguides made from sinusoidally modulated 10 nm thick films of Permalloy. The films were deposited on silicon dioxide mesas with sinusoidal modulation prepared by focused electron beam induced deposition. The period of modulation was 100 nm and the amplitudes of modulation were changing from 0 to 20 nm. Via precise engineering of the 3D shape morphology at a nanometer level, the magnitude as well as the direction of the uniaxial magnetic anisotropy of thin Permalloy films can be controlled. The final structure is depicted in Figure 1 a).

The quantification of the induced magnetic anisotropy was done by Kerr magnetometry with an external magnetic field along and perpendicular to the ripples. Figure 1 b) presents magnetization loop in such experiment. Black curves correspond to the situation where the magnetic field is parallel to the ripples. This direction can be considered as a magnetic easy axis. Similarly, red curves correspond to the case where the magnetic field is perpendicular to the ripples (hard axis). Figure 1 c) displays a polar plot of the relative remanence M_R/M_S as a function of the angle between the external magnetic field and ripples.

From hard axis loops we extracted the anisotropy field using the piecewise fitting of saturation and slope. The spin wave propagation was observed by micro-focused Brillouin light scattering. We will show that in sinusoidally modulated thin films the curvature-induced magnetic anisotropy is strong enough to overcome the shape anisotropy of the waveguide and that the curvature has only minor impact on spin wave propagation.

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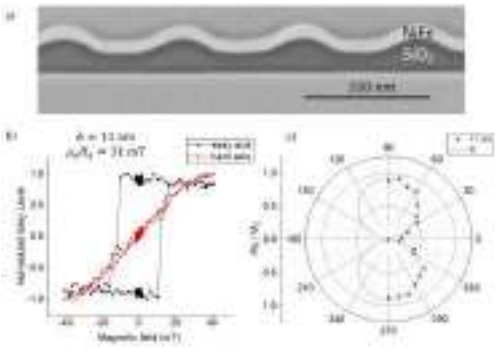

Fig.1 a) STEM micrograph showing the Permalloy layer on top of thickness-modulated silicon dioxide grown by FEBID. b) The hysteresis loop of the structure with the height of modulation $h = 11$ nm. Black curve corresponds to the magnetic easy axis, red curve to the magnetic hard axis. c) Normalized remanent magnetization, M_r/M_s, over the saturation magnetization M_s as a function of the angle θ of the external magnetic field clearly confirms the existence of a uniaxial magnetic anisotropy in the direction parallel to the ripples.

P380 - Magnetic asymmetry around the 3p absorption edge in pump-probe experiments of Fe and Ni

15. Spin waves, magnonics, ultrafast magnetization dynamics and optically driven spin excitations

Somnath Jana[1, 2] , *Yaroslav O. Kvashnin*[1], *Rameez S. Malik*[1], *Ronny Knut*[1], *Inka L. M. Locht*[1], *Robert Stefanuik*[1], *Igor Di Marco*[1], *Raghuveer Chimata*[1], *Marco Battiato*[3], *Martina Ahlberg*[4], *Johan Akerman*[4], *Justin M. Shaw*[5], *Hans Nembach*[5], *Johan Soderstrom*[1], *Olle Eriksson*[1], *Olof Karis*[1]

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With the advancement of the laser driven tabletop extreme ultraviolet (XUV) source, measuring element-resolve magnetization dynamics in the few femtosecond time scale becomes possible in lab-based setups. The magnetic signal is probed by measuring the transverse magneto-optical Kerr effect (T-MOKE) at the M edges of the 3d magnetic systems. The T-MOKE signal, namely the magnetic asymmetry A(E), is commonly assumed to be approximately proportional to the magnetization of the sample. In relating the asymmetry to the magnetization, the following assumptions are made: $A(E) \alpha \varepsilon_{xy}(E) \alpha M_z$; where $\varepsilon_{xy}(E)$ is an off-diagonal component of the dielectric tensor and M_z is the projection of the magnetization on the direction of the field. In this work, we found that the T-MOKE signal is not always proportional to the magnetization of the sample, which also lead us to identify possible magnetic excitations in elemental Fe and Ni sample during the ultrafast demagnetization.

We have performed pump-probe experiments using photon energies that cover the M-absorption edges of Fe and Ni between 40 to 72 eV. Density functional theory was used to calculate the magneto-optical response of the three different magnetic configurations as pictorially described in the figure, where A, B and C closely represent Stoner excitation, long wavelength magnon and short wave length magnon, respectively. In the case of Fe, we find that the calculated asymmetry is strongly dependent on the specific type of magnetic excitation. Our modelling also reveals that during remagnetization Fe is to a reasonable approximation described by magnons, even though small non-linear contributions could indicate some degree of Stoner excitations as well. In contrast, we find that the calculated Ni asymmetry is rather insensitive to the type of magnetic excitation with very weak non-linear behavior. However, due to the large magnetic asymmetry found for Ni, there is non-linearity in the relation between asymmetry and the off-diagonal component of the dielectric tensor that underestimates the demagnetization by ~ 12%. From the total energy considerations, Stoner-like excitations should dominate in the demagnetization process of fcc Ni, while short wavelength magnons and longitudinal decrease of the moments are equally probable in case of bcc Fe. Our experimental and theoretical results thus emphasize the need of considering a coupling between asymmetry and magnetization that is more complex than a simple linear relationship, and that this is crucial for the microscopic interpretation of ultrafast magnetization experiments.

A. Collinear decreased atomic magnetic moments:

B. Gradually tilting atomic magnetic moments:

C. Randomly tilting atomic magnetic moments:

P381 - Magnetic Properties of the Quasi-1D Compound Ca1-xNaxCr2O4 Studied with Neutrons & Muons

15. Spin waves, magnonics, ultrafast magnetization dynamics and optically driven spin excitations

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The peculiar physical properties of one-dimensional (1D) and quasi-one-dimensional (Q1D) compounds have attracted considerable interest in condensed matter physics since decades. In Q1D metals, the electron system, described as a Fermi-liquid in higher dimensional lattices (2D, 3D), starts to behave like a Luttinger-liquid, that is a system in the vicinity of a quantum critical point, so the magnetic ground state of Q1D metals is dominated by quantum mechanical effects. As a consequence, the low-temperature properties are found to be exotic and without counterpart in higher dimensional systems. For the Q1D compounds containing characteristic 1D zigzag chains the magnetic order is determined not only by the spin density of the chain but also by the competition between the nearest-neighbor (*J1*) and the next-nearest-neighbor (*J2*) correlations. This frustration of the magnetic interactions by the geometry of the lattice can be tuned by **(1)** inducing lattice changes through e.g. hydrostatic pressure, or **(2)** altering the spin density of the Q1D chains through chemical substitution.

In this work we present the results of the measurements carried out by muon spin rotation/relaxation (μ^+SR) and neutron powder diffraction on the Q1D zigzag-chains solid solution $Ca_{1-x}Na_xCr_2O_4$. In particular, we have studied the members of the solid solution with $x = 1$ ($NaCr_2O_4$), $x = 0$ ($CaCr_2O_4$) **[1,2]** and the intermediate compound $x = 0.5$ ($Ca_{0.5}Na_{0.5}Cr_2O_4$) **[3]**. The $x = 1$ results show a unique spin structure where the Cr moments in each zig-zag chain are aligned ferromagnetically along the c-axis, whereas antiferromagnetically along the a-axis between the adjacent zig-zag chains. The $x = 0$ results show the formation of a complex magnetic order below T_N, that is consistent with an incommensurate AF (IC-AF) order. Initially the investigation on the intermediate members of the solid soultion $Ca_{1-x}Na_xCr_2O_4$ as a function of the Na content, was expected to show a magnetic lock-in transition where the IC-AF for a certain x would coordinate itself with the atomic lattice, hereby forming the C-AF order. However, the μ^+SR spectra only show a fast-relaxing component, possibly indicating a spin-glass state. Moreover, an additional pressure dependent μ+SR investigation, showed that the magnetic order is almost completely unsensitive to pressures (up to $p \gg 25$ kbar), hereby revealing that the effect from the tuning of the spin density of the chains is clearly dominant.

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P382 - Magnetization dynamics in antiferromagnetically coupled ferromagnetic trilayers

15. Spin waves, magnonics, ultrafast magnetization dynamics and optically driven spin excitations

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Magnetic trilayer films, in which two ferromagnetic layers couple antiferromagnetically via a nonmagnetic spacer layer that mediates the Ruderman–Kittel–Kasuya–Yosida (RKKY) interaction, led to the discovery of the giant magnetoresistance effect [1]. In addition, it was subsequently realized that the interlayer coupling affects the magnetization dynamics of such trilayer systems [2]. Magnetization in the two layers can precess in-phase and out-of-phase, which is commonly referred to as the acoustic and optical mode, respectively. The rich magnetization dynamics in these systems allows the formation of a complex spin wave dispersion relation, in particular the realization of a nonreciprocal dispersion [3]. In this work, we have characterized the precessional motion of magnetization in antiferromagnetically coupled trilayer films in the time domain using the time-resolved magneto-optical Kerr effect (TRMOKE) [4]. We have observed both the acoustic and optical modes with different precession frequencies and damping constants, and both the modes varied systematically with the variation of the external magnetic field as shown in Fig. 1. To understand the complex magnetization dynamics, we have analytically calculated the precession frequencies of these trilayer films using the Landau-Lifshitz equations. We have found that the presence and the strength of the RKKY interaction results in a deviation from the behavior described by the Kittel's formula. For the acoustic mode, the RKKY interaction modifies the precession motion mainly by changing the static magnetization configuration, whereas for the optical mode, the RKKY interaction produces an additional dynamic field due to the out-of-phase precession. The results are qualitatively consistent with our analytical calculations.

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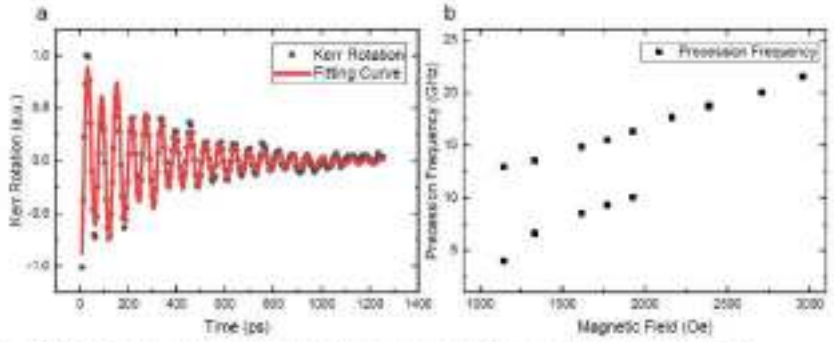

Fig. 1. (a) TRMOKE measurement of the out-of-plane component of the magnetization precession. The measurement was performed on a CoFeB(2.5 nm)/Ru(0.5 nm)/CoFeB(5.0 nm) trilayer film in an applied in-plane magnetic field of 1990 Oe. (b) Magnetic field dependence of the magnetization precession frequencies.

P383 - Magneto-Optical Functions at the 3p resonances of Fe, Co & Ni: Ab-initio description and experiment

15. Spin waves, magnonics, ultrafast magnetization dynamics and optically driven spin excitations

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The author has chosen not to publicise the abstract.

Field 5

Field 6

P385 - Magnon straintronics and lateral spin-wave transport insulating based ferrimagnet arrays

15. Spin waves, magnonics, ultrafast magnetization dynamics and optically driven spin excitations

Alexandr Sadovnikov[1] , *Grachev Andrew*[1], *Beginin Evgeny*[1], *Sheshukova Svetlana*[1], *Sharaevsky Yuri*[1], *Nikitov Sergey*[1]
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In recent years much research has been directed towards the use of spin waves (SWs) for signal processing at microwave and subterahertz frequencies due to the possibility to carry the information signal without the transmission of a charge current [1]. The effect of the electric field on the magnetic configuration results from the modification of the effective internal magnetic field. Here we report the experimental observation of the spin-wave coupling in different magnonic structures based on adjacent magnetic yttrium iron garnet stripes and array of magnetic stripes [2], which demonstrates the collective spin-wave phenomena. As a major result, we have demonstrated by the means of the space-resolved Brillouin light scattering (BLS) technique, that non-identical MCs within close proximity demonstrates the efficient spin-wave coupling at the frequency of the magnonic forbidden gap of one of the MCs. To demonstrate the switching in spin-wave propagation along the bilateral stripes, we use the BLS technique in the backscattering configuration. Probing laser light with a 532 nm wavelength was focused on the transparent GGG side of the composite structure. If the voltage is applied to one or both electrodes in bilateral structure, the spatial spin-wave intensity distribution is transformed. Thus, we show the voltage-controlled spin-wave transport along bilateral magnonic stripes. Strain coupling of the PZT and YIG stripes was achieved in the experiment using the heat cured two-part epoxy strain gage adhesive. The three-channel isolator-based directional coupler (Fig.1) distinguishes itself as an ideal platform for magnonics in three key aspects: first, dual tunability with both the magnetic and electric field; second, it supports large spin-wave propagation distances, which is appropriate for spin-wave interference in magnonic logic applications; and third, its versatile magnonic component with the voltage-controlled frequency-selective characteristics.

The direct measurement of voltage-controlled spin-wave switching in a bilateral composite structure, where the dipolar stray fields produced by the spin wave in one magnetic stripe affects the spin-wave behavior in two neighbor stripes, was performed using BLS and microwave spectroscopy.

A model describing the spin-wave transmission response and predicting its value is proposed based on the self-consistent equations of strain-mediated magnetostriction. The full micromagnetic and finite-element simulation of tunable lateral spin-wave transport in YIG/PZT bilayer was performed. Our work shows that the strain-mediated spin-wave channels provide a useful window into the transformation of the spin-wave spectra and spin-wave dynamics. This revelation is of particular importance when we consider the practical advantages that the composite magnon-straintronic structure could provide to fabricating magnonic platforms for energy-efficient signal processing.

This work was supported by the Russian Science Foundation (#18-79-00198).

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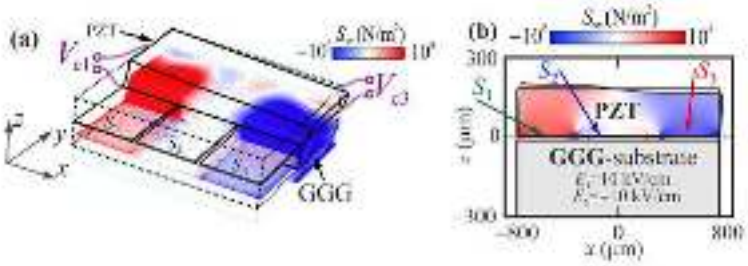

Figure 1: The distribution of stress tensor component S_{xx} showing a local deformation of the PZT layer (a) and induced stress on the surface of YIG stripes (b).

P386 - Micromagnetic Simulation of Topological Defect Dynamics in a Square Micromagnet

15. Spin waves, magnonics, ultrafast magnetization dynamics and optically driven spin excitations

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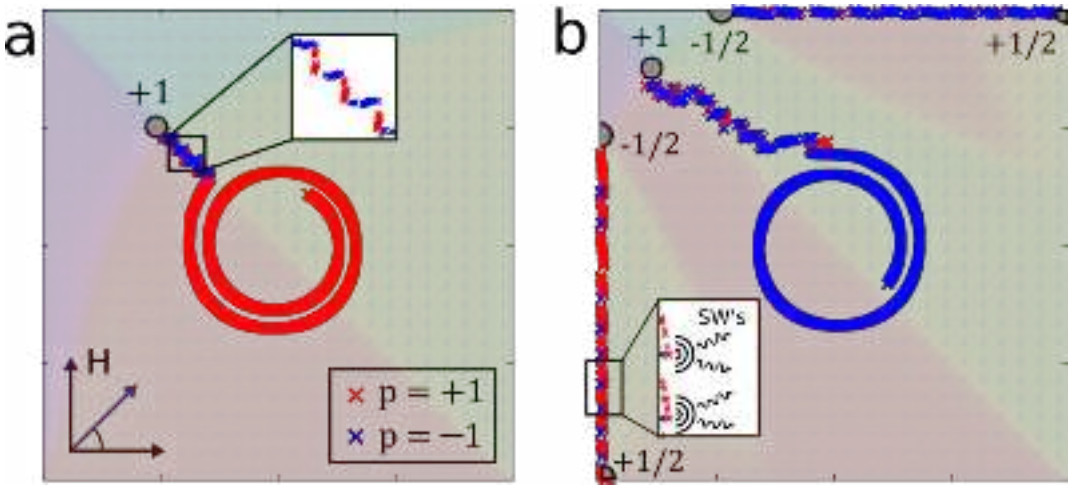
The magnetodynamic properties of a square thin film micromagnet (LSMO) with a flux-closure magnetic ground state were investigated by micromagnetic simulations. The system was excited with an applied magnetic field, displacing the vortex core sufficiently far from its equilibrium position to result in a non-linear relaxation upon removal of the field. We observe an initial zigzag motion of the vortex core, followed by the familiar gyrotropic motion. Moreover, we find that creation of edge topological defects leads to periodic emission of bursts of short wavelength spin waves emanating from these defects, which can be explained through the mechanism of Walker breakdown. This finding could prove useful to the development of nanoscale devices for periodic generation of high-frequency microwave radiation.



P387 - Modified exchange coupling in an [Co/Pt]/(Pt)/Py bilayer exchange spring by insertion of a Pt spacer

15. Spin waves, magnonics, ultrafast magnetization dynamics and optically driven spin excitations

Andreas Frisk[1] , *Maciej Dabrowski*[2] *, David Burn*[1] *, David Newman*[2] *, Robert J. Hicken*[2] *, Gerrit van der Laan*[1]

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Structures with canted magnetic moments are important for the delivery of reduced critical current densities and turn-on time within spin-torque oscillators [1-3]. Such a structure can be realised with an exchange spring. These are usually engineered with anisotropies such that the moments of both hard and soft layers are aligned in the same direction, either in-plane (IP) or out-of-plane (OoP). If instead the hard and soft layers have different anisotropy directions (IP and OoP) then the exchange coupling creates a canted magnetic state at remanence. Using x-ray magnetic circular dichroism (XMCD) and x-ray ferromagnetic resonance (XFMR) at the Co and Fe $L_{2,3}$ edges [4], at both the Advanced Light Source in the US and the Diamond Light Source in the UK, we have studied the effect of inserting a Pt spacer layer on the exchange coupling within [Co/Pt]/(Pt)/Py (tri-)bi-layer exchange springs with canted magnetic moments (Py = $Fe_{20}Ni_{80}$).

Samples of Pt(300)/$[Co(2)/Pt(9)]_{10}$/Pt(x)/Py(y)/Pt(30) (thickness in Å) were grown on Al_2O_3 (0001) substrates, using DC magnetron sputtering, with x = 0 and 15 Å and y = 550 and 100 Å. By making the Py layer (y = 550 Å) thick compared to the 110 Å [Co/Pt] layer, the Co moments are canted from the OoP direction. Element resolved hysteresis loops, measured by XMCD, show that the IP shape anisotropy of the Py dominates and pulls the Co moments from their preferred OoP direction towards the IP direction. Using the thinner Py layer, the Py at the interface is instead canted towards the OoP direction, while the Py magnetization relaxes towards the in-plane direction away from the interface. By inserting a Pt spacer layer, the exchange coupling was decreased, resulting in Co moments that were less strongly canted. For samples with the thickness in this study a static exchange coupling was always observed. The canting of the moments is in agreement with work by Hsu and Saravanan et al. [1, 5].

The dynamic exchange coupling between the layers was investigated using XFMR which gives the element resolved FMR. XFMR measurements performed with an IP bias field confirmed that the [Co/Pt] and Py layers are strongly coupled in the samples without the Pt spacer. For a 4GHz RF field, both Co and Fe exhibit a resonance field of 20mT, while in the sample with a Pt spacer only the Fe exhibits a resonance for an IP bias field. See Fig 1 for IP field scans of the resonance amplitude measured by XFMR at the Fe and Co $L_{2,3}$ edges for a 4GHz RF-field. Vector network analyser FMR (VNA-FMR) was also performed with biasing field IP and OoP. VNA-FMR with IP biasing field was in agreement with the XFMR, while for OoP there was a complex behaviour.

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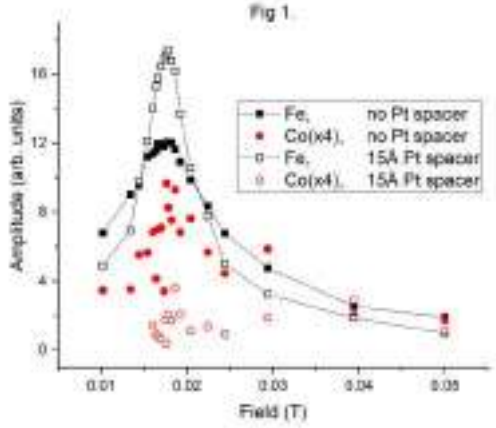
Fig 1.


Amplitude (arb. units)
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Fe, no Pt spacer
Co(x4), no Pt spacer
Fe, 15Å Pt spacer
Co(x4), 15Å Pt spacer

P388 - Nanoscale Detection of Spin Wave Deflection Angles in Permalloy

15. Spin waves, magnonics, ultrafast magnetization dynamics and optically driven spin excitations

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Since the introduction of the term magnonics[1], spin waves are considered as promising approach for next generation data transmission. However, the scaling of magnetic devices into the sub µm region is accompanied by challenges such as the scalability of the production process, or even more fundamental, the observation of the desired effect as optical methods are limited by their wavelength of 300 nm.

Fortunately, the MAXYMUS x-ray microscope at BESSY II routinely achieves magnetic resolutions down to 15 nm using the XMCD effect[2]. A fast photon-sorting algorithm allows for an acquisition of a dynamic spin wave video within a couple of minutes with time resolutions down to a few ps.

The video in real space and time domain yields information about spin amplitude and phase at the same time. With temporal Fourier analysis, a ‘dynamic picture’ of such a spin wave is extracted. *k*-Space transformation, allows for the separation of overlapping spin wave modes. Additionally, the absolute spin angle of the spin wave is calibrated by measuring a XMCD spectrum of the sample and comparing it to the contrast of a movie[3].

To demonstrate the power of combining this measurement technique and analysis method for magnonics research we measured a 50 nm permalloy film in Demon-Eshbach geometry. An exemplified result is shown in Fig. 2. The color represents the relative phase, the amplitude is encoded in brightness. The total area displayed is 40 x 5 µm^2 with an acquisition time of less than 5 minutes. The dispersion relation is in good agreement with literature, proving the reliability of STXM for spin wave research[3]. By comparing the contrast of the video to the contrast expected from the XMCD spectrum we can calculate the absolute spin deflection angle. [3] Thus, STXM measurements yield a complete set of information on absolute amplitude and phase of the spin wave.

In summary, STXM gives massive new opportunities for the time-resolved observation of nano magnetic structures such as spin waves, skyrmion movement, or domain wall oscillations. With resolutions down to 15 nm in space and 35 ps in time, there is an almost endless amount of opportunities to investigate magnetic structures and their dynamic behavior.

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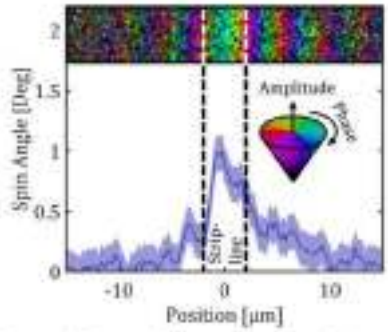

Figure 1: Dynamic illustration of a spin wave. Color encodes relative phase, brightness encodes amplitude. White lines denote the position of the stripline. Absolute spin wave angle. As expected the

P389 - Nonlinear autoresonance in thin YIG film

15. Spin waves, magnonics, ultrafast magnetization dynamics and optically driven spin excitations

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At present, for studying properties of complex systems often use different effective theoretical finite-difference methods. One of those methods called micromagnetic modeling successful applying to predict the evolution of magnetic systems, by solving the Landau-Lifshitz equation for magnetic nano-structures. The research of micromagnet modeling is focused on the phenomenon of the nonlinear amplification of the magnetic subsystem oscillations in thin yttrium iron garnet (YIG) () films by autoresonance [1]. This autoresonance (autophasing) effect was predicted in the works of S.V. Batalov and A.G. Shagalov for thin films with one-axis anisotropy along axis perpendicular to the film plane.

However, the theory does not take into account the geometry of the sample (demagnetizing factor), dipole-dipole spins interaction. Micromagnetic modeling was performed using MUMAX3 [2]. Parameters of the sample like the saturation magnetization, the exchange interaction, the magnetic anisotropy constant, and the Gilbert coefficient corresponding to the properties of the YIG were set because this material has a low magnon damping level, which is provide the stability of linear and nonlinear wave processes. The interaction between the cells was calculated using the Landau-Lifshitz equation. The thickness of the film was chosen from the condition of the optimum number of magnetic lengths allows to create autoresonance.

The aim of this work was to verify the theoretical model using micromagnetic simulation in the sample consisting of the matrix rectangular cells with appropriate size, with parameters corresponding to the properties of the YIG. For the comparative convenience the simulation results and the solution of the nonlinear Schrödinger equation in YIG, one-axis anisotropy with an easy axis perpendicular to the film plane was additionally taken into account.

During the modelling, the sample was magnetized along the easy magnetization axis perpendicular to the film plane in saturation state, then the sample was placed in a transverse RW field with a frequency varying linearly with the time. It is shown that when the frequency of the external alternating field is reduced below the frequency of the ferromagnetic resonance, stable oscillations of the magnetic subsystem are manifested, so-called breathers. The breather amplitude dependence on the rate of frequency change was studied. The optimal parameters for the autoresonance effect appearance are determined.

Obtained data give a new result and supplement for the previously calculated solution of the nonlinear Schrödinger equation for the magnetization dynamics.

The work was carried out within the framework of the state assignment on the topic "Spin" №AAAA-A18-118020290104-2, "Alloys" and project №18-10-2-37 of the Program of the UB RAS, supported by Grant of the President of the Russian Federation № MK-4959.2018.2

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P390 - Principle studies of spin-lattice dynamics mediated by RKKY and dipole-dipole interaction

15. Spin waves, magnonics, ultrafast magnetization dynamics and optically driven spin excitations

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In systems with magnetic order, there exists collective, temperature dependent motion of the spins as well as atoms that are always more or less coupled. The understanding of how atomic spins couple with lattice vibrations is of fundamental importance for different fields of basic research, such as ultrafast magnetism, spintronics, multiferroics or magnetocalorics. It is dominantly caused by distance dependent exchange coupling between the magnetic moment [1], such as for Ruderman–Kittel–Kasuya–Yosida-like (RKKY) Heisenberg or dipole-dipole interaction. Both exhibits changes in the magnetic order, say from ferro to antiferromagnetic states, related to the crystal structure, which is affected by displacements and call for deeper studies.

We report on an investigation of atomistic coupled spin-lattice dynamics by means of the Landau-Lifshitz-Gilbert and Newton equation as reported in our recent publication [2]. The exchange and force constant parameters of the Hamiltonian are approached by RKKY and dipole-dipole as well as Born-Landé exchange, respectively. But also antisymmetric anisotropic interaction as the Levy-Fert-type Dzyaloshinskii-Moriya interaction [3] will be considered.

For low dimensional systems, we focus on the ground state as well as the evolution from disordered to ordered states in dependence on the intrinsic parameters of the Hamiltonian, temperature, system size, and external perturbation (such as magnetic field or spin-polarized current). The angular momentum transfer will be followed primarily via correlation functions, e.g. between the spin- and lattice system. It turns out that spin precession and lattice vibrations have a crucial influence on each other, especially near magnetic order changes or on the thermal equilibrium position of the atoms.

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P391 - Reconfigurable magnonic crystals based on a hybrid PMA/YIG platform

15. Spin waves, magnonics, ultrafast magnetization dynamics and optically driven spin excitations

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The author has chosen not to publicise the abstract.

Field 5

Field 6

P392 - Scaling of ultrafast demagnetization in 4f antiferromagnets

15. Spin waves, magnonics, ultrafast magnetization dynamics and optically driven spin excitations

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Antiferromagnetic spintronics are a promising route towards more efficient and stable devices, because antiferromagnets are less susceptible to external fields and foster a broad range of magnetic interactions with the potential for higher speeds and energy efficient manipulation. The prospect of employing antiferromagnets in devices opens new functionality pathways through properties that aren't available with ferromagnets. These include driving transitions between different spin arrangements, manipulating the ordering wave vector (which is 0 for ferromagnets) and more. Furthermore, ultrafast dynamics in antiferromagnets can include inter-sublattice exchange of angular momentum, thus overcoming speed limits associated with angular momentum dissipation to the lattice, as is inherent to ferromagnets.

Here we present a study of ultrafast magnetization dynamics of RERh$_2$Si$_2$, a series of 4f antiferromagnets (RE is a Lanthanide between Pr and Ho). We directly observe the dynamics of the magnetic order parameter using resonant X-ray diffraction at the RE ions' M$_{4,5}$ edges, as well as coherent rotations of the spin structure. We observe dynamics ranging in time scale from 300 fs to 1 ns, depending on the RE ion. These materials are nearly identical in every aspect except the RE ion, which facilitates a direct comparison of the 4f dynamics. We identify systematic scaling relations for these dynamics, which will be discussed.

P393 - Slow magnetic polaritons in superconductor– antiferromagnet – superconductor layered structure

15. Spin waves, magnonics, ultrafast magnetization dynamics and optically driven spin excitations

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Magnetism and superconductivity are two fundamental (commonly antagonistic) phenomena in condensed matter physics. Coexistence of magnetic and superconductor ordering in artificial micro and nano structurers promises a unique possibility for applications, in particular in magnonics and spintronics. In present work we consider the superconductor –insulator – superconductor (SC/I/SC) structure with antiferromagnetic (AFM) insulator spacer.

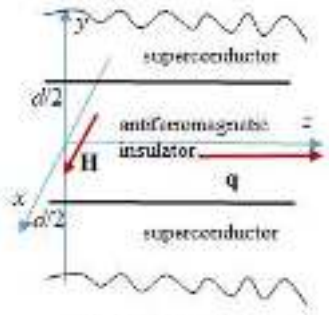
The interaction of slow TM electromagnetic wave (Swihart wave) in SC/I/SC structure and magnetization oscillation in AFM insulator results in formation of coupled waves - slow magnetic polaritons. The wave slowness is determined by the ratio of insulator thickness d to London penetration depth λ_L. The cases of “easy plane” and “easy axis” AFMs in tangential external magnetic field normal to the anisotropy axis is considered. The dispersion relations for coupled waves is obtained from Maxwell equations, AFM and SC material equations, and with appropriate boundary conditions.

As a result, in the vicinity of crossover point between slow electromagnetic Swihart wave dispersion curve and AFM eigenmode (corresponding to the pole of magnetic permeability tensor diagonal component) the repulsion of coupled waves dispersion branches takes place. For the parameters of the structure the estimations give $5\ 10^9$ s^{-1} for frequency gap value at $\Omega=10^{14}$ s^{-1} and $\bar{k}=10^3$ cm^{-1} for crossover frequency and wave number respectively. Note that the plasma frequency in the system of superconducting electrons $\omega_p \sim 10^{15}$ s^{-1} lies well above the considered range.

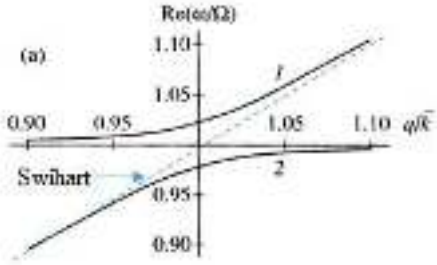
If the dielectric thickness turns out to be of the order of the coherence length of superconductors, then such a system can demonstrate the Josephson effect and one should expect significant effect of slow magnetic polaritons on electrodynamics of the junction. For SC/AFM/SC junction the generalized Josephson relationship between phase gradient and magnetic field is deduced. It resulted to the system of coupled equations for magnetization precession and phase variation. The effect of resonant interaction between slow magnetic polaritons and Josephson current wave upon current-voltage characteristics (CVC) is studied for “short” and “long” junctions. For example, for short junction two series of non-equidistant peaks on CVC is obtained. For infinitely long junction CVC have two peaks at at voltages $V_{1,2}$. The position of one of them depends upon AFM resonance frequency Ω, the position of the other nonlinearly depends upon external magnetic field. Thus, the repulsion and nonlinearity of two dispersion law branches drastically changes the SC/AFM/SC Josephson junction electrodynamics as against to the case of nonmagnetic barrier. On the other hand, the interaction can be used to excite and detect AFM dynamics in the subterrahertz frequency range.

Note, due to the lack of coupling between Swihart wave and magnetization oscillations in ferromagnet, the effect involved is specified namely for antiferromagnet. Also, due to small static magnetization of AFM in comparison with ferromagnet, one can neglect its influence on superconductor parameters.

The work was carried out within the frame work of the state task.



Structure geometry



Dispersion law of slow magnetic polariton

P395 - Spin wave propagation in perpendicularly magnetised CoNi multilayer systems

15. Spin waves, magnonics, ultrafast magnetization dynamics and optically driven spin excitations

Manu Sushruth[1] , *Matias Grassi[2], Kosseila Ait-Oukaci[3], Yves Henry[2], Matthieu Bailleul[2], Sébastien Petit-Watelot[3], Daniel Lacour[3], Michel Hehn[3], Joo-Von Kim[1], Thibaut Devolder[1],* ***Jean-Paul Adam***[1]

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Magnonics is an emerging technology for low-power signal transmission and data processing based on spin waves (SWs) propagating in magnetic materials. Nowadays such SW-based computing concept is discussed and undergoes benchmarking in the framework of beyond-CMOS strategies, due to its nanometer wavelengths and Joule-heat-free transfer of spin information over macroscopic distances. Majority of the SW studies has been conducted using insulators or in-plane magnetized metallic thin films. Compared to insulators, the metallic magnetic thin films are of main interest because of well controlled properties in the thin films and easier coupling to CMOS integrated circuits. However despite these obvious advantages, the studies on SW propagation in metallic PMA films are still rather scarce. One of the main reason is due to higher damping in PMA systems resulting in shorter SW propagation lengths.

In this work we demonstrate SW propagation in PMA systems having a potential towards energy efficient low power option. We develop an all electrical experiment to perform the phase-resolved spectroscopy of propagating magneto-static forward volume spin waves (MSFVSW) in micrometer sized Co (0.2nm) Ni (0.6nm) (61 repetitions) 50nm thick SW conduits with perpendicular magnetic anisotropy. Using FMR technique, the damping parameter of the blanket film was determined to be 0.015. The MSFVSW are excited and detected by 200 nm wide CPW antennas. We also developed an analytical model which accounts for the main features of the apparatus transfer functions.

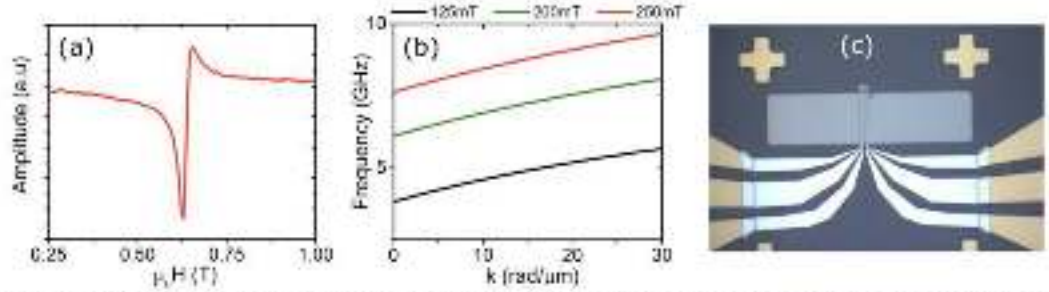

Figure 1: (a) Experimentally obtained FMR trace at 10GHz for a blanket CoNi multilayer film. (b) Analytically calculated dispersion relation (wavevector vs frequency) for magnetostatic forward volume spin waves in CoNi multilayer system for different given magnetic field values. (c) Macroscopic view of the fabricated device showing the contacts, CPW antennae and CoNi SW conduits.

P396 - Spin-wave phase change via resonant scattering in magnetic spacer

15. Spin waves, magnonics, ultrafast magnetization dynamics and optically driven spin excitations

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We developed an analytical theory of the spin waves (SWs) propagation through a ferromagnetic layer: B embedded in ferromagnetic medium A (see Fig. 1(a)). In each part of the system (A and B) the exchange interaction has been taken into account. Additionally, the Dzyalozhinskii-Moriya interaction (DMI) in the ferromagnetic layer B have been included. The coupling between the layer B and its surrounding A have been assumed as the interlayer exchange, which results in Hoffmann type of boundary conditions between A and B.

A systematic analysis of investigated system with respect to material parameters have been done. The resonant transmission – Fabry-Perot-like – has been found in the absence of DMI. For system presented in Fig. 1(b), the phase of transmitted wave is changing in step-like manner from resonant peak to resonant peak. Reflected wave changes the phase monotonously by 2π (from resonant peak to resonant peak). The change of the phase for reflected wave varies between resonances from -π/2 to π/2 (Fig. 1(b) dashed grey curves). The change of the phase in transmission is a non-monotonic function of the frequency (Fig. 1(b) dashed pink curve).

Further analysis shown, that when the layer B is weakly coupled to the surrounding medium A then the transmission is significantly reduced except the sharp resonances with the shape of Dirac delta peaks. On the other hand, decreasing of magnetization saturation of spacer leads to the increasing of distance between resonant peaks. Moreover, the phase in transmission becomes higher and the jumps becomes deeper.

According to our model, the presence of DMI leads to the asymmetry between the clockwise and counter-clockwise precessing spin waves. In the layer with DMI only clockwise precessing spin waves can propagate, while counter-clockwise precessing spin waves one have evanescent character. Moreover, the DMI makes the transmission phenomena more complex. The influence of the width of the layer and the DMI value within the layer on the reflection, transmission and their phases of SW have been investigated as well.

The analytical results have been compared to the outcomes of micromagnetic simulations done with the aid of Mumax3 package.

For the sake of illustration, the following parameters were considered: the gyromagnetic ratio $\gamma = 17.58 \cdot 10^{-6}$, magnetizations saturation $M_A = 1.2 \cdot 10^3$ *Oe* and $M_B = 0.8 \cdot 10^3$ *Oe*, the exchange parameters $\alpha_A = 2.7 \cdot 10^{-12}$ cm^2 and $\alpha_B = 2 \cdot 10^{-12}$ cm^2, the external field $H = 0.5 \cdot 10^3$ *Oe*, the activation frequency $\omega = 8.79$ *GHz*, the interlayer exchange between A-B and B-A ferromagnetic layers respectively $A_{AB} = 1.35 \cdot 10^{-5}$ *cm* and $A_{BA} = 10^{-5}$ *cm*, the DMI value is zero and a width of the intermediate layer d is equal to $120 \cdot 10^{-7}$ *cm*. We assumed the amplitude of the incident wave to be unit $I_A = 1$.

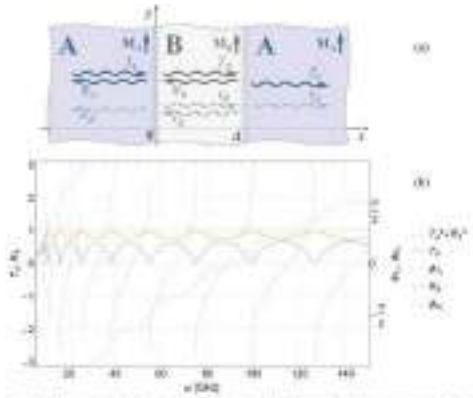

Fig. 1.(a) The geometry of the system: a ferromagnetic layer B sandwiched between same or finite ferromagnetic media A. (b) The amplitudes and argument of reflection (R_{++}, φ_{++}) and transmission (T_{++}, φ_{T++}) dependent on a frequency, respectively.

P397 - Tailoring the magnetodynamic properties of dipole coupled 1D magnonic crystals by shape anisotropy

15. Spin waves, magnonics, ultrafast magnetization dynamics and optically driven spin excitations

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We present magnetodynamic properties of dipolarly coupled 1D magnonic crystals (MCs) by Ferromagnetic resonance spectroscopy (FMR). We have studied the influence of static and dynamic dipolar coupling on the magnetodynamic properties in MCs through varying the lattice width and spacing. To this end, we have prepared two series of samples, one with stripes of fixed width (50 nm) and variable edge-to-edge separation - s = 50 – 500 nm and another one with fixed edge to edge separation (50 nm) and variable width - w = 50 – 300 nm. In these series switching from static to dynamic dipolar coupling is observed when the lattice width exceeds the lattice separation resulting in excitation of collective mode in latter in contrast to wire modes observed in the former. The static dipolar coupling field of the MCs has been extracted and a non-linear variation is observed with lattice separation. The coupling strength of dynamically coupled MCs is calculated from collective mode splitting and is found much higher than statically coupled MCs [1].

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P398 - Theory of ultrafast demagnetization and spin transfer torque in noncollinear spin valves

15. Spin waves, magnonics, ultrafast magnetization dynamics and optically driven spin excitations

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It has been shown that a femtosecond laser pulse can induce rapid demagnetization of a nickel thin film [1]. Mutual relaxation of electronic, spin and phononic subsystems can partially explain the ultrafast magnetic processes. However, recent theoretical and experimental results suggest that ultrafast demagnetization of conducting metals is a combination of more physical processes. A vast part of ultrafast demagnetization in metallic system can be explained by generation of spin-polarized currents of hot electrons excited by the laser pulse [2]. This effect can be described by means of superdiffusive spin-dependent transport model [3, 4]. The model solves equations of motion for hot electrons above the Fermi level moving through a metallic multilayer including spin-dependent scattering at the interfaces. The transport in the bulk is treated semiclassically taking into account spin and energy dependent electron velocities and lifetimes. Importantly, spin-polarized currents of hot electrons excited by a laser pulse can be potentially used as a mediator of spin momentum in spintronics. Experiments demonstrate that superdiffusive spin flow can not only reduce magnetization in a magnetic film but also exert spin transfer torque and induce magnetization dynamics. To this end, noncollinear magnetic configurations are necessary in order to generate spin transfer torque due to the hot electron flow. Such a configuration can be obtained in multilayer structures or in magnetic textures like domain walls.

We have studied the effect of ultrafast demagnetization in noncollinear magnetic configurations and spin transfer torque using generalized spin-dependent superdiffusive transport model [5]. We have shown that hot electron flow can sufficiently explain the magnetization dynamics observed experimentally. Moreover, formation of THz spin waves in the magnetic layer induced by hot electrons flow has been demonstrated via atomistic spin dynamics. More recently, we studied the angular dependence of ultrafast demagnetization and spin transfer torque in magnetic trilayers using rotation of the quantization axis between magnetic layers with noncollinear magnetic moments. The electronic transport between the magnetic layers has been described using energy and spin-dependent transmissions and reflections calculated via ab initio methods. We have shown that the angular dependence of demagnetization and spin torque action can be substantially modified via the trilayer geometry and materials. Moreover, we have simulated transport of hot electrons generated in a Neel domain wall. It is shown that spin transfer torque generated by a single femtosecond laser pulse is sufficient to shift a single Neel domain wall on a distance of few nanometers. This suggests that the average domain wall velocity reaches values of about 1 km/s.

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P399 - Transient and chaotic dynamics in strongly bound vortex pairs

15. Spin waves, magnonics, ultrafast magnetization dynamics and optically driven spin excitations

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We have previously shown that vertically stacked spin-vortex pairs, where core polarizations are parallel and the vortex chiralities are antiparallel (P-AP), with strong direct attraction between the cores, have two stable states -- the coupled state and the decoupled core-core states. In the coupled state the vortex cores are strongly bound by the attractive monopole-like force, and can rotate about their magnetic ``center-of-mass" with the rotational resonance frequency of the order of 1 GHz. In the decoupled state the two individual cores gyrate independently, with the gyrational resonance frequency of the order of 100 MHz.[Cherepov PRL 109, 097204 (2012)] The coupled state is generally stable in zero applied field, but can be stochastically decoupled by thermal agitation at elevated temperatures.[Bondarenko AIP 7, 056007 (2017)]

Lowering the temperature to 77~K suppresses the stochastic behaviour and uncovers the highly nonlinear intrinsic dynamics of the system. Our analysis shows that the decoupling of the two vortex cores is resonant and is enhanced by the presence of dynamic chaos. [Bondarenko PRB 99, 054402 (2019)] We detail the regions of the relevant parameter space, in which the various mechanisms of the resonant core-core dynamics are activated. We show that the presence of chaos can reduce the thermally induced spread in the decoupling time by up to two orders of magnitude.

We furthermore show that decoupling of the vortex cores is possible with low-amplitude field excitation of sub-nanosecond duration. The relevant vortex-core dynamics is presented. We also explain how the excitation's anharmonicity and phase control can be used to significantly speed up the decoupling process.[Holmgren APL 112, 192405 (2018)] This makes the P-AP vortex-pair interesting for oscillators, with the two intrinsic resonance frequencies separated by an order of magnitude, and where ultrafast low-power switching between the two oscillation regimes is possible.

P400 - Tuning spin-torque nano-oscillator nonlinearity using He^+ irradiation

15. Spin waves, magnonics, ultrafast magnetization dynamics and optically driven spin excitations

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Spin-torque nano-oscillators (STNOs) are promising candidates for nanoscale broadband microwave generators [1]. The STNO microwave signal properties, such as frequency, frequency tunability, linewidth, are mainly governed by the nonlinearity N [2]. Here we use He^+ irradiation to tune N of all-perpendicular [Co/Pd]-Cu-[Co/Ni] spin-valve STNOs. As [Co/Ni] free layer has the He^+ fluence-dependent perpendicular magnetic anisotropy H_k (so as the effective magnetization $\mu_0 M_{eff}$, $\mu_0 M_{eff} = \mu_0 M_s - \mu_0 H_k$), we tune M_{eff} by employing different fluences [3]. As a consequence, current-induced frequency tunability df/dI_{dc} are continuously engineered in Fig.1, indicating the tuned nonlinearity as $df/dI_{dc} \propto N$ [2]. We control N in an in-plane field from strongly positive to moderately negative as summarized in Fig.1f. As the STNO linewidth is a parabolic function of N [2], we can dramatically improve the linewidth by about two orders of magnitude by controlling $N0$. Our results are in good agreement with the theory for nonlinear auto-oscillators, confirm theoretical predictions of the role of nonlinearity, and demonstrate a straightforward path towards improving the microwave properties of STNOs [4].

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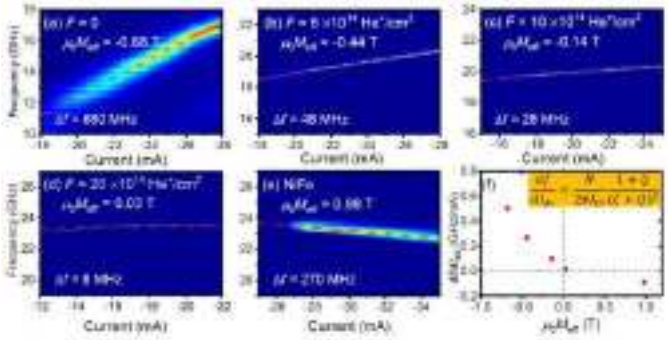

Fig 1. (a-e) The power spectral density (PSD) as functions of current (I_{dc}) in nano-contact(NC) STNOs with different He^+ irradiated fluences and nonirradiated NiFe free layer at in-plane field $\mu_0 H = 0.72$ T. The NC radii are 55 nm. The red dashed lines are the linear fits of the frequency. Δf indicates the minimal linewidth. Note that NiFe free layer in Fig.1e is utilized to provide higher M_{eff}. (f) The df/dI_{dc} (the slopes of linear fits in Fig. 1a-e) vs. $\mu_0 M_{eff}$.

P401 - Ultrafast Control of Spin Interactions in Honeycomb Antiferromagnetic Insulators

15. Spin waves, magnonics, ultrafast magnetization dynamics and optically driven spin excitations

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Light provides ultrafast, direct and non-thermal control of exchange and Dzyaloshinskii-Moriya interactions. We consider two-dimensional honeycomb lattices described by the Kane-Mele-Hubbard model at half-filling and in the strongly correlated limit, i.e. the Mott insulator regime of a canted antiferromagnet. Based on the Floquet theory, we demonstrate that changing the amplitude and frequency of polarized laser pulses, tunes the amplitude, the sign and even the ratio between the exchange and Dzyaloshinskiii-Moriya spin interactions. Furthermore, the renormalizations of the spin interactions are helicity independent. Our results pave the way for ultrafast optical spin manipulation in recently discovered two-dimensional magnetic materials.

P402 - Ultrafast demagnetization dynamics in half metallic Co2FeAl Hesuler alloys

15. Spin waves, magnonics, ultrafast magnetization dynamics and optically driven spin excitations

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Ultrafast demagnetization, an excitation of ferromagnetic material with an ultrashort laser pulse leading to the magnetization quenching on sub-picosecond timescales is one of the hot topics in magnetism[1]. Both theoretical and experimental efforts have been made to understand the origin of this phenomena for the last two decades[2,3]. One possible explanation for the conservation of angular momentum is the scattering of various quasi-particles which leads to transfer of angular momentum from the spin system to lattice system[3,4].

In this work, we have investigated element-specific magnetization dynamics in half-metallic Co_2FeAl (CFA) films using time-resolved magneto-optical Kerr effect (TR-MOKE). Half-metallic Heusler alloys can provide 100 % spin polarization around Fermi level E_F due to the band gap in one of the spin channels and are potential materials for spintronics devices[6]. The ultra-short pulses of extreme ultraviolet (EUV) photons in a broad energy range (35-72 eV) are produced using high harmonics generation (HHG) process. The use of these EUV photons for probing the magnetic materials provides elemental specificity and femtosecond time resolution. In half metals, slow demagnetization dynamics (t_M) are expected due to a band gap in minority spin channel which blocks the spin-flip scattering[5]. In CFA films, a similar demagnetization time (t_M) is observed for Fe and Co which does not depend on the degree of ordering and also has been reported in the previous studies[7]. However, our results show that remagnetization dynamics (t_R) proceeds slowly on a longer time scale and varies with the degree of structural ordering. We correlate these slow remagnetization dynamics with Gilbert damping. The first-principles electronic structure calculations show that Gilbert damping (a) decreases monotonously as the structural ordering evolves from A2 to B2 to $L2_1$ and strongly depends on the half-metallic character of the corresponding phase[8,9]. The atomistic spin dynamics simulations, based on the obtained values of damping, reproduce the observed changes in the remagnetization.

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P403 - Ultrafast demagnetization in [Co/Pd] multilayers probed with X-ray Absorption Spectroscopy

15. Spin waves, magnonics, ultrafast magnetization dynamics and optically driven spin excitations

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The microscopic origin of the ultrafast demagnetization process is a fundamental problem of modern magnetism that remains intensely debated more than 20 years after its discovery by Beaurepaire & al.[1] In the itinerant electron picture, the exchange-splitting and thus magnetization is reduced by localized spin-flip Stoner like excitations. On the contrary, in the Heisenberg picture of localized spins, delocalized spin fluctuations are generated, which reduce the long range magnetic order. In addition to the exchange interaction, the spin-orbit interaction mediating the dissipation of angular momentum to the lattice is also considered a key ingredient in the ultrafast demagnetization process. This complex phenomena calls thus for measurement techniques capable of probing the energy resolved charge, spin and the orbital moment dynamics on a femtosecond time scale.

Here we use soft X-ray Absorption Spectroscopy (XAS) with femtosecond X-rays produced by the Linac Coherent Light Source (LCLS) to probe charge and band structure dynamics around the Fermi energy in a [Co/Pd] magnetic multilayer. Comparing the X-ray Magnetic Circular Dichroism (XMCD) with the XAS, we further discuss the spin and orbital moment dynamics with respect to the energy resolved charge dynamics induced by the femtosecond pump laser. Comparing XAS changes at both L_3 and L_2 absorption edges below and above the Fermi energy highlights the role played by the $3d_{5/2}$ states in this system.

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P404 - Ultrafast demagnetization with terahertz and optical pump frequencies

15. Spin waves, magnonics, ultrafast magnetization dynamics and optically driven spin excitations

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Discovered more than 20 years ago [1], ultrafast demagnetization in ferromagnets is still a topic of extensive discussions [2, 3]. One open question is how the spin angular momentum transfer to the lattice depends on the nature of the photoexcited electron distribution (thermal vs nonthermal). Thus, new methods for investigation of the underlying microscopic processes are needed. A promising approach is to tune the electron distribution directly after excitation through variation of the photon energy. Low photon energies (in particular smaller than the thermal energy of 25 meV at 300 K) are expected to induce a transient distribution that enables a much smaller phase space for electron scattering than a distribution induced with optical photon energies (~1 eV). Here, we perform a direct comparison of the ultrafast magnetization dynamics in thin iron film following excitation with ultrashort optical (400 nm) and terahertz (1 THz) pump pulses [4-6]. Using a combination of different measurement and data analysis techniques [7] we extract the genuine time constants of ultrafast demagnetization for both pump photon energies.

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P405 - Ultrafast dynamics of the proximity-induced vs. intrinsic magnetism in CoPt alloys

15. Spin waves, magnonics, ultrafast magnetization dynamics and optically driven spin excitations

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Alloys and multilayer structures containing ferromagnetic transition metal atoms and elements such as Pt with large spin-orbit coupling are possible materials for novel storage devices. These ferromagnetic composites provide also an interesting playground for a fundamental understanding of ultrafast magnetism, all-optical switching, and the interplay between intrinsic and induced magnetic moments.

We performed an element-specific study on spin dynamics in CoPt alloys, with different Co and Pt concentrations. By employing the transverse magneto-optical Kerr spectroscopy in the range 40-72 eV, we are able to resonantly probe magnetic moments of each type of the atoms in the system and thus separate their responses, resolving any differences in the dynamics of Co and Pt atoms. The results show that despite the fact that Pt possess only induced magnetic moment, it is partially decoupled from Co, which is revealed by the distinct demagnetization rates and amplitudes observed in the experiments. Both subsystems demagnetize simultaneously only in case of strong optical excitation. While for the low pump fluence, Pt spins are significantly slower than Co. Overall, for all studied alloys, demagnetization rate was significantly improved comparing to pure Co. This can be explained by large spin-orbit coupling introduced by heavy Pt atoms.

We also report on unusual ultrafast enhancement of the magnetic state in some of the CoPt alloys. For these samples, an increase in magnetic moment to up to 130% of its static value was observed in 10-30 ps after the pump pulse. We attribute the enhancement to the magneto-volume effects as a result of local heating.

P406 - Ultrafast phonon dynamics in laser-excited nickel: quantification of electron-lattice interaction

15. Spin waves, magnonics, ultrafast magnetization dynamics and optically driven spin excitations

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The behavior of ferromagnets after laser excitation is governed by the interplay of electrons, lattice and spins. In the case of 3d-ferromagnets, strong coupling between electrons and spins leads to ultrafast demagnetization on the femtosecond time scale [1]. The lattice plays an important role in the magnetization dynamics, since it drains energy from the electrons on similar timescales. The electron-phonon coupling G_{ep} is an important parameter in models describing the microscopic energy flow, e.g. the microscopic three-temperature model [2] or atomistic spin simulations based on the two-temperature model (TTM). However, literature values of G_{ep} for nickel vary widely [2] [3], and the information available on the lattice response was mostly obtained indirectly from optical techniques [4].

In this work, we study the lattice response of nickel directly using femtosecond electron diffraction (FED). We present FED results for a variety of excitation conditions. We compare the experimental results to spin-resolved DFT calculations of G_{ep} in combination with a TTM. While a regular TTM cannot describe the experimental results, good agreement is achieved for a modified TTM assuming strong coupling between electrons and spins. Our results suggest that the non-equilibrium dynamics in laser-excited nickel is governed by highly efficient energy transfer to both the spin as well as lattice degrees of freedom.

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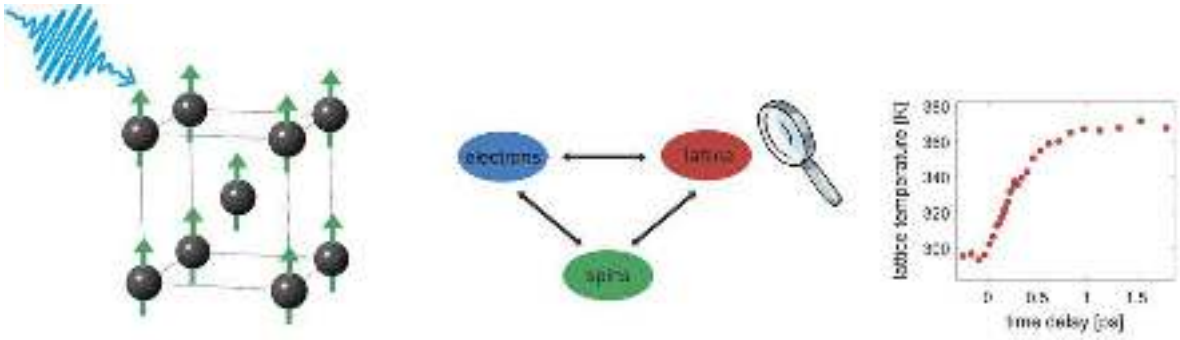

P407 - Ultrafast Probing of Anisotropic Magnetoresistance from 0 to 25 THz

15. Spin waves, magnonics, ultrafast magnetization dynamics and optically driven spin excitations

Lukáš Nadvorník[1, 2] , ***Martin Borchert***[1, 2, 3], *Liane Brandt*[4], *Richard Schlitz*[5], *Gerhard Jakob*[6], *Mathias Kläui*[6], *Sebastian Gönnenwein*[5], *Martin Wolf*[2], *Georg Woltersdorf*[4], *Tobias Kampfrath*[1, 2]

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Spin dependent scattering effects give rise to the anisotropic magnetoresistance (AMR) effect, where the conductivity of magnetic materials depends on the angle in between the direction of the applied electric field and the magnetic order parameter [1]. Consequently, the AMR effect is routinely used to detect magnetic order of ferromagnets, ferrimagnets and even antiferromagnets [2]. In this contribution, we aim at pushing the AMR effect beyond the bandwidth of conventional electronics (<10 GHz), by ultrafast measurements throughout the entire terahertz (THz) range. Detection relies on polarization-resolved THz transmission experiments using a femtosecond-laser-driven table-top THz setup. We measure the AMR effect of various common magnetic materials from 0.2 to 28 THz and compare the results to conventional DC measurements. Agreement between DC and the low-frequency part of the THz measurements is excellent. The broad frequency range allows us to analyze the non-trivial frequency dependence of the magnitude of the AMR effect and to compare it to the frequency response of scattering processes described by the Drude model. Our results show that THz pulses can be used as an ultrafast probe of magnetic order.

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P408 - Ultrafast spin and charge accumulation in magnetic thin films driven by terahertz pulses

15. Spin waves, magnonics, ultrafast magnetization dynamics and optically driven spin excitations

Julius Heitz[1, 2] , *Lukáš Nádvorník*[1, 2], *Tom Seifert*[3], *Yannic Behovits*[1, 2], *Alexander Chekhov*[1, 2], *Martin Wolf*[2], *Tobias Kampfrath*[1, 2]

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Magnetization reversal by spin-transfer torque [1], giant magnetoresistance [2] and the emission of terahertz (THz) radiation [3] are intriguing spintronic applications, each of which relies on well-controlled generation and manipulation of spin currents. The established methods to convert charge currents to spin currents are the anomalous and spin Hall effects (AHE, SHE), whose inverse were demonstrated recently up to THz frequencies [3]. This makes them excellent candidates to extend the bandwidth of spin information processing into the THz range. However, so far no direct observation of AHE-related ultrafast spin accumulation at sample interfaces has been reported. In this contribution, we study the interaction of ultrashort intense THz pulses with magnetic thin films. In our experiment, the strong THz electric field (up to ~0.5 MV/cm) is used to drive ultrafast charge currents in the plane of the structure. We make use of a time-resolved magnetooptical probe to monitor to what extent such an excitation can lead to ultrafast out-of-plane spin and charge redistribution.

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P409 - YIG/n-InSb spin waves detector for magnon spintronics

15. Spin waves, magnonics, ultrafast magnetization dynamics and optically driven spin excitations

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Detection of the spin waves (SW) in "conductor - magnetic dielectric" structures are interesting for information processing systems based on magnon spintronics [1]. In order to convert the spin current associated with the SW propagating in such a magnetic material as yttrium iron garnet (YIG) films into the electric current one can use a heavy metal with the strong spin-orbit (SO) coupling placed in the contact with YIG. Also, effects of the dc voltage (U) generation by propagating SW in hybrid structures composed of YIG and semiconductor, such as InSb which has the strongest SO coupling, can be utilized to detect the SW [2]. In this work, we study effects of the magnetostatic surface waves (MSSW) propagation and detection in YIG/n-InSb microstructure with the thickness (d) and planar dimensions of the semiconductor element that is less than in [2] by the orders and with the antennas for the MSSW excitation integrated directly on the YIG surface.

Polycrystalline n-InSb microstripes (Fig. a) with d≈0.5 μm, width b≈100 μm and length L≈200 μm were formed on the top of the epitaxial YIG film (d≈8 μm) by thermal evaporation, photolithography and ion etching. The Hall mobility and electron concentration of n-InSb were $\mu_e \approx 20000$ cm^2/V•s and $n_e \approx 5.8 \cdot 10^{16}$ cm^{-3}, respectively. Microstripe antennas for the SW excitation and detection in YIG were also fabricated directly on the YIG surface using magnetron sputtering, photolithography and ion etching.

SW transmission measurements were done using a vector network analyzer along with a microwave probe station for in-plane magnetic field 100 Oe<H<2000 Oe applied along the antennas that corresponds to the excitation of MSSW (Fig. b). DC voltage U(f) generated at the edges of the InSb stripes due to the MSSW propagation was measured in carrier modulation (100 kHz) mode in order to separate the thermal voltage induced by the microwave heating of InSb and inertialess effects associated with the transfer of the MSSW impulse to the electrons of InSb.

We found that InSb in our structures introduces an additional electronic losses for MSSW of the order of k"=Im k≈2-5 cm^{-1}, while dispersion k=k(f) remains unchanged in comparison with structures without InSb. For the MSSW power P less than threshold of the parametric instability processes, U(f) was proportional to P: U(f)=G(f)P(f). The sensitivity G increased with the increase of MSSW wave-number k and reached maximum values at frequencies corresponding to the upper limit of the MSSW bandwidth (Fig c). The sensitivity for the studied structure in linear regime was found to be as high as G≈0.02 V/W. It abruptly dropped as the power exceeded the three-magnon parametric instability threshold.

The work supported by the RFBR project 16-29-14058.

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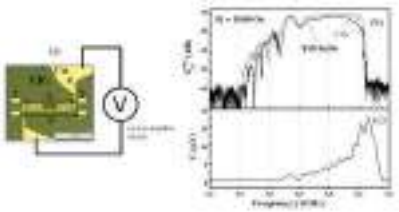

16. Magnetotransport, spintronics, spin orbitronics and spin caloritronics.

P410 - Ab-Initio Computational Study of the Magnetic Properties of Boron Carbon Nitrogen Nanoribbon

16. Magnetotransport, spintronics, spin orbitronics and spin caloritronics.

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The field of spintronics has been continuously attracting researchers. Efforts have been made in the quest to find good candidates for spintronic devices. One particular type of material called graphene is under extensive study as a feasible component for spintronic applications in room temperature. Pristine graphene, however, is diamagnetic. Thus, a lot of research has been performed to modify the graphene-based structure to achieve meaningful magnetic properties. A new type of graphene-based one-dimensional material called Boron Carbon Nitrogen Nanoribbon (BCNNR) has been of interest due to the theoretical predictions that it shows half-metallic property. Here we present the results of a computational study of Mn-doped zigzag BCNNR with different width, the objective of which is to determine whether the presence of Mn-dopants will give rise to ferromagnetism and what type of conditions must be met for the stability of the magnetism to be preserved. We have found that the concentration and the atomic distance among the dopants would affect the magnetic ordering of this type of material. These results would provide a meaningful theoretical prediction of Mn-doped BCNNR as a basic candidate of future spintronic materials.

P411 - Anisotropic magnetoresistance of tetragonal CuMnAs single crystal

16. Magnetotransport, spintronics, spin orbitronics and spin caloritronics.

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The Emerging field of antiferromagnetic (AFM) spintronics is drawing a lot of attention due to promising applications in storage devices [1]. One of the promising materials is an AFM metal CuMnAs. Its transport properties have been mostly studied on thin films. So far the main focus has been on spin-orbit torque, allowing for a selective manipulation of magnetic moments in the AFM [2]. This amounts to an effective writing of information. As a method for readout, anisotropic magnetoresistance (AMR) is being used (although little explored), giving different readout signals for two orthogonal orientation of magnetic moments. In this work, we explore resistivity and AMR in a geometry which overcomes the limitations of thin films.

To this end, we have prepared a transport device out of a bulk single crystal grain of tetragonal CuMnAs [3] using Focused Ion Beam micromachining (FIB, see Fig. 1a). This technique, allowing for precise control over sample geometry, lets us measure resisitivity along arbitrary crystallographic directions. For the first time, we report temperature dependence of both in-plane and out-of-plane resistivity, uncovering large structural transport anisotropy between both principal crystallographic axes. This is further discussed in the context of *ab initio* calculations assuming various types of impurities in our samples.

The AMR measurement in magnetic field **B** with rotation of the sample around the c-axis (out-of-plane direction) shows only moderate response (~0.1 %) to **B** with saturation at around 6 T (see Fig. 1b). In the first approximation, we could describe the dependence of the change of resistivity on the direction of **B** as $\Delta\rho(\theta) \sim \cos(2\theta)$ where θ is the angle between the a-axis and **B**. However, we observe a tilt of the peaks towards higher θ for temperatures above 300 K (Fig 1b) and to the lower θ for temperatures under 300 K. This behaviour is discussed by means of the Stoner–Wohlfarth model for AFM suggesting an uniaxial magnetic anisotropy not pointing along any principal crystallographic axis. In addition, the calculated AMR values tend to be larger than experimental data, suggesting a multidomain character of the sample.

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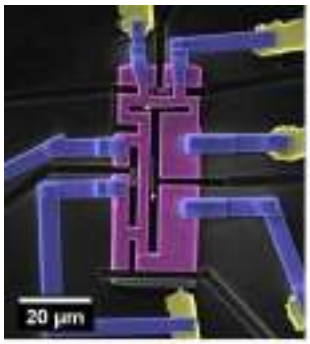

Fig 1a: Transport device (purple) of tetragonal CuMnAs single crystal prepared by FIB. Device is conductively connected to a Au contact pads (yellow) by an Ia-CVD Pt (blue).

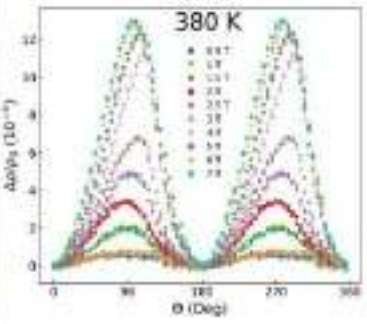

Fig 1b: Anisotropic magnetoresistance at 380 K in various magnetic fields.

P412 - Anomalous Hall effect in topological antiferromagnets

16. Magnetotransport, spintronics, spin orbitronics and spin caloritronics.

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Quantum Anomalous Hall effect has been recently demonstrated to emerge in certain classes of co-planar antiferromagnets possessing spin-orbit coupling. In this work, we investigate the emergence of both quantum anomalous Hall and disorder-induced Anderson Chern insulating phases in two dimensional hexagonal lattices, with non-trivial antiferromagnetically ordered 3D magnetic state and in the absence of spin-orbit coupling. Using tight-binding modeling of topological antiferromagnets, we study the transport properties and the band structure and show that such systems display not only a spin-polarized edge-localized current, but also an impurity-induced transition from trivial metallic to topological insulating regimes, through one edge mode plateau. We compute the gaps' phase diagrams due to the consideration of a second nearest neighbours , and demonstrate the robustness of the edge channel against deformation and disorder.

P413 - Antiferromagnetic CuMnAs: Ab initio description of finite temperature magnetism and resistivities

16. Magnetotransport, spintronics, spin orbitronics and spin caloritronics.

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Ab initio treatment of finite temperatures is a complicated task, especially when dealing with a complex multi-sublattice materials such as antiferromagnets (AFM). We will present calculated results for temperature-depended electrical resistivity in tetragonal CuMnAs and we will discuss different scattering mechanisms (phonons, magnons, and alloying). The theoretical research is supported by data measured for this multicomponent bulk AFM and agree well with experiments.

The alloy analogy model (AAM) within the tight-binding linear-muffin-tin orbital method with the coherent potential approximation [1,2] was used. Previously, the same technique was successfully employed, e.g., for multi-sublattice half-Heusler ferromagnet NiMnSb with temperature-induced magnetic disorder [3]. The fully-relativistic framework and a description of the non-collinear magnetic moments is needed for our study, as well as the LDA+U approach.

Not only the AAM reproduces correctly experimental data but the calculated results also clarify characteristics of tetragonal CuMnAs grown by solid-state reaction [4]. Calculated in-plane and out-of-plane resistivities and their anisotropy helped to identify, that the samples are supposed to have about 10 % of Cu impurities on the Mn sublattice. The finite-temperature calculations with properly described both phonons and magnons were essential for this purpose, because measured residual resistivities could correspond to various impurities [5] but the alloying influences extremely the temperature-dependent resistivities.

The role of the spin fluctuations is significant close to the Néel temperature. Our preliminary data in Fig. 1 show increasing resistivities, both in-plane and out-of-plane, when the model of tilted moments [3] describes the spin disorder. The increase is mostly monotonic and the anisotropy is larger for nonzero U. More detailed analysis will be presented.

Moreover, we will present technical details of our methods. The Hubbard U for this AFM is still not known precisely [6] but the anisotropy of resistivities and finite-temperature results also depend on U; therefore, our data clarify also its value. Based on the successful treatment of this multi-sublattice AFM by the AAM, our framework can be further used even for more complex spintronic materials.

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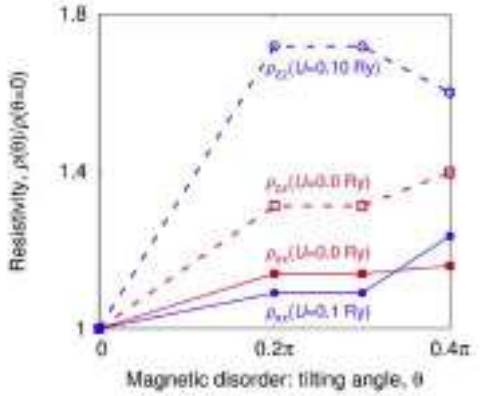
1.8
1.4
1
Resistivity, ρ(θ)/ρ(θ=0)
ρ_{zz}(U=0.10 Ry)
ρ_{zz}(U=0.0 Ry)
ρ_{xx}(U=0.0 Ry)
ρ_{xx}(U=0.1 Ry)
0
0.2π
0.4π
Magnetic disorder: tilting angle, θ

P414 - Antiferromagnetic spin Seebeck effect near the Neel point

16. Magnetotransport, spintronics, spin orbitronics and spin caloritronics.

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Thermal spin injection from an insulating magnet to the adjacent heavy metal is referred to as spin Seebeck effect (SSE), in which the thermally excited magnons play the central role in carrying spin angular momenta [1]. So far the SSE has been observed in several ferrimagnetic insulators [2], but recently it was demonstrated that the SSE can be observed even in antiferromagnetic insulators under magnetic fields [3, 4].

In Ref. [4], the antiferromagnetic SSE in MnF_2 was measured over a wide range of temperatures including the Neel point T_N, and it was found that the SSE signal is roughly proportional to the external magnetic field. On theory side, existing publications are based on the Holstein-Primakoff bosons, which are justified only at low enough temperatures $T << T_N$ [5,6]. Therefore, it is of vital importance to develop a theory of the antiferromagnetic SSE at elevated temperatures.

Here we develop a theory of the antiferromagnetic SSE near T_N. To this end, we use a time-dependent Ginzburg-Landau (TDGL) model [7], whose applicability near T_N has been established in the field of dynamic critical phenomena. Starting from the TDGL equation for an antiferromagnetic insulator (AFI) with uniaxial anisotropy and thermal noise field satisfying fluctuation-dissipation theorem, we calculate the antiferromagnetic SSE near T_N, and found that the signal is proportional to both the AFI spin susceptibility and the external magnetic field.

The present result predicts that a cusp structure of AFI's spin susceptibility near T_N should also appear in the antiferromagnetic SSE signal.

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P415 - Colossal Magnetoresistance in La-doped EuTiO3

16. Magnetotransport, spintronics, spin orbitronics and spin caloritronics.

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The discovery of colossal magnetoresistance in divalent cation substituted manganites ($R_{1-x}Sr_xMnO_3$ where R = La, Nd etc) in late 80's caused a surge of interest in magnetoresistance of other transition metal oxides[1]. Colossal magnetoresistace in manganites usually occurs around the paramagnetic -ferromagnetic phase boundary or ferroamgnetic-antiferromagentic phase boundaries. On the other hand, colossal magnetoresistance of magnitude 60-90 % in a field of 7 T occurs in the cluster glass state of $La_{1-x}Sr_xCoO_3$ (x = 0.15-0.17) [2]. Magnetoresistance of other preovskites oxides having magnetic ions such as Cr, Ru, Mn, and Fe are much smaller (typically < 1-3 %). Magnetoresistance in Ti-based oxides (Titanates) are very few. $EuTiO_3$ is a rare titanate because Eu ion is divalent unlike trivalent state possed by other rare earth ions such as R = La, Pr, Nd etc. The observation of magnetodielectric effect in $EuTiO_3$ rekindled recent interest in this material[3]. More recently, topological Hall effect has been reported [4].The antiferromagnetic insulating $EuTiO_3$ becomes ferromagnetic metallic upon partial substitution of La^{3+} for Eu^{2+}. We have carried out a systematic investigation o magnetism and magnetoresistance in $Eu_{1-x}La_xTiO_3$ (x = 0- 0.1). Our results show that the magnetoresistance has negative sign and has huge value (~ 60 % in 0.5 T) in 1 % La-doped $EuTiO_3$.[5] As the La content increases, the negative magnetoresistance systematically decreases in magnitude and its sign turns into positive. We discuss possible mechanisms of negative colossal magnetoresistance and transformation in the sign of magnetoresistance with La content.

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P416 - Comparison of Spin Hall Angles for Epitaxial and Polycrystalline Platinum Thin Films

16. Magnetotransport, spintronics, spin orbitronics and spin caloritronics.

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Platinum (Pt) is widely used in pure spin current spintronics and one of the most studied spin Hall material. The first attempt to make a quantitative measurement of the spin Hall angle (θ_{SH}) for Pt was reported by Kimura et al.[1]. However, different values of the θ_{SH} have also been reported by other groups. The origin of the dispersed θ_{SH} values has not been understood until recent experimental report[2], where different polycrystalline Pt resistivity is one of the main reasons for the spread of θ_{SH} values. The contribution of extrinsic spin Hall effect mechanism in Pt is enhanced by impurities, leading to a higher θ_{SH} value and lower electrical conductivity. On the other hand, for single crystalline platinum with higher conductance than polycrystalline platinum, it is ambiguous how θ_{SH} values change. To understand the large difference in θ_{SH} values, the effect of crystallinity on θ_{SH} values is indispensable. In this work, we have studied both epitaxial and polycrystalline Pt films to clarify the effect of crystallinity on the spin Hall properties.

In Our study, Pt thin films on both sapphire and Si/SiO_x substrates were fabricated using the magnetron sputtering at a substrate temperature of 550°C. The crystallographic structure of Pt thin films was measured by x-ray diffraction (XRD). We then studied the spin Hall magnetoresisitance (SMR)[3] in the $Pt/Co/AlO_x$ multilayers to estimate the θ_{SH} for the epitaxial Pt . These multilayers were patterned in the form of a Hall bar (Figure 1) with 30 µm × 100 µm by using photolithography and milling process. Moreover, we have also performed spin pumping measurements in the epitaxial $Pt/Ni_{80}Fe_{20}$ multilayers, and we compare these results with the SMR results.

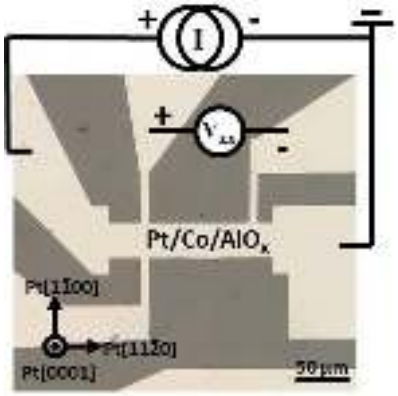

Figure 1: Optical microscopy image of the Hall bar.

P417 - Controllable excitation of quasi-linear and bullet modes in a spin-Hall nano-oscillator

16. Magnetotransport, spintronics, spin orbitronics and spin caloritronics.

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The ability of the spin-Hall effect to generate spin currents in a simple thin-film geometry has facilitated the development of a variety of spin-Hall nano-oscillator (SHNO) configurations. Two fundamentally different auto-oscillation modes were observed in SHNOs, depending on the geometry and the experimental conditions. The quasi-linear mode continuously evolves from the linear eigenmodes of the magnetic system. In contrast, the self-localized bullet mode does not evolve from the linear spectrum but is instead abruptly spontaneously formed at the auto-oscillation onset. Only one of these modes is typically dominant in SHNOs demonstrated so far, even though the other mode may appear under special conditions whose significance is not yet well understood. Since the two modes exhibit substantially different oscillation characteristics, beneficial for different specific applications, it is highly desirable to identify the mechanisms controlling the preferential formation of each of these modes and develop approaches to control them.

Here, we experimentally demonstrate a spin-Hall nano-oscillator that enables controllable excitation of the quasi-linear and bullet dynamical modes. This is facilitated by the injection of spin current into an extended region of the active magnetic film, avoiding the conditions that result in the preferential formation of the bullet mode. Thanks to the ability to excite these fundamentally different modes in the same device, we were able to directly compare their spatial and temporal characteristics and show that the operation of the SHNOs in the regime of quasi-linear mode oscillations is favorable for the generation of short microwave pulses, while the bullet-mode regime is limited in this respect by the significant time required for the formation of this dynamical state. Our results provide insight into the dynamical mechanisms relevant to the practical applications of SHNOs as nano-scale microwave sources.

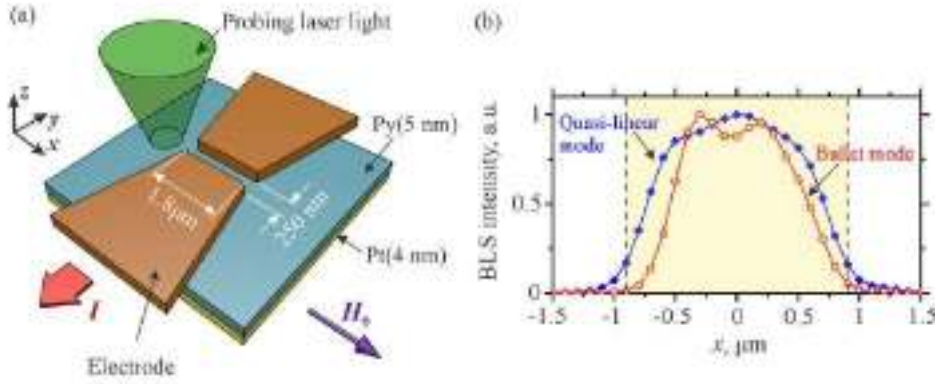

Figure: (a) Schematic of the experiment. (b) Spatial profiles of the quasi-linear and bullet modes. The shadowed area shows the region of the nano-gap.

P418 - Correlation between charge ordering and quantum effects in heterovalent substituted hexaferrites

16. Magnetotransport, spintronics, spin orbitronics and spin caloritronics.

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[3] National University of Science and Technology MISiS, Russia
[4] Imam Abdulrahman Bin Faisal University, Saudi Arabia

Nd,Zn- and Ti-substituted hexaferrites were produced. The behaviour of the lattice parameters as function of the composition can be described by differences in the ionic radii between Fe^{3+} (0.64 Å) and Nd^{3+} (0.98 Å), Zn^{2+} (0.74 Å) and Ti^{4+} (0.42 Å). Anomalous behavior of the frequency dependences of the permittivity and permeability for $Sr(Nd,Zn)_xFe_{12-x}O_{19}$ ($0.1 \leq x \leq 1.0$) samples was observed. Presence of second peaks for compounds with x=0.1 and 0.9 confirms double oxidation state for iron ions. In addition, theoretically this can confirm our assumption for charge disproportionation for compounds x=0.3, 0.5 and 0.7 under the influence of the crystal field energy. Moreover, if for compositions 0.1 and 0.9, there is a clear second peak, which can correspond to the charge state Fe^{4+}. For other compounds (x=0.3, 0.5 and 0.7), the absence of a clear second peak may be due to the charge disproportionation of a part of Fe^{4+} under the influence of the crystal field energy. This phenomenon is a kind of charge ordering in multicomponent oxides based on transition metals ions with a high oxidation degree such as Fe^{4+} ($3d^4$). In such materials with a temperature change can observe the charge redistribution between equivalent crystallographic positions (according to the following scheme: $2Fe^{4+}=Fe^{3+}+Fe^{5+}$). The peculiarities of the non-linear behavior of permeability for $BaFe_{12-x}Ti_xO_{19}$ ($0.1 < x < 1.0$) samples with a mixed valence state of iron theoretically can be described by the effect of the spin states crossover. Diamagnetic substitution lead to transformation in magnetic structures due to frustration. This changes the field of magnetocrystalline anisotropy and the electromagnetic characteristics. Reflection losses as function of the frequency for all $Sr(Nd,Zn)_xFe_{12-x}O_{19}$ and $BaFe_{12-x}Ti_xO_{19}$ ($0.1 \leq x \leq 1.0$) samples was measured. A deep reflection minimum was observed in the frequency range of 8-15 GHz due to intense EMR weakening caused by NFMR. It was demonstrated that the values of not strongly correlates with the level of substitution for $Sr(Nd,Zn)_xFe_{12-x}O_{19}$ samples and correlates well for $BaFe_{12-x}Ti_xO_{19}$ samples. If for $Sr(Nd,Zn)_xFe_{12-x}O_{19}$ ($0.1 \leq x \leq 1.0$) samples was observed only one peak for $BaFe_{12-x}Ti_xO_{19}$ (x=0.5 and 1.0) samples we observed presence of second peak. At the same time for Ti-substituted sample with lowest concentration (x=0.1) it was determined oly one broad peak. This can be assumed that presence of the second peak can be result of mixed valence state of iron ions (Fe^{3+}-Fe^{2+}). And if for compounds with x=0.5 and x=1.0 second peak has clearly seen. For x=0.1 broad peak may be result of two peaks (with low intensity) overleaping. It must be noted that average width () for Ti-substituted samples decrease with increase of Ti^{4+} ions content. Intensity of the RL peaks () increase with increase of Ti^{4+} ions content. This can be explained by the features of the indirect exchange interactions in $BaFe_{12-x}Ti_xO_{19}$ ($0.1 \leq x \leq 1.0$) samples with the mixed valence state of iron ions. An increase in the concentration of titanium ions leads to an increase in the concentration of bivalent iron (Fe^{2+}). This enhances the interlattice double exchange between Fe^{2+}-O-$Fe^{3+}$and the intra lattice superexchange interactions Fe^{3+}-O-Fe^{3+}

P419 - Dzyaloshinskii-Moriya interaction and spin-orbit torque in Co/Gd/Pt ferrimagnetic multilayers

16. Magnetotransport, spintronics, spin orbitronics and spin caloritronics.

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The author has chosen not to publicise the abstract.

Field 5

Field 6

P420 - Evaluation of Gilbert damping in magnetic wires on LiNbO3 using rectifying effect

16. Magnetotransport, spintronics, spin orbitronics and spin caloritronics.

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1 University of Hyogo
2 Korea Advanced Institute of Science and Technology
3 RIKEN
4 Japan Synchrotron Radiation Research Institute
5 Gifu University

The study of magnetic domain in laterally confined micro/nano-structures can offer an ideal system to understand the basic physical mechanism on magnetism as well as to be development of magnetic devices such as non-volatile magnetic random access memory and microwave devices. Recently, some artificial nano/microscale magnets with heterojunctions have been investigated for their possible multifunctionality and controllability. In a Ni wire fabricated on $LiNbO_3$ substrate, an uniaxial magnetic anisotropy was found to be spontaneously induced and stripe domain structure was formed when the longitudinal axis of Ni wire was placed on the direction of X-axis direction of $LiNbO_3$. [1] The uniaxial magnetic anisotropy induced by the heterojunction might contribute the modulation of magnetization dynamics. The rectifying electric ferromagnetic resonance spectroscopy helps investigate the magnetization dynamics in this system. In this study, to understand the heterojunction-induced effect for the magnetization dynamics, we measured the rectifying spectroscopy and evaluated the damping factor.

We fabricated a system comprising various thick Ni, NiCu, and Fe-based alloy metallic wires onto a single crystalline Y-cut 128 $LiNbO_3$ substrate by using electron-beam lithography and lift-off process. The wire is placed at the center strip line of the coplanar waveguide electrode (CPW) consisting of Cr (5 nm)/Au (80 nm). We measured the rectifying spectra through the GSG-type microwave probe connected to the CPW electrode as shown in Fig. 1(a). The coordinate axes are defined in Fig. 1(a).

In Ni wire, we found that the magnetic field angle dependence of rectifying voltage amplitude was proportional to $\sin 2\varphi \cos\varphi$ when the applied magnetic fields were enough to force the magnetization to direct along the magnetic field direction as shown in Fig. 1(b). Here, φ is the angle between the applied magnetic field direction and longitudinal axis of the wire. The voltage amplitude is peak-to-peak voltage as defined in the inset of Fig. 1(b). Next, we evaluate the damping factors from the full width at half maximum (FWHM) of the obtained rectifying spectra. The estimated damping factor, a, are shown in the inset of Fig. 1(b). As a result, the estimated damping factor of Ni deposited on $LiNbO_3$ substrate was enlarged comparing with the value of other bulk case measured at room temperature. These results are attributed to that the heterojunction might induce the lattice distortion in the Ni layer and damping factor is enlarged by the magnetoelastic or magnetostriction-induced modulation of spin-orbit and crystalline anisotropy. [2 – 4]

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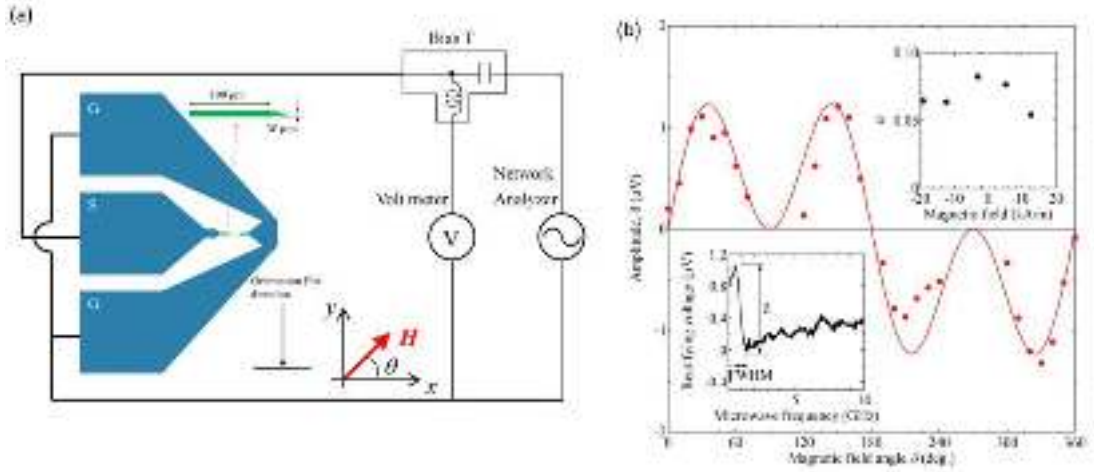
(a)
Bias T
Network Analyzer
Volt meter
V
H
θ
x
y
(b)
Amplitude, A (uV)
Magnetic field angle, θ (deg.)
Microwave frequency (GHz)

P421 - Evaluation of spin Seebeck coefficients in CoFe/Pt and CoFeB/Pt alloy multilayers

16. Magnetotransport, spintronics, spin orbitronics and spin caloritronics.

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The spin Seebeck effect (SSE) is a recently discovered phenomena where a spin current, J_S, arises when a thermal gradient is applied to a magnetic layer [1]. This spin polarised current results in a voltage via the inverse spin Hall effect (V_{ISHE}) if a paramagnetic contact with strong spin-orbit coupling, such as Pt is deposited on top of the magnetic layer [2]. The SSE is being investigated as a promising candidate for spintronic and energy harvesting applications [3], however, when the magnetic layer is conducting, the anomalous Nernst effect (ANE) also contributes to the measured V_{ISHE} [4]. It is therefore essential to identify the different contributions to the measured V_{ISHE} so that we can investigate the impact of each of these on the potential applications of the SSE (such as thermoelectric efficiency of an energy harvesting device).

In this study, we consider sputtered FM/Pt bi-layer thin films where FM=$Co_{50}Fe_{50}$, $Co_xFe_{80-x}B_{20}$ (x=20 and 40) for improved thermoelectric performance. We present measurements of V_{ISHE} using a setup similar to Sola *et. al*. [5] where a temperature gradient is applied normal to the film surface and V_{ISHE} is measured as a function of magnetic field (shown in the figure).

We extract different SSE coefficients for the alloys and compare to previous work on $Co_{20}Fe_{60}B_{20}$ [6]. These include the most common coefficient $S_{\nabla T}$ (where V_{ISHE} is normalized by temperature gradient ∇T) and the heat flux coefficient S_{JQ} (where V_{ISHE} is normalized by the heat flux J_Q), which has been shown to be more reliable for thin films [5]. We show that when S_{JQ} is normalized by the resistivity of the bilayer film to account for the differences in the Pt layers – to obtain the SSE coefficient $S_{JQ\rho}$ -$Co_{20}Fe_{60}B_{20}$ shows the largest thermoelectric response at almost three times the other alloys (shown in the table). We argue in this case, the increased response may be due to the decreased spin wave damping in $Co_{20}Fe_{60}B_{20}$ [7]. Finally, we compare these results to measurements of the bare thin films (without the Pt layer) to disentangle the ANE from the SSE contributions.

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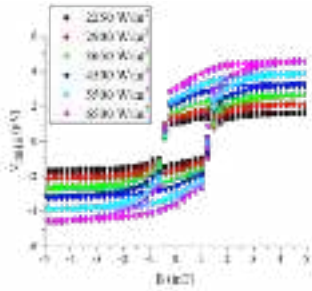

Sample	S_{YI} (nV/K)	S_{JQ} (nVm/W)	$S_{JQ\rho}$ (mV/WΩ)
$Co_{40}Fe_{40}Pt$	2.53 ± 0.14	11.32 ± 0.86	33.81 ± 2.58
$Co_{41}Fe_{41}B_{18}/Pt$	8.64 ± 0.48	55.38 ± 0.42	22.82 ± 1.73
$Co_{23}Fe_{63}B_{20}/Pt$	26.39 ± 1.67	91.18 ± 0.74	88.32 ± 7.17

(Left) : Raw SSE voltage, V_{SHE} as a function of applied magnetic field for different temperature gradients $J_Q = \kappa\nabla T$ for $Co_{23}Fe_{63}B_{20}/Pt$. The coercivity is almost 2 mT. (Right) : The values of the different SSE coefficients showing the highest response for $Co_{23}Fe_{63}B_{20}/Pt$.

P422 - Ferroelectric control of spin physics within the Rashba semiconductor GeTe

16. Magnetotransport, spintronics, spin orbitronics and spin caloritronics.

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In the compelling quest for multifunctionality inside electronic devices, the spin degree of freedom promises to play a key role. An increasing number of compounds with broken inversion symmetry and strong spin-orbit coupling shows peculiar spin textures in the band structure. Among them, ferroelectrics allow for a *non-volatile inversion of the spin texture through their reversible spontaneous ferroelectric polarization*. Such functionality holds potential for technological applications exploiting spin effects controlled by electric fields.

Ferroelectric Rashba semiconductors [1] are characterized by the ferroelectric switchability of their Rashba spin texture, and the semiconductivity of these compounds could enable the realization of a new generation of memories, transistors and neuromorphic elements based on the non-volatile electric control of either charge or spin transport. We refer to Germanium Telluride as father compound of ferroelectric Rashba semiconductors [2].

By using spin- and angle-resolved photoemission spectroscopy, we have already demonstrated the existence of two opposite spin textures in GeTe, corresponding to opposite ferroelectric states [3, 4]. In this work, we provide a proof of the *ferroelectric switchability of bulk GeTe through gate electrodes*, essential to obtain GeTe-based devices. Surprisingly, the ferroelectric switching is achievable despite the effective field screening expected in semiconductors. The relatively high conductivity of the material impedes the use of characterization techniques employed for common ferroelectric oxides. For this reason, the polarization switching was measured as resistance variation of metal/GeTe heterojunctions induced by the application of short voltage pulses and ascribed to the different local band bending in the semiconductor due to the screening of the polarization charge. Piezoresponse Force Microscopy was used to correlate the microscopic distribution of ferroelectric domains underneath the gate with the electrical resistivity of the junction. The ferroelectric switching of GeTe offers a modulation of resistance up to 300%. The switching is robust, with endurance up to 10^5 cycles. Ferroelectric minor loops permit to obtain the quasi-continuum of intermediate states typical of memristors.

The ferroelectric control of the spin texture is expected to reflect in the *tunability of spin transport properties*. Here we show sizable spin-to-charge interconversion in GeTe. The spin Hall effect in GeTe is investigated by exploiting the unidirectional spin Hall magnetoresistance [5]. The tunability of the inverse spin Hall effect is studied by spin pumping measurements in Fe/GeTe heterostructures [6].

With the possibility of crafting the spin texture of GeTe down to the nanoscale [4], this work could pave the way to the implementation of fully reconfigurable computing devices based on both spin and charge transport in multifunctional semiconductors.

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P423 - Growth and Characterisation of Antiferromagnetic CuMnAs Thin Films

16. Magnetotransport, spintronics, spin orbitronics and spin caloritronics.

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The antiferromagnet (AF) CuMnAs was the first to exhibit electrical switching via Néel order spin orbit torques (NSOTs).[1] Since this observation there has been a great deal of interest in potential applications for memory and logical processing devices. Such devices would benefit from insensitivity to external magnetic fields, an absence of stray-field constraints and terahertz spin control.[2] The tetragonal phase of CuMnAs has proven a useful test material for AF spintronics because its magnetic ordering breaks inversion symmetry within the unit cell giving rise to NSOTs, it can be grown epitaxially on GaAs and GaP and has a relatively high Néel temperature of around 480K.[3] However, a significant lattice mismatch with GaAs of almost 6% and scarcity of high quality GaP substrates has presented challenges to growth via molecularbeam epitaxy. It is possible to incorporate other group V elements such as P and Sb to compete with As for the group V lattice site, which will alter the lattice constant. Based on previous studies of CuMnP and half Heusler alloy, CuMnSb it will also be possible to tune the band structure and Néel temperature.[4, 5] These properties can be characterised via in-situ RHEED, XRD, SQUID and transport measurements. Presented here are the steps for growth and results from the study of group V doped CuMnAs thin films.

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P424 - Influences of interfacial oxidization on surface magnetic energy, damping and SOTs in Pt /FM/CAP

16. Magnetotransport, spintronics, spin orbitronics and spin caloritronics.

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Recently, spin-orbit-torques (SOTs) induced by in-plane charge currents have attracted much attention because the mechanism can efficiently reverse the magnetization in multilayers of heavy-metal(HM)/ferromagnet(FM)/insulator-capping with strong spin-orbit coupling (SOC). Although most of the research to date has focused on the HM/FM interface at which the generation of non-equilibrium spin-polarization or transmission of spin-current (J_S) and the enhancement in magnetic damping through the spin-pumping process occur, several recent works have suggested that the physical and chemical properties of the capping (CAP) can also change the characteristics of spin torques via modification of reflection, absorption, and/or scattering of the J_S at the FM/CAP interface. In addition, our previous work [1] demonstrated that the insertion of an ultrathin magnetic dusting layer between FM and MgO layers can play an important role in the determination of magnetic damping. Nevertheless, there is still a dearth of experimental work studying how the FM/CAP interface contributes to surface magnetic energy (K_S), magnetic damping (α), charge-to-SOT conversion efficiencies (θ_{DL}, and θ_{FL}) in HM/FM/CAP heterostructures.

In this presentation, we present our experimental results [2] that investigate how a naturally formed magnetic oxide at the interface influences the magnetic and spintronic properties. We examined six different series of layer stacks consisting of Pt (5) / FM / CAP (thickness in nm). The FM is either Co (3 to 15) or Py (2 to 10) and the CAP is insulating MgO(2)/Ta(2), HfO_x (3) or metallic TaN (3). We illuminate, by utilizing X-ray photoelectron spectroscopy (XPS) and spin-torque ferromagnetic resonance (ST-FMR) measurements, an additional relaxation pathway of spin current in Pt/FM/CAP systems, namely the FM-oxide at the FM/CAP interface. The XPS showed the presence of interfacial FM-oxide, and ST-FMR demonstrated the deterioration of PMA associated with a formation of interfacial FM-oxides: K_S(MgO-CAP) < K_S(HfO_x-CAP) < K_S(TaN-CAP) for both Co and Py samples. The SOT-efficiencies (θ_{DL} and θ_{FL}) were not substantially influenced by the CAP, confirming that both the DL- and FL-SOTs originate mainly from the Pt/FM interface. The interfacial oxide, especially CoO at Co|MgO interface, significantly influences both α and inhomogeneous linewidth-broadening (ΔH_0) indicating an extra magnetic damping, for instance, spin pumping process across the Co/CoO interface. This implies that the interfacial FM-oxide is a decent spin-current conductor, for instance, by incoherent magnon generation at the interfacial CoO, even above its magnetic ordering temperature (T_N). Our results facilitate a better understanding of the interfacial-oxide contributions on the PMA, magnetic damping, and SOTs in Pt/FM/CAP systems.

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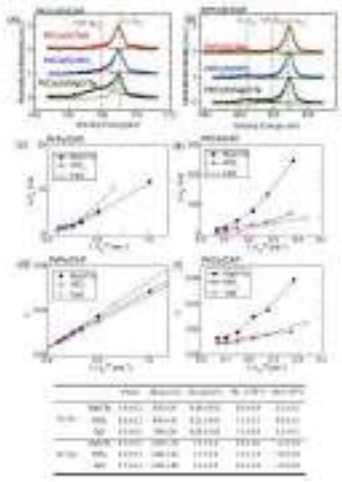

P425 - Interface generated spin pumping in Co2FeAl/MoS2 bilayer heterostructures: Experiment and theory

16. Magnetotransport, spintronics, spin orbitronics and spin caloritronics.

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The author has chosen not to publicise the abstract.

Field 5

Field 6

P427 - Longitudinal and transverse magnetoresistance in films with tilted out-of-plane magnetic anisotropy

16. Magnetotransport, spintronics, spin orbitronics and spin caloritronics.

Gregory Kopnov

Tilted off-plane magnetic anisotropy induces two unusual characteristic magnetotransport phenomena: extraordinary Hall effect in the presence of an in-plane magnetic field, and nonmonotonic anisotropic magnetoresistance in the presence of a field normal to the sample plane. We show experimentally that these effects are generic, appearing in multiple ferromagnetic systems with tilted anisotropy introduced either by oblique deposition from a single source or in binary systems co-deposited from separate sources. We present a theoretical model demonstrating that these observations are natural results of the standard extraordinary Hall effect and anisotropic magnetoresistance, when the tilted anisotropy is properly accounted for. Such a scenario may help explain various previous intriguing measurements by other groups.

P429 - Low operational current spin Hall nano-oscillators with perpendicular magnetic anisotropy

16. Magnetotransport, spintronics, spin orbitronics and spin caloritronics.

Himanshu Fulara[1, 2] , *Mohammad Zahedinejad*[1, 2], *Roman Khymyn*[1, 2], *Shreyas Muralidhar*[1], *Ahmad. A. Awad*[1, 2], *Mykola Dvornik*[1, 2], *Johan Åkerman*[1, 2, 3]

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Spin Hall nano-oscillators (SHNOs) have emerged as one of the most promising spintronic devices as they are pure spin current driven microwave nanoscale sources and exhibit robust mutual synchronization phenomena both in long chains and two-dimensional arrays at frequencies amenable to neuromorphic computing applications [1-4]. However, there have been limited efforts to adapt SHNOs to well-established existing technologies such as silicon CMOS processes. In addition, a major limitation of these SHNO devices is the localized nature of auto-oscillations arising due to easy-plane anisotropy and the geometry of the device and inhibits their utilization as a nanoscale signal carrier for magnonoic applications [1,5].

Here, we experimentally demonstrate how perpendicular magnetic anisotropy (PMA) can efficiently overcome the localization of auto-oscillations resulting in the propagation of spin waves in nano-constriction based W/CoFeB/MgO devices grown on CMOS compatible substrates. High frequency electrical measurements combined with micromagnetic simulations show very small operational current excitation of propagating spin waves in a wider frequency spectrum ranging
from 5 to 22 GHz. Thanks to large spin Hall angle of β-W layer along with strong PMA field due to thinner CoFeB interfaced with MgO layer, we obtain a lowest threshold auto-oscillation current density of 1.5×10^7 A/cm^2. In addition, we make use of these propagating spin waves to demonstrate robust mutual synchronization up to nine SHNOs in a chain. Our demonstration highlights the critical role of PMA induced significant improvement in microwave signal generation characteristics of SHNOs, making these oscillators directly compatible with CMOS technology as well as the most amenable to integrate into nanomagnonic circuits.

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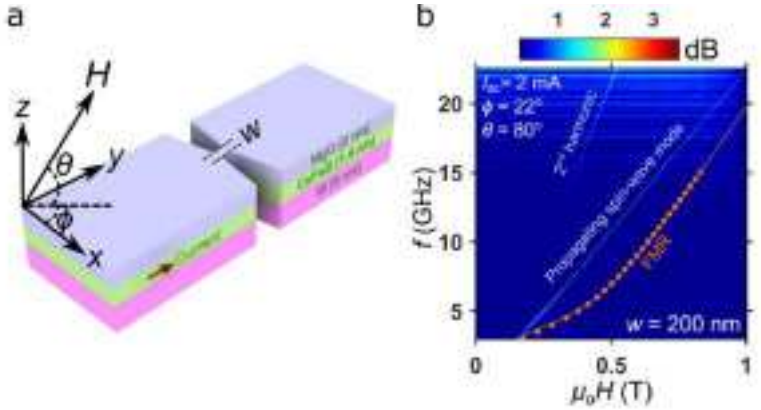

Figure 1: (a) Schematic of a SHNO device with a nano-constriction width w. (b) Auto-oscillating propagating spin-waves, excited on a 200 nm nano-constriction width SHNO device.

P430 - Magnetic proximity effect in 5d transition metals calculated by GGA+U method

16. Magnetotransport, spintronics, spin orbitronics and spin caloritronics.

Karel Knížek[1] , *Pavel Novák[1], Zdeněk Jirák[1], Jiří Hejtmánek[1]*

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Spin Seebeck effect (SSE) refers to the conversion of a heat current into a spin current in a magnetically ordered material (FM). The thermally generated spin current can be converted to an electrical current by means of the inverse spin Hall effect (ISHE) in the attached thin layer of conductive nonmagnetic metal (NM) with appreciable spin-orbit coupling and hence spin Hall angle [1]. Nevertheless, because of the presence of the interface of two materials, other effects influencing the spin current transfer must be taken into account, like the efficiency of the spin momentum transfer through the FM/NM interface characterized by the spin mixing conductance, or the dynamic coupling between the magnetization in FM and the ordered spins in NM due to the magnetic proximity effects (MPE).

Platinum with large positive spin Hall angle is among the most efficient representatives for spin current detection. However, it was argued that the spin current measured by Pt is not purely established since the measurement is contaminated by a strong MPE [2,3]. In order to compare the importance of MPE in Pt and other transition metals typically used for the spin current detection, we have performed GGA+U calculation of MPE for a series of *5d* transition metals Me = Ta, W, Re, Os, Ir, Pt and Au. For the interfaced FM we have selected magnetite Fe_3O_4, since one of the highest SSE signal was observed in this material [4]. Supercell with stoichiometry $Fe_{18}O_{24}Me_{24}$ was constructed for the purpose of calculation. Another advantage of magnetite Fe_3O_4 is an easy structural transition from the metallic phase to the insulating maghemite Fe_2O_3 by simply creating vacancies at octahedral Fe sites (supercell $Fe_{16}O_{24}Me_{24}$), thus allowing investigation of MPE induced by both metallic and insulating FM. All possible variants of the interfaces at the atomic level were tested, namely metal-metal bonding, *i.e.* Fe(octahedral)-Me and Fe(tetrahedral)-Me, and metal-oxygen-metal bonding, *i.e.* Fe(octahedral)-O-Me and Fe(tetrahedral)-O-Me.

The calculations confirmed significant magnetic proximity effect in Pt, nevertheless the size of the effect depends on the character of the interface. The induced moments of the Pt atoms adjacent to FM/NM interface were calculated up to 0.4μ_B in the case of FM=Fe_3O_4 and up to 0.5μ_B for FM=Fe_2O_3. The magnetic moments induced through the Fe-O-Me bond are more than twice bigger than for the Fe-Me interface. On the other hand, the difference between the induced moments by Fe in tetrahedral or octahedral coordination is only about 0.05μ_B. Sizable moments due to MPE were also calculated for Ta up to 0.2μ_B. MPE for the other tested transition metals was generally much smaller and the induced moments did not exceed 0.1μ_B. The exceptional behavior of Pt is connected with the position of the Fermi level just at the edge of the wide *5d*-band.

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P431 - Magnetoresistance of phase separated (Ga,Fe)N containing GayFe4-yN embedded nanocrystals

16. Magnetotransport, spintronics, spin orbitronics and spin caloritronics.

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Gallium nitride (GaN) and related compounds are key material systems for state-of-the-art optoelectronic and high-frequency technology. When doped with Fe, GaN undergoes crystallographic phase separation at Fe-cation concentrations above 0.4%, leading to the self-assembly of Fe-rich nanocrystals (NCs) [1,2]. By fine tuning the growth parameters during a metal-organic vapour phase epitaxy process, the growth of ordered planar arrays of magnetic $Ga_yFe_{4-y}N$ ($0 < y < 1$) NCs embedded in GaN is obtained [3-5].

Here, the study of magnetotransport through a planar assembly of $Ga_yFe_{4-y}N$ NCs embedded in GaN over the temperature range 2-300 K is reported. The values of resistivity and magnetoresistance (MR) as a function of temperature point to two conduction mechanisms, namely, a conventional Arrhenius-type one down to 50 K and Mott variable range hopping at lower temperatures, where the spin-polarized current flows between NCs in a regime in which phonon-scattering effects are not dominant. Furthermore, a sizeable anisotropic magnetoresistance as high as 16% at 2 K and 2% at 300 K is found and is attributed to the magnetic anisotropy of the NCs [6].

The control over the nanocrystals properties by growth parameters and the above magnetotransport properties open wide perspectives for the manipulation of the Fe-rich NC's magnetic moment *via* an external electric field [7].

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P432 - Magnetotransport of carrier induced dilute magnetic semiconducting Zn(Fe)O and Zn(Fe,Al)O thin films

16. Magnetotransport, spintronics, spin orbitronics and spin caloritronics.

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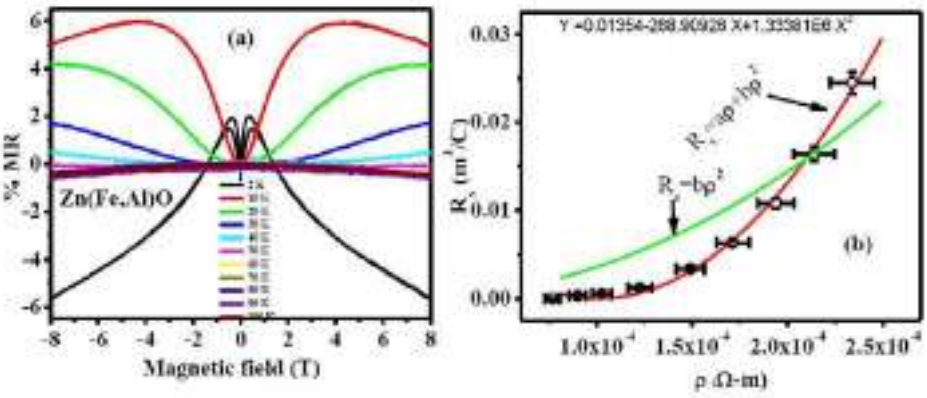
The magneto-transport properties of *n*-type ferromagnetic Zn(Fe)O and Zn(Fe,Al)O with different Fe concentration, a diluted magnetic semiconductor based on II-VI semiconductors, are measured and the sp-d exchange between electron and Fe 3d spins have been determined. Incorporation of 1% Al in Zn(Fe)O film enhances ferromagnetic properties of those diluted magnetic semiconductor films. The detailed temperature dependent transport properties have been investigated. Different type of transport properties (Variable range hopping, Efros' variable range hopping, thermal excitation) are found to dominate in different temperature ranges. Magnetoresistance of the films have been measured to investigate the sp–d exchange interaction between the conducting s electron spins and the d electron spins localized at the magnetic Fe impurities. A variety of MR behaviors were observed depending on the operating temperature range down to a temperature of 2 K [Fig(a)]. Influenced by the s–d exchange interaction, the decrease of spin-disorder scattering with increasingly aligned spins of the Fe^{2+} ion impurities are found to be mainly responsible for the unusual magnetoresistance behavior in the higher magnetic field at low temperature of this carrier induced dilute magnetic semiconducting films. The temperature dependent carrier concentration and hall mobility have been estimated from Hall Effect measurement of both the films. Theory of the anomalous Hall effect in n-type magnetic semiconducting films has been employed and the relative role of side-jump and skew-scattering mechanisms assessed for Zn(Fe,Al)O ferromagnetic film have been investigated in details [Fig.(b)].



P433 - Magnetotransport properties of correlated topological semimetal YbCdSn

16. Magnetotransport, spintronics, spin orbitronics and spin caloritronics.

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The author has chosen not to publicise the abstract.

Field 5

Field 6

P434 - Magnetotransport Properties of Mn-doped Bismuth Thin Films

16. Magnetotransport, spintronics, spin orbitronics and spin caloritronics.

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Bismuth as a semimetal has a unique role in condensed matter physics. Its combination of important properties originating from the three-dimensional Dirac dispersion enabled the observation of important phenomena such as strong diamagnetism [1], and the various effects such as the Seebeck effect [2] and Shubnikov-de Haas oscillations [3]. Recent studies on topological materials place great emphasis on the electrical transport properties of semimetals and semiconductors in the presence of a magnetic field.

In this work we study how the effect of magnetic impurities in Bi thin films affects the magnetotransport properties of these structures. In particular, a series of Bi thin films doped with Mn have been prepared on $SrTiO_3$ substrates with the magnetron sputtering technique. Doping was achieved by repeating ten times the pattern bilayer Bi/Mn. The temperature of the substrate was fixed at 80 ^oC during deposition and the Ar pressure at 3 mtorr. Eventually, the structure of the samples was $SrTiO_3/Bi_{1-x}Mn_x$, with x determined by the two repeating layers' thickness and ranging between x=0.03 – 0.12. Structural characterization of the samples with X-Ray Diffraction (XRD) showed a (00*l*) predominant texture and a crystallite size calculated with Scherrer equation varying from 27.3 nm for pure Bi film to 12.1 nm for the film with Mn-doping of x=0.12. Magnetotrasport measurements were also performed for samples with lateral dimensions 4x4mm^2 with electric contacts of copper wire mounted to the sample with indium, for magnetic field from -7 T to 7 T and temperature from 7 to 300 K. Magnetoresistance was measured both with magnetic field parallel and perpendicular to the current. Hall measurements proved that Hall effect is not linear for most of the samples and thus an anomalous Hall effect contribution was calculated. Pure Bi films showed p-type charge carriers with a calculated density of $1.02x10^{15}$ cm^{-2} at 7 K, increasing as temperature rises. For Mn-doped Bi films the charge carriers were also p-type with calculated densities of $7.63x10^{14}$ cm^{-2} and $7.24x10^{15}$ cm^{-2} for x=0.06 and x=0.12, respectively. Magnetoresistance (R_{xx}) data as a function of sample position were also acquired for magnetic fields up to 0.6 T and with in-plane rotation of the sample, at low temperatures.

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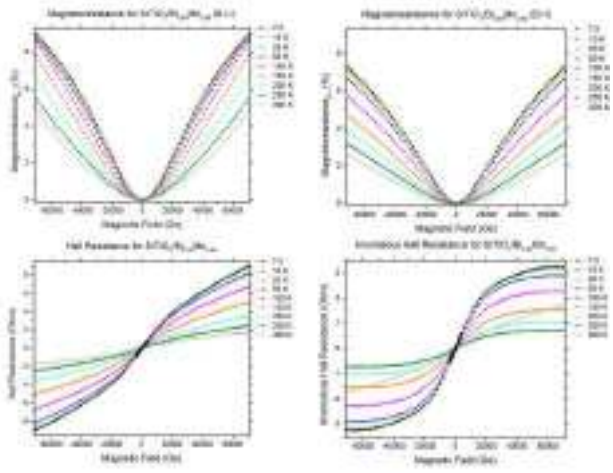

P435 - Magnons Driven by the Spin-Orbit Torque

16. Magnetotransport, spintronics, spin orbitronics and spin caloritronics.

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Recent theoretical studies suggest that spin orbit-torque (SOT) can drive the magnon gas into a quasi-equilibrium state described by the Bose-Einstein statistics with non-zero chemical potential, suggesting the possibility of electrically-driven Bose-Einstein condensation (BEC) of magnons. Variations of the chemical potential of the magnon gas were recently detected in measurements of spin relaxation rates of a nitrogen-vacancy center in diamond coupled to spin waves in a magnetic insulator. However, there was no direct experimental evidence that the magnon gas driven by SOT forms a quasi-equilibrium distribution, and the dependence of the effective thermodynamic characteristics has not been established.

We have studied the effects of SOT on the magnon distribution in Permalloy (Py) over a broad spectral range, by utilizing the micro-focus Brillouin light scattering (BLS) spectroscopy. Pure spin current was injected into Py due to the spin-Hall effect in the adjacent Pt layer. The BLS spectra, reflecting the current-dependent spectral density of magnons, allowed us to analyze the spectral magnon population function and determine the thermodynamic characteristics of the magnon gas. Our analysis clearly indicates that the magnon distribution can be described by the Bose-Einstein statistics expected for the quasi-equilibrium state. We determined the current-dependent chemical potential and the effective temperature of the magnon gas (Fig. 1), and showed that, for one polarization of the spin current, the effective temperature of the magnon gas becomes significantly reduced, while the chemical potential stays almost constant (Fig. 1a). In contrast, for the opposite polarization, the effective temperature remains nearly unaffected, while the chemical potential linearly increases with current, until it closely approaches the lowest-energy magnon state (Fig. 1b), indicating the possibility of spin current-driven Bose-Einstein condensation.

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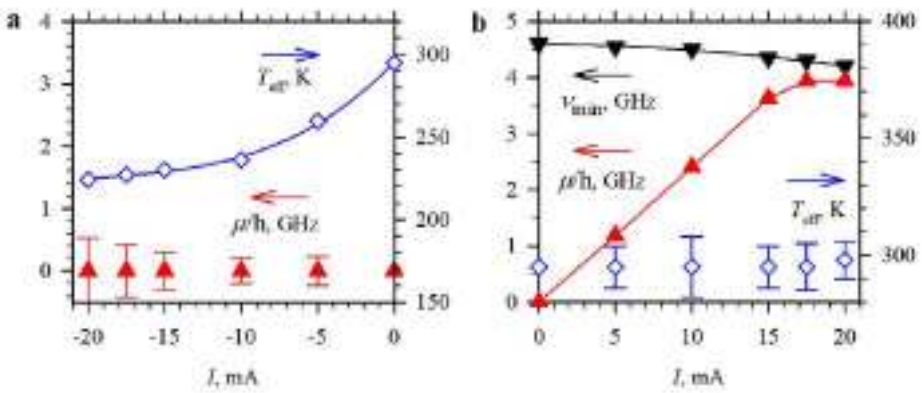

P437 - Quantitative temperature dependence of the Spin Seebeck effect in a mixed valent manganite

16. Magnetotransport, spintronics, spin orbitronics and spin caloritronics.

Avirup De[1] , *Arup Ghosh*[1], *Rajesh Mandal*[1], *Satishchandra Ogale*[1, 2], *Sunil Nair*[1, 2]
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The author has chosen not to publicise the abstract.

Field 5

Field 6

P438 - Realizing Two-Dimensional Flexible Spin Circuits

16. Magnetotransport, spintronics, spin orbitronics and spin caloritronics.

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Graphene is a two-dimensional crystal, that is an outstanding medium for spin-polarized electron transport with spin communication abilities surpassing tens of microns at room temperature [1]. Graphene is also known for it's exception resilience, which makes it ideal for flexible nanoelectronic applications [2]. In this work, we combined these superlative attributes and create flexible spin circuits, demonstrating for the first time, a spin transport ability up to 15 µm long channels at room temperature [3]. Comprehensive measurements allowed us to observe robust spin transport and spin precession, leading to high spin diffusion coefficients ~0.2 $m^2 s^{-1}$, with an enhanced spin diffusion length ~ 10 µm in the graphene on flexible substrates, despite the conventionally known rough topography of such surfaces. Our innovation paves the way for two-dimensional spin based nanoelectronics and exploring strain related applications and surface mountable spin sensors.

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P439 - Resolving conflict in reported values of spin diffusion length and spin pumping in FM/NM systems

16. Magnetotransport, spintronics, spin orbitronics and spin caloritronics.

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Manipulating and understanding interfacial spin transport is fundamental for modern spintronic devices. To fully exploit related interface phenomena, such as spin-orbit torques or spin-pumping, the dependence of the structure and properties of the interface on key transport parameters must be quantified. Our previous work has shown the enhancement in interfacial transport with improved structural matching between FM and NM materials [1], as well as the dependence of spin transport on the thickness of the NM layer [2]. The nature of the parameters governing this transport however remains a subject of debate with the reported values seemingly affected by the different experimental methods and analyses. In particular, experimental values for the spin-diffusion length of the NM layer are inconsistent; for Pt, spin diffusion lengths have been reported from 1 nm up to 10 nm [3,4] depending on the method used. The role of the interface structure and its influence on the effective spin-diffusion length are also unclear.

Here we present results and new analysis of spin transport on a variety of crystalline and amorphous NM/FM and FM/NM systems that properly quantifies spin transport across the interface. Building upon the proposed linkage of resistivity and the spin diffusion length [5] new experimental analysis here resolves the difference in previously reported values for the spin diffusion length of Pt, see figure below. This analysis demonstrates that the larger values for the spin diffusion length are correct, and lower values obtained from spin-pumping studies are limited by an incomplete understanding of the role of the interface. This understanding allows us to exploit interfacial phenomena to tailor structures with tunable magnetisation dynamics, in particular the Gilbert damping parameter, α, by separating FM/NM ‘building blocks’ with appropriate insulating layers to block spin transport. The relation between the spin barrier structure and the extrinsic damping is also evaluated. Further details can be found in reference [6].

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Sample	Spin-flip Probability ε	Constant λ_{sf}	Thickness Dependent λ_{sf}
Pt(fcc)/Co(fcc)	0.17	1.6 nm	9.4 nm
Co(fcc)/Pt(fcc)	0.26	1.6 nm	9.5 nm
Pt(fcc)/a-CoFeB	0.11	1.6 nm	6.6 nm
Co(hcp)/Ru(hcp)	0.004	-	22 nm
Co(fcc)/Ru(hcp)	0.003	-	22 nm

Fig1: Extracted interfacial transport parameters for various FM/NM and NM/FM systems

P441 - Skyrmions creation and control in NiFe/heavy metal hetrostructures

16. Magnetotransport, spintronics, spin orbitronics and spin caloritronics.

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Recent optimizations of perpendicular magnetic anisotropy (PMA) NiFe thin films with Zr or Hf dusting at Ta/NiFe and/or NiFe/MgO interfaces [1], and current induced Spin-orbit-torque (SOT) and magnetization switching [2] showed that heavy metal/NiFe interface may also be used in SOT-related phenomena beyond more conventional Ta/FeCoB or Pt/Co systems. Here we have studied similar Ta/Zr/NiFe/Zr/MgO/Ta and Ta/NiFe/Hf/MgO/Ta heterostructures, with thinner and thicker NiFe, closer to the transitions from PMA to paramagnetic and from PMA to in-plane anisotropy regions.

In these regions, we have observed, by using polar Kerr microscopy, the appearance of skyrmions that may be observed in heavy metal/ferromagnetic/oxide ultrathin trilayers with the most usual Co or FeCoB as ferromagnetic layer. Skyrmions are topologically protected chiral magnetic textures that have been predicted to have some promising potential applications for low power and high density magnetic memories, and logic devices [3]. The dynamics of skyrmions can be controlled by using electric field effects and these topological spin structures have attracted a lot of attention as their texture allows large SOT-current induced velocities with possibly less pinning as compared to domain walls [4].

Here, we will present results on the control of these topological spin structures by SOT, and in particular the effect of temperature, where anisotropy, one of the key parameter in stabilizing skyrmions is strongly varying. We have studied magneto-transport properties, in particular anomalous Hall effect (AHE) and planar Hall effect (PHE) on Hall cross devices fabricated using standard optical lithography and ion milling techniques. The 2nd harmonic AC Hall voltage measurements were performed as a function of the applied field and angle to estimate the damping like and field like torques.

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P442 - Spin diffusion equation in superconductors: Analysis near Tc

16. Magnetotransport, spintronics, spin orbitronics and spin caloritronics.

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Much attention is now focused on the interplay of the spin current and superconductivity, and a new research field of superconducting spintronics has been rapidly growing [1]. In discussing the spin transport phenomena in metals and superconductors, the most basic theoretical apparatus is the spin diffusion equation [2]. Indeed, the real space profile of the spin current is described by the spin diffusion equation, which can now be experimentally measured using the lateral spin valve technique [3]. Despite its importance, however, only a little is known about the spin diffusion equation in the superconducting state [2,4].

Here, we microscopically derive the spin diffusion equation in the superconducting state near the transition temperature Tc on the basis of the weak-coupling BCS model with s-wave pairing and with impurity spin-orbit scattering. Applying the general relation between the relaxation function and the response function [5], which in the present context is translated into the relation between the spin diffusion equation and the dynamic spin susceptibility, we examine how the spin diffusion equation is renormalized in the superconducting state. We find that both the spin relaxation time and the spin diffusion coefficient are increased below Tc, resulting in an enhancement of spin diffusion length in the superconducting state [6].

The present result may provide an explanation, in terms of the conventional singlet Cooper pairs, for the recent observation of an enhanced spin pumping signal below Tc in a Py/Nb/Pt system, which would otherwise be attributed to the spin transport mediated by triplet Cooper pairs [7].

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P443 - Spin pumping effect in non-uniform magnetization structure

16. Magnetotransport, spintronics, spin orbitronics and spin caloritronics.

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A major task of the spintronics field is to generate and control a spin currents effectively. A ferromagnet/normal metal junction system induces a spin current in the normal metal because the angular momentum is transferred from a precessing localized spin to the conduction electron spin via the s-d interaction. This effect, called spin pumping effect, was established as one of typical methods to generate spin current into a normal metal, resulting in enhanced Gilbert damping of the magnetization dynamics.[1,2] Generated spin current is indirectly detected as charge voltage by the inverse spin Hall effect. In general, the efficiency of spin current generation due to spin pumping effect in a uniform magnetization is evaluated via a spin mixing conductance at the interface of a junction system. However, the spin mixing conductance generally depends not only on the interface magnetization but also on the internal structure of the magnetization. It has a possibility of the enhancement of the spin pumping by considering a proper internal structure of the magnetization.

In this study, in order to reveal the role of the magnetization structure in the spin pumping effect, we numerically investigate the spin current in the presence of a dynamical non-uniform magnetization structure. The spatial phase-modulated magnetization is realized by employing the spatial gradient of the cone-angle and azimuthal-angle to the localized spin texture. We obtain the pumping spin and charge current by calculating the 2×2 spin-dependent scattering matrix for the two terminal system where normal leads are attached to the magnetic system. The time-dependent spin current is calculated by using the recursive Green's function and Brouwer's formula. In the case of the cone-angle modulation, numerical results revealed that the spin current is enhanced compared to the case of uniform magnetization structure. We point out that the enhancement of the spin current is explained by the adiabatic spin motive force.[3] The azimuthal-angle modulation is a simple model of spin wave excitation. For the azimuthal-angle modulation, we found that the spin current is enhanced in one lead that is selected by the phase velocity of the spin wave. We explain these results in terms of the non-adiabatic spin motive force.[4] We also show that the charge current is directly induced by these phase modulations of the magnetization. It means one does not need the inverse spin Hall effect for the electrical measurement.

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Schematic view of spatial gradient of azimuthal-angle.

P445 - Spin transport in epitaxial Fe/Pd heterostructures

16. Magnetotransport, spintronics, spin orbitronics and spin caloritronics.

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The interfacial parameters in FM/NM systems i.e., spin memory loss, magnetic proximity, interface transparency, affect the precise estimation of spin Hall angle (SHA) and spin current transmission efficiency across the FM/NM interface, and therefore, a unifying consensus about the role of interfacial properties in governing spin-transportation in FM/NM systems is largely missing [1, 2]. To study the role of interfacial parameters and spin relaxation mechanism on the spin torques efficiency in the FM/NM layers interface we have chosen epitaxial Fe/Pd bilayer system.

In the first set of samples; epitaxial MgO(100)/Fe(t_{FM})/Pd(5nm) samples, the role of interface roughness (ranges from 0.2 to 1.2 nm) on the spin angular momentum transportation; spin torques, across the Fe/Pd interface has been studied, considering interfacial transparency and spin memory loss, by performing spin torque ferromagnetic resonance (ST-FMR) measurements. A four-fold anisotropy was observed in all the samples. Surprisingly, the effective Gilbert damping constant and interfacial spin mixing conductance are found to be independent of the interface roughness in the range 0.2 to 1.2nm. The effective Gilbert damping constant was found to be 4.8×10^{-3}. These findings contradict those reported by W. Zhang et al. [3], where it has established that interface roughness reduces spin-mixing conductance. Our findings suggest that the effect of the interface roughness on spin-mixing conductance depends on choice of materials in the heterostructures. In the second set of samples MgO(100)/Fe(t_{FM})/Pd(t_{NM}); here t_{FM} and t_{NM} were varied in the range of 2.5 - 15 nm, detailed *out-of-plane* FMR measurements were performed to understand the Elliott-Yafet and Dyakonov-Perel-like spin relaxation mechanisms in these heterostructures.

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P446 - Spin-orbit torque dependence on strain and magnetization for NiMnSb with broken inversion symmetry

16. Magnetotransport, spintronics, spin orbitronics and spin caloritronics.

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The author has chosen not to publicise the abstract.

Field 5

Field 6

P447 - Structural analysis on Co2FeAl0.5Si0.5/Ag/Co2FeAl0.5Si0.5 GMR device sample

16. Magnetotransport, spintronics, spin orbitronics and spin caloritronics.

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A Heusler alloys is one of the main stream research studies in materials science due to its possible applications in spintronic devices. Such a half-metallic ferromagnetic material has a unique property for exhibiting only one spin channel at the Fermi level [1]. $Co_2FeAl_{0.5}Si_{0.5}$ (CFAS) is one of half-matallic ferromagnets which is used as a ferromagnetic layer in spintronic devices. In order to achieve high spin polarisation in CFAS, high structural ordering such as $L2_1$ or B2 is required. Therefore high temperature deposition or post annealing is often required in a Heusler-alloys thin film. [2]

We fabricated giant magnetoresistive (GMR) devices consisting of a layer stack of Si(substrate)/W(10)/CoFeAlSi(10)/ Ag(3)/CFAS(2.5)/Ru(3) (thicknesses in nm) by pattering a series of nanopillars ranging from 100 nm × 150 nm to 1000 nm × 500 nm by using electron-beam lithography (JEOL JBX-6300 FS with a BEAMER attachment). The patterned negative resist mask was used for Ar^+ milling, so that the GMR nanopillars were etched till the bottom CFAS layer. The sample was then covered by SiO_2 in plasma enhanced chemical vapour deposition (PECVD). The top of a pillar was opened by removing the negative resist. The bottom electrode was formed by opening electrode through SiO_2 by using reaction ion etching (RIE).

Figure 1(a) shows a cross-sectional transmission electron microscope (TEM) image of the GMR device. From the TEM image the thickness of the Ag layer is measured to be 4.7nm which is about 40% thicker than the designed thickness. There is a potential to further improve the GMR ratio after re-calibrating the deposited Ag layer thickness. Nano beam diffraction (NBD) is obtained in the CFAS layer along the [011] direction and the corresponding lattice constant is measured to be 0.595nm. The coexistence of diffraction spots and rings in NBD indicates that the CFAS layer is partially crystallised into the B2 ordering.

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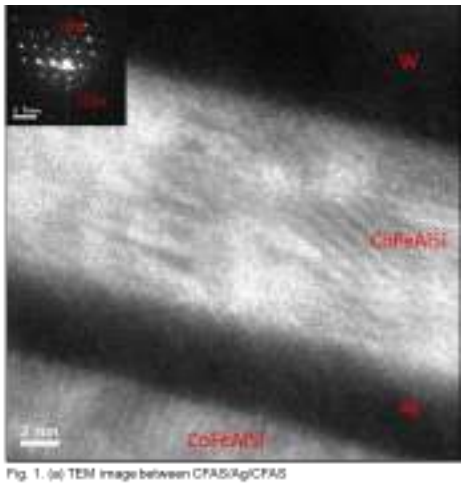

Fig. 1. (a) TEM image between CFAS/Ag/CFAS

P448 - Study of spin light-emitting diodes based on InGaAs/GaAs structures with (In,Fe)Sb injector

16. Magnetotransport, spintronics, spin orbitronics and spin caloritronics.

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Diluted magnetic semiconductors (DMS) are semiconductor materials doped with atoms of transition elements. Such materials are considered promising as elements of spintronics devices [1]. To date, DMS (A3,Fe)B5 and, in particular, (In,Fe)Sb are considered the most promising, since its Curie temperature exceeds 300K [2]. For this reason the integration of (In,Fe)Sb into GaAs based devices is one important task. The main purpose of this work is the introduction of (In,Fe)Sb as a ferromagnetic injector into GaAs-based spin light-emitting diodes.

The sample for investigation was fabricated by a combined epitaxial method. First, the semiconductor structure with InGaAs/GaAs quantum well was grown on the p-GaAs substrate by the metal-organic vapor phase epitaxy and a thin MgO layer was formed on it. Then the DMS (In,Fe)Sb layer was deposited by the pulsed laser sputtering. At the last stage, a diode structure was formed using thermal evaporation, photolithography and chemical etching. The introduction of MgO provides high sharpness of the boundary between DMS and GaAs, while it has not a significant effect on the crystalline quality, since MgO grows epitaxially on GaAs [3].

For electroluminescence (EL) studies, a forward bias was applied to the diode sample (a negative voltage was applied to (In,Fe)Sb with respect to the substrate). When structure is introduced into perpendicular magnetic field, the EL emission becomes partially circularly polarized. The degree of circular polarization P_{EL} is calculated by the formula:

$$P_{EL}=(I(\sigma^+)-I(\sigma^-))/(I(\sigma^+)+I(\sigma^-)),$$

where $I(\sigma^+)$, $I(\sigma^-)$ are intensities of EL components polarized along the left and right circles, respectively. Figure 1 shows $P_{EL}(B)$ measured at different temperatures.

$P_{EL}(B)$ is a non-linear function. Such type of dependence is associated with the injection of spin-polarized electrons from ferromagnetic layer. The maximum P_{EL} value was obtained at 10K and was ~ 0.7%. As the temperature increases, both the EL intensity and the P_{EL} monotonically decrease. At temperatures above 200K EL intensity signal becomes comparable with noise level which did not allow us to reliably measure P_{EL}. It should be noted, that in similar sample but without MgO the EL is not observed. So one can make a conclusion, that MgO is a protective layer, which prevents the negative impact of (In,Fe)Sb on the luminescence characteristic of the structure.

The observed change of $P_{EL}(B)$ dependences shapes with the change of temperature can be attributed to different magnetization mechanisms in (In,Fe)Sb. In particular, Zeeman splitting in InSb can give rise either to additional P_{EL} increase at high magnetic fields or to some decrease of polarization degree depending on the sign [4].

Thus, in this work, the spin injection of electrons from the DMS (In,Fe)Sb into the semiconductor structure based on GaAs with further recombination and emission of EL radiation in the QW region was obtained.

This study was supported by the Minobrnauka (projects SP-2450.2018.5 and 8.175.2017/PP).

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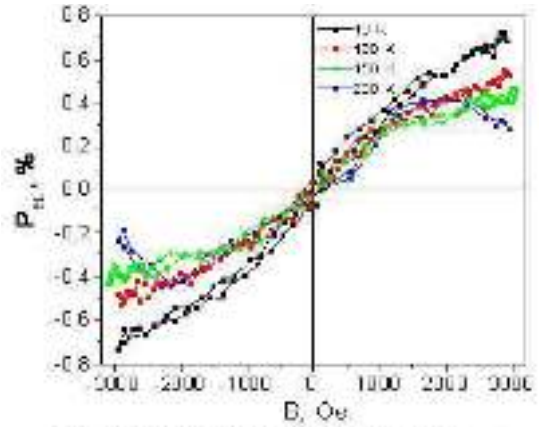

Figure 1. Magnetic field dependence of P_{FL}.

P449 - Switching of 3-terminal magnetic tunnel junction by spin-orbit and spin-transfer torques

16. Magnetotransport, spintronics, spin orbitronics and spin caloritronics.

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Current-induced torques offer a unique possibility for fast and low-power switching of nanomagnets. Both spin-transfer torque (STT) and spin-orbit torque (SOT) have already demonstrated efficient control of magnetic tunnel junctions (MTJs) [1]. Deterministic switching of MTJs is crucial for the development of magnetic random access memories (MRAMs) offering nonvolatility, low write energy, and low standby power consumption, as well as potential for high read/write rates. However, up-to-date two-terminal STT MRAMs suffer from endurance and reliability issues due to the aging of the tunnel barrier, particularly at high writing speed. These drawbacks can be overcome by introduction of SOT as a reversal mechanism [2], which allows for the separation of read and write paths in a three-terminal device [3]. Besides the enhancement of endurance and reliability, SOT holds a promise for faster and more energy efficient control of magnetization [4,5]. However, a further understanding of the SOT switching mechanism and time-scales underlying spin-current-induced dynamics is crucial for future development.

Here we report all-electrical measurements of magnetization switching driven by SOT and STT in the same 3-terminal perpendicular MTJ device allowing to directly compare the effects of both. The measurements show that SOT-induced switching can be faster than STT-induced switching, but its total achievement is strongly dependent on the parameters such as external magnetic field and current density, STT being more energy efficient but limited to relatively long pulses (> 5 ns), whereas SOT becomes more efficient in short pulse regime. We further employ SOT, STT, and voltage control of magnetic anisotropy to optimize the MTJ switching. By combining these effects in a single device, we show improved switching efficiency for STT-assisted SOT-switching allowing us to achieve reproducible sub-ns switching.

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P450 - Switching of antiferromagnetic CuMnAs memory devices by sub-nanosecond electrical pulses

16. Magnetotransport, spintronics, spin orbitronics and spin caloritronics.

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Antiferromagnetic spintronic memory devices take advantage of fast magnetization dynamics overcoming the GHz limit of their ferromagnetic counterparts used in contemporary microelectronics, e. g. in magnetic random-access memories (MRAMs). On the other hand, manipulation of magnetic moments in antiferromagnets is substantially more difficult due to the zero net magnetization and consequent insensitivity to magnetic fields [1]. One of few proposed possibilities is to utilize the Néel spin-orbit torques induced by electrical current which can be employed for an efficient control of magnetic moments in materials meeting particular symmetry requirements [2]. Recently, such effect has been experimentally used for electrical switching of epitaxially grown CuMnAs thin film samples [3] which in combination with the electrical readout may conveniently operate as memory devices [4]. Manipulation of the magnetic state in CuMnAs has been also demonstrated by THz electromagnetic radiation pulses [5].

In the present study, we report on electrical switching of CuMnAs memory cells with pulse lengths in a nanosecond and sub-nanosecond range. We investigate samples of various thicknesses grown on GaP, GaAs and Si substrates. By changing pulse parameters (length, voltage, pulse count and repetition rate), we evaluate their switching ability and efficiency and examine the underlying physical mechanisms controlling the switching process.

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P451 - Temperature Dependence of Bulk Perpendicular Magnetic Anisotropy in CoFeB:Gd thin films

16. Magnetotransport, spintronics, spin orbitronics and spin caloritronics.

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Rare earth-transition metals (RE –TM) alloys are promising materials for low-power and high-speed Spintronic applications. The key phenomenon that supports these applications is the presence of a bulk perpendicular magnetic anisotropy (PMA) in these ferrimagnetic alloys. Knowledge of the anisotropy and magnetisation behaviour across a temperature range through the ferrimagnetic compensation point is of fundamental interest and relevant to spintronic applications such as in heat-assisted magnetic recording device [1] and spin-orbit torque switching. In this work, we report a detailed systematic study of the temperature dependence of the PMA and magnetisation reversal behaviour in RE-TM thin films.

The sample stack comprises of a Ta (5nm)/RE-TM (20nm)/Ta (1nm) co-sputtered on oxidized Si substrates for different RE concentration and RE-TM thickness. Gd was the RE material used, while the TM was $Co_{20}Fe_{60}B_{20}$, which is a c commonly used alloy in spintronics. Measurements were made with magneto-optical Kerr effect (MOKE) magnetometry in the polar geometry where the magnetisation behaviour was studied over a temperature range of 70-300 K. The Gd contribution was 17.8-24.9 atomic%.

MOKE hysteresis measurements showed significant changes in the anisotropy and magnetisation behaviour as a function of temperature. With increasing temperature, the squareness of the hysteresis loop increased approaching the compensation temperature and the switching exhibited a maximum coercivity, H_c, either side of the compensation temperature. Further increase in the temperature is characterised by a flipping of the magnetization direction, characteristic of such ferrimagnets, and a reduction of the remanence ratio with further temperature increases (see figure 1) [2,3]. This effect may be attributed to a change in compressive stress within the samples with temperature [4]. In this case, a compensation temperature of 185K was determined.

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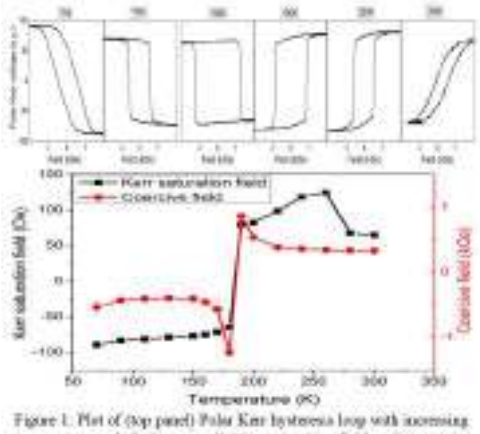

Figure 1. Plot of (top panel) Polar Kerr hysteresis loop with increasing temperature and (bottom panel) Kerr saturation field and coercivity against temperature in Ta(5nm)/ CoFeB(3d) (20nm)/ Ta(1nm) thin-film.

P453 - Tunable magnetic anti-skyrmion size and helix period in tetragonal Heusler material

16. Magnetotransport, spintronics, spin orbitronics and spin caloritronics.

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The quest for more energy efficient data storage has encouraged research in materials hosting non-collinear magnetic structures with tunable magnetic properties. One promising candidate for carrying information is magnetic skyrmions, which are topologically protected vortices of magnetization that can be stabilized by Dzyaloshinskii-Moriya Interaction (DMI) in chiral non-centrosymmetric magnets [1]. Recently, a new kind of non-trivial spin texture called anti-skyrmions has been discovered in inverse tetragonal Heusler compound, $Mn_{1.4}Pt_{0.9}Pd_{0.1}Sn$, with D_{2d} crystal symmetry at room temperature [2]. The topologically protected anti-skyrmions (aSk) can be manipulated using ultra-low current densities (w.r.t. those required for triggering magnetic domain wall motion) due to their insensitivity to defects and thus hold great promise for efficient spintronics application and high density data storage devices such as race-track memories [3] However, in order to enable applications, it is important to control the size of these chiral spin textures.
Here we show, using Lorentz transmission electron microscopy and magnetic force microscopy observations in the sister Heusler compound $Mn_{1.4}PtSn$, that the size of both the period of the helix and that of the aSk can be varied by more than an order of magnitude, from ~100 nm to more than 1 micron. We attribute this size-tunability to the long-range magneto-dipolar interactions. The dynamic variation of the aSk over such a wide range will have a great impact on spintronics applications where the size could, for example, be useful in devices for easy creation or reading.

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