Feb 25 - Mar 8 [2013]
Cargèse, Corsica
France

EUROPEAN SCHOOL ON MAGNETISM 2013

MAGNETISM FOR ENERGY

FROM FUNDAMENTALS TO MATERIALS

MAGNETISM.eu
A GATEWAY TO THE EUROPEAN MAGNETICS COMMUNITY

Joint European Magnetic Symposia

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Laboratoire d'Alliances Nanosciences-Energies du Futur

COMMUNAUTÉS DE RECHERCHE ACADÉMIQUE RhôneAlpes
ENERGIES

WILEY-VCH

CAMBRIDGE UNIVERSITY PRESS

CRC Press
Taylor & Francis Group

INSTITUT D'ÉTUDES SCIENTIFIQUES DE CARGÈSE

THE EUROPEAN SCHOOL ON
MAGNETISM

February 25th - March 8th, 2013 - Cargèse, France

THE EUROPEAN SCHOOL ON MAGNETISM

The European School on Magnetism (ESM) is a joint action of the European magnetism community, and is organized in cooperation with the JEMS conference (Joint European Magnetic Symposia). ESM aims at providing young scientists with a thorough up-to-date insight into the fundamentals of magnetism.

As with previous sessions of ESM, the 2013 School is based on a broad range of lectures, with special attention given to a specific topic. The topic selected for 2013, Magnetism for Energy, covers a wide range of phenomena and materials, dealing with both fundamental issues of condensed matter physics and materials science, and addressing applications and wider environmental issues.

THE EUROPEAN SCHOOL ON MAGNETISM

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Magnetism for Energy - From fundamentals to materials

The European School on Magnetism (ESM) is an educational event organized every two years by the European magnetism community. ESM is closely linked with its conference counterpart, the Joint European Magnetic Symposia, the largest European conference on Magnetism. JEMS2012 was held in Parma, Italy, 9-14 Sep. 2012 while JEMS2013 will be held on the island of Rhodes, Greece, 25-30 Aug. 2013. The joint JEMS and ESM actions aim at supporting European activity in magnetism, through the dissemination of knowledge and the education of young scientists.

The European School on Magnetism aims at providing a thorough understanding of the fundamentals of magnetism. It is aimed at young scientists (essentially PhD students and post-docs) and consists of a ten-day training course combining lectures, tutorials, computer and text-book based practicals, interactive question sessions, and an open-access on-site library dedicated to magnetism. The organization of ESM is supported by a European advisory committee as well as the International Advisory Committee of JEMS, and benefits from financial support from various institutions. ESM2013 with gather together 17 lecturers and close to 90 participants coming from 22 different countries, mainly from Europe, but also from South-America, Japan, Russia, Ukraine and Israel.

As with previous sessions of ESM, the 2013 School aims at providing a thorough insight into magnetism through a broad series of fundamental lectures, and to address a specific topic of current interest in more detail. The topic chosen for the 2013 School is : "Magnetism for Energy – from fundamentals to materials". Specialised lectures will deal with functional magnetic materials that play, or are expected to play, an important role in improving the efficiency and performance of devices in electric power generation, conditioning, conversion, transportation, information-communication technology and other energy-use sectors of the economy.

The first set of specialized lectures concerns materials science. The development of high performance hard magnetic materials revolutionised the design of motors and generators, and are of growing importance in the renewable energy sector, being exploited in (hybrid) electric vehicles and gearless wind turbines. Soft magnetic materials are also critical for energy related applications, being exploited in motors and generators, as well as in inductors and transformers. Many energy related applications are particularly demanding with respect to the working temperature of the hard and/or soft magnetic materials they exploit, with (hybrid) electric vehicles and gearless wind turbines operating at temperatures of up to 160°C, while temperatures of over 300°C may be experienced in nuclear power generation systems and bore-hole drilling equipment. While most people are somewhat familiar with hard and soft materials, since they are used in a range of established technologies, magnetocaloric and magneto-elastic materials are little known outside the laboratory. Having long been used for cooling at cryogenic temperatures, magnetocaloric materials are now being explored for room temperature refrigeration, having the potential for higher appliance efficiency than vapour-compression refrigerators, along with suppression of the use of greenhouse gas refrigerants. Magnetoelastic materials are being developed for use in actuators and sensors, and have potential for use in energy harvesting devices. The criticality of certain raw materials, in particular the rare earth elements used in high performance hard magnetic materials and magnetocaloric materials, owing to limited resources and / or monopolies on material supplies, is an impetus to "reduce, recycle and replace", to paraphrase the mantra of today's environmentalists. These aims may be achieved through improved system design and more efficient manufacturing of large volumes of magnetic material parts, by recycling appliances and the materials within, and by developing new materials with reduced dependence on critical elements. Beyond their exploitation in the direct conversion of energy in macroscopic devices, the different functional magnetic materials considered have great potential for use in micro-systems (e.g. actuators, sensors), for the supervision and management of energy networks.

The second set of specialized lectures deals with spintronics, i.e., the interplay between charge carriers and magnetism, either through electrical current or the direct effect of electric field. This field provides a rich playground for condensed-matter physics, while opening new perspectives for information/communication related technologies (data storage, processing and transmission). It is expected that the ever-increasing energy demands of the information and communication sectors may be partially off-set by the relative energy efficiency of magnetic devices (e.g. non-volatile memories vs volatile memories, the latter requiring power to maintain the stored information ; voltage control vs current control, the latter leading to Joule losses. . .).

We hope that the broad range of lectures from leading experts of the magnetism community, dealing with fundamentals, through materials to devices, and including insights from industry, will make ESM2013 a valuable, inspiring and memorable experience for all participants.

Nora Dempsey and Oliver Gutfleisch

Timetable of the European School on Magnetism ESM2013 - Updated 29 Jan 2013

	Mo 25/02	Tue 26/02	We 27/02	Th 28/02	Fr 01/03	Sa 02/03	Su 03/03	Mo 04/03	Tu 05/03	We 06/03	Th 07/03	Fr 08/03	
9h-9h30		Opening / Intro.	Kuzmin (2/3)	Kuzmin (3/3)	Sandeman (2/3)	Fruchart (1/2)	Excursion	Fruchart (2/2)	Fähler	Jewell	Cugat	Transfer to Ajaccio airport / harbour	9h-9h30
9h30-10h													9h30-10h
10h-10h30													10h-10h30
10h30-11h		Coffee	Coffee	Coffee	Coffee	Coffee + Posters		Coffee	Coffee	Coffee + Posters	Coffee		10h30-11h
11h-11h30		Wulfhekel (1/3)	Wulfhekel (3/3)	Tutorials / Library	Heyderman	Questions		Franco	Herzer		Tutorials / Library		11h-11h30
11h30-12h										Questions			11h30-12h
12h-12h30	Transfer from Ajaccio airport / harbour and registration		Clips poster										12h-12h30
12h30-13h										Fill-in evaluation			12h30-13h
13h-13h30		Lunch	Lunch	Lunch	Lunch	Lunch		Lunch	Lunch	Lunch	Lunch		13h-13h30
13h30-14h													13h30-14h
14h-14h30					Sports								14h-14h30
14h30-15h		Wulfhekel (2/3)	Lacroix	Sandeman (1/3)		Gutfleisch		Sandeman (3/3)	Viret	Valenzuela	Lombard		14h30-15h
15h-15h30													15h-15h30
15h30-16h													15h30-16h
16h-16-30		Coffee	Coffee + Posters	Coffee		Coffee		Coffee	Coffee	Coffee	Coffee		16h-16-30
16h30-17h		Kuzmin (1/3)		Fiorillo		Tutorials / Library		Questions	Tutorials / Library	Picozzi	Questions, evaluation and closing		16h30-17h
17h-17h30			Questions										17h-17h30
17h30-18h													17h30-18h
18h-18h30													18h-18h30
18h30-19h		Welcome party											18h30-19h
19h-19h30										Banquet			19h-19h30
19h30-20h													19h30-20h
20h-20h30													20h-20h30
20h30-21h													20h30-21h
21h-21h30													21h-21h30
21h30-22h													21h30-22h
22h-22h30													22h-22h30

PROGRAM

Introduction to the school (1h30)

Opening of the school and general introduction : Nora Dempsey and Oliver Gutfleisch, *Chairs*

I **Basic concepts (4h)**
- An introduction to magnetism in three parts : Wulf Wulfhekel, *Karlsruhe, Germany* (*p.13*)
- Magnetism for ions : Wulf Wulfhekel, *Karlsruhe, Germany.*

II **Magnetism in matter (4h30)**
- Mean field and beyond : Temperature dependance of spontaneous magnetization and anisotropy : Michael Kuzmin, *Dresden, Germany* (*p.15*).
- Exchange and ordering, Localized and band magnetism : Claudine Lacroix, *Grenoble, France* (*p.17*).

III **Temperature effects (4 . 5h)**
- Thermodynamics and phase transitions in magnetic systems : Karl Sandeman, *London, United Kingdom* (*p.25*).
- Mean field and beyond : Temperature dependance of spontaneous magnetization and anisotropy : Michael Kuzmin, *Dresden, Germany* (*p.15*).

IV **Magnetic characterization (4h)**
- Measurements in bulk magnetic materials (including anisotropy, magnetometry, calorimetry, susceptibility, high fields, neutrons, ...) : Fausto Fiorillo, *Torino, Italy* (*p.19*).
- Magnetic imaging techniques : Laura Heyderman, *Villigen, Switzerland* (*p.27*).

V **Magnetization processes (3h)**
- Simple concepts of magnetization processes - from macrospins to materials : Olivier Fruchart, *Grenoble, France* (*p.31*).

VI **Functional materials (6.5h)**
- Permanent magnets for energy - From fundamentals to applications : Oliver Gutfleisch, *Darmstadt, Germany* (*p.34*).
- Soft magnetic materials, from statics to radiofrequencies : Victorino Franco, *Sevilla, Spain* (*p.33*).
- Magneto-caloric materials : Karl Sandeman, *London, United Kingdom* (*p.25*).
- Magnetoelastic materials (magnetic shape memory, magnetostrictive) : Sebastian Fahler, *Dresden, Germany* (*p.35*).

VII **Devices (3h)**
- Challenges for bulk hard and soft magnetic materials in high performance electromagnetical devices : Geraint W. Jewell, *Sheffield, United Kingdom* (*p.42*).
- Magnetic MEMS for energy : Orphée Cugat, *Grenoble, France* (*p.47*).

VIII **Spintronics (4.5h)**
- Spin torque in spin valves and domain walls (macrospin to domain walls) : Michel Viret, *Paris, France* (*p.41*).
- Spin currents and spin caloritronics : Sergio O. Valenzuela, *Barcelona, Spain* (*p.44*).
- Multiferroics and magnetoelectric fields : Silvia Picozzi, *L'aquila, Italy* (*p.45*).

IX **Industry perspectives (3h)**
- Application oriented development of amorphous and nanocrystalline soft magnetic materials : Giselher Herzer, *Vacuumschmelze, Germany* (*p.37*).
- From physics to product - From MRAM to Magnetic Logic Unit : Lucien Lombard, *Crocus Technology, France* (*p.49*).

Tutorials (2-4h each)

Several tutorials will be organized to practice the use of numerical or analytical techniques, related to topics covered by the lectures. Computers will be provided on-site and readily setup for the tutorials. Each tutorial is typically 2-4h. Attendees will be asked for their wishes to attend such or such tutorials, however it is not possible to attend all tutorials. The list of tutorials will be updated on a regular basis.

- Energy losses in magnetic materials : Fausto Fiorillo, *Torino, Italy*
- Magnetization switching of single particles and assemblies - The Stoner-Wohlfarth model : Victorino Franco, *Sevilla, Spain*
- Units in Magnetism : Olivier Fruchart, *Grenoble, France*
- The random anisotropy model : Giselher Herzer, *Vacuumschmelze, Germany*
- Mean field approach in magnetism : Claudine Lacroix, *Grenoble, France*

Question-Answer sessions (5-10h)

The purpose of a research School is to provide young scientists with the basics in a working field. With this respect interactivity between students and lecturers should be promoted. Like in the previous editions, a key aspect of this interactivity is the possibility to raise questions at the end as well as during the course of the lectures. Besides, several sessions of questions will take place, during which the lecturers or voluntary students will present in more detail issues raised by the students during the lectures or anonymously through a question-box.

AN INTRODUCTION TO MAGNETISM IN THREE PARTS

Wulf Wulfhekel [1]

Introduction

The lecture on magnetism in three parts serves an an introduction to the origin of the magnetic moment in matter, the relevant magnetic phenomena and magnetic energies involved. It is aimed at bringing all students to a common and fundamental level and serves to lay the foundation for the more specialized lectures on aspects of magnetism.

Part I : The magnetic moment of the atom and crystal fields

Part I will begin with a short review of the Maxwell equations, the definition of the magnetic field H, the magnetic flux density B, the Magnetization M and their units in different systems. The source of magnetic moments in matter, i.e. circular charge currents and spin angular momentum, will be discussed. The magnetic moment of atoms and ions will be describes quantum mechanically based on Hund's rules and the Landé g-factor. Also problems is this perturbative approach will be mentioned related to the spin-orbit interaction and Berry phase phenomena in current density fields. When single atoms are placed in an environment, their rotational symmetry is broken by the crystal field of their neighbours. As a consequence, part of the orbital magnetic moment is quenched. Also depending on the size of the crystal field splitting, the ground state can deviate from that predicted by Hund's rule. We will discuss both 3d and 4f magnetism and their differences. Finally, we will discuss the thermodynamics of non-interacting magnetic moments in an external field and discuss simple models of the interaction of magnetic moments via quantum mechanical exchange. In the last part, we also discuss the technical use of the discussed phenomena.

Part II : The continuum model of magnetism

Taking a step back from the microscopic view, we will describe the densely packed discrete quantum mechanical magnetic moments as a continuum of a classical magnetization field of constant absolute value. This continuum model has been very successful in the description of ferromagnets even down to the nm scale. This is due to the fact that with size, the quantum mechanical nature is quickly lost in favour of a classical behaviour. We will discuss the relevant contributions to the total energy, i.e. the Zeeman energy of an external field, the magnetic anisotropy energy, the exchange energy and the dipolar energy, i.e. the Zeeman energy of the magnetic structure in a field that it creates itself. While the first terms are all local in nature, the last term is non local as it links every moment with every moment by dipolar interactions. The treatment of the first terms is rather straight forward ; the latter term brings complexity to the continuum model. We will discuss the special case that all magnetic moments stay aligned, i.e. the single domain limit. We will investigate the magnetostatic behaviour of single domain particles including all terms in the energy.

Part III : Thermal stability and hysteresis in single domain

particles In the last part, we will discuss the phenomenon of magnetic hysteresis, i.e. the fact that a ferromagnetic state has a memory. We will explain for ideal systems, how the coercivity and the remanence arises and discuss the thermal stability of the magnetization. We will show in how far this idealized Néel-Brown behaviour is realized in real samples and what effects lead to a deviation from the theory. This last part of the lecture has high relevance for magnetic information storage and we will illustrate, how this topic might develop in the near future. We will end with a short overview over dynamic phenomena in magnetic samples, such as the consequences of the magnetization being related to angular momentum. This causes precessional motion of the magnetic moments when exposed to an effective field.

1. Karlsruhe Institute of Technology, Germany

References

There are many good textbook that focus on magnetism. Particularly suited (reflecting my personal taste) are :

[1] Soshin Chikazumi, *Physics of Ferromagnetism*, Oxford University Press, 2nd edition, 672 pages (2009).
- Very comprehensive and comprehensible book that has recently been updated in the second edition.

[2] Stephen J. Blundell, *Magnetism in Condensed Matter*, Oxford University Press, 256 pages (2001).
- The most comprehensible and compact book on magnetism.

[3] J.M.D. Coey, *Magnetism and Magnetic Materials*, Cambridge University Press, 628 pages (2010).
- A very comprehensive and clearly written book with a lot of information also on magnetic materials. It is also available as e-book, eventually for free from your home university library.

MEAN-FIELD AND BEYOND :TEMPERATURE DEPENDENCE OF SPONTANEOUS MAGNETIZATION AND ANISOTROPY.

Michael Kuzmin [1]

Magnetic anisotropy energy is defined as part of the non-equilibrium thermodynamic potential of a ferromagnet that depends on the direction of the magnetization vector M. The approach is valid on condition that $|\boldsymbol{M}|$=const. The anisotropy energy is usually presented as an expansion in powers of $\boldsymbol{m} = \boldsymbol{M}/|\boldsymbol{M}|$ or, alternatively, in trigonometric functions of the spherical angles θ and ϕ. The form of this expansion is determined by the point symmetry group of the crystal. For example, for the hexagonal point groups C_6v, D_6, D_3h or D_6hs one has :

$$E_a = K_1 sin^2\theta + K_2 sin^4\theta + K_3 sin^6\theta + K_3' sin^6\theta cos6\varphi + \tag{1}$$

The coefficients in this expansion are known as anisotropy constants.
One of the most important sources of magnetic anisotropy is crystal (electric) field. It can be presented as an expansion of the effective (electrostatic) potential around the position of a particular atom over a suitably chosen basis. Alternatively, the crystal field is expanded in Stevens' operator equivalents O_n^m , which are functions of the operator of total angular momentum. Thus, e.g., $O_2^0 = 3J_z^2 - J(J+1)$ etc. The form of the crystal field expansion is dictated by the local symmetry group of the corresponding site. So for the hexagonal point groups C_6v, D_6, D_3h or D_6h the expansion of the crystal field Hamiltonian in the Stevens operators is as follows :

$$\mathcal{H}_{CF} = B_{20}O_2^0 + B_{40}O_4^0 + B_{60}O_6^0 + B_{66}O_6^6 \tag{2}$$

The quantities B_{nm} are called crystal field parameters.
The single-ion model of magnetic anisotropy relates the coefficients in both expansions, (1) and (2). Namely, in the above example,

$$\begin{aligned}
K_1 &= -3J^2 B_{20} B_J^{(2)}(x) - 40J^4 B_{40} B_J^{(4)}(x) - 168J^6 B_{60} B_J^{(6)}(x) \\
K_2 &= 35J^4 B_{40} B_J^{(4)}(x) + 378J^6 B_{60} B_J^{(6)}(x) \\
K_3 &= -231J^6 B_{60} B_J^{(6)}(x) \\
K_3' &= J^6 B_{66} B_J^{(6)}(x)
\end{aligned} \tag{3}$$

where

$$x = \frac{\mu H_{mol}}{kT} \tag{4}$$

and H_{mol} is the molecular field. Thus, temperature dependence of the anisotropy constants is described by three special functions, $B^{(n)}$, $n = 2, 4, 6$, called generalised Brillouin functions. The main postulate of the molecular field theory is the proportionality relation, $H_{mol} = \lambda M$, where λ is the molecular field constant. Depending on the nature of the electronic states – carriers of magnetism – one can formulate a localised or an itinerant version of the theory. Temperature dependence of spontaneous (H = 0) magnetization in the localised theory is given by a pair of parametric equations,

$$\begin{aligned}
kT &= \mu\lambda M_0 x^{-1} B_J(x) \\
M &= M_0 B_J(x)
\end{aligned} \tag{5}$$

The parameter x runs from 0 to ∞. A pair of equations similar to (5, 6) is also obtained in the itinerant version of the theory. The molecular field approximation is inaccurate in the limiting cases $T \to 0(x\infty)$ and $T \to T_C(x \to 0)$. For $T \to 0$ it predicts an exponential approach to saturation, whereas in real ferromagnets the magnetization follows Bloch's $\frac{3}{2}$ power law : $M \approx M_0(1\breve{} const.T^{3/2})$. This behaviour

1. Technische Universität Darmstadt

finds an explanation in the spin-wave theory. Near the Curie point the prediction of the molecular field theory is that $M \approx const. * (1 \breve{} T/T_C)\beta$, with $\beta = \frac{1}{2}$. The real situation rather more like a cross-over from $\beta = \frac{1}{4}$ to $\beta = \frac{1}{2}$, so that no power law is strictly fulfilled. Sometimes a power law with $\beta \approx \frac{1}{3}$ is used, but this is an approximation valid in a rather limited interval of temperatures. In practice, it is more convenient to use an empirical formula,

$$M = M_0 \left[1 - s \left(\frac{T}{T_c} \right)^{3/2} - (1 - s) \left(\frac{T}{T_c} \right)^{5/2} \right]^{1/3} \tag{6}$$

where s is an adjustable parameter describing the shape of the curve ($0 < s < 2.5$). Equation (7) applies anywhere between $T = 0$ and T_C.

Recommended Literature

1. J. S. Smart, *Effective Field Theories of Magnetism* (Saunders, Philadelphia, 1966).

2. M.D. Kuz'min and A.M. Tishin, Theory of Crystal-Field Effects in 3d-4f Intermetallic Compounds. In : *Handbook of Magnetic Materials*, edited by K.H.J. Buschow (North-Holland, Amsterdam, 2008), Vol. 17, Ch. 3.

EXCHANGE AND ORDERING-LOCALIZED AND BAND MAGNETISM

Claudine Lacroix [1]

1 Origin of exchange Interplay between Coulomb repulsion and Pauli principle Intra- and inter-atomic exchange

2 Exchange interaction in insulators Origin of superexchange Goodenough-Kanamori rules

3 Exchange in metals RKKY interactions Double exchange Band magnetism

4 Magnetic ordering Different types of ordering Rome of dimensionality : 1D/2D/3D systems Classical versus quantum spins

References

[1] R. Skomski, *Simple models of magnetism* (Oxford – 2008)
[2] S. Blundell, *Magnetism in Condensed matter* (Oxford – 2001)
[3] J. Stöhr and H.C. Siegmann, *Magnetism* (Springer – 2006)
[3] P. Mohn, *Magnetism in the solid state* (Springer- 2006)

Other books (more difficult) :
- K. Yosida, *Theory of magnetism* (Springer- 1996)
- P. Fazekas, *Electron correlation and Magnetism* (World scientific – 1999)

1. Institut Néel, CNRS-UJF, Grenoble, France

THERMODYNAMICS AND PHASE TRANSITIONS IN MAGNETIC SYSTEMS

Karl. G. Sandeman [1]

As William Gilbert noted in his 1600 treatise *De Magnete*[1], magnetic order is found below some critical temperature. But why and how does magnetic order emerge from disorder, or indeed from another ordered state ? Such questions are at the heart of the study of magnetic phase transitions. This lecture will discuss the thermodynamics of phase transitions, applied to the case of magnetic materials. We will examine mean field approaches including Landau theory, using the limitations of such approaches to motivate a discussion of Ginzburg-Landau theory and the roles of fluctuations and of spin waves. The material presented here will inform the discussion of magnetic phase transitions for room temperature magnetic cooling in the *Magnetocaloric materials* lecture. There are a number of suitable references on the topic of thermodynamics and phase transitions, not just in magnetic materials,[2,3,4] but also more generally.[5,6,7] A selection is given below.

References

1. William Gilbert, *De Magnete* (Peter Short, London, 1600). Searchable English version available at http ://www.gutenberg.org/files/33810/33810-h/33810-h.htm
2. N.W. Ashcroft and N.D. Mermin, *Solid State Physics* (Holt-Saunders Int., New York, 1976) Chapter 33.
3. S.J. Blundell, *Magnetism in Condensed Matter* (Oxford University Press, Oxford, 2001) Chapters 5-8.
4. J.M.D. Coey, *Magnetism and Magnetic Materials* (Cambridge University Press, Cambridge, 2010) Chapters 5 and 6.
5. P. M. Chaikin, and T. C. Lubensky *Principles of Condensed Matter Physics* (Cambridge University Press, Cambridge, 2000).
6. *The Physics of Phase Transitions – Concepts and Applications*, Ed. P. Papon, J. Leblond and P.H.E. Meijer (Springer-Verlag, Berlin Heidelberg, Germany, 2006) Chapter 7.
7. H. Nishimori and G. Ortiz, *Elements of Phase Transitions and Critical Phenomena* (Oxford University Press, Oxford, 2010) Chapters 1 and 2.

1. Department of Physics, Blackett Laboratory, Imperial College London, London, SW7 2AZ, United Kingdom

MEASUREMENTS IN BULK MAGNETIC MATERIALS

Fausto Fiorillo [1]

Introduction

This lecture will provide an introduction to a few important methods employed in the investigation of intrinsic and technical properties of magnetic materials. We shall treat in particular the following topics : 1 : Generation of intense magnetic fields ; 2 : Investigation of magnetic structures by neutron diffraction ; 3 : Measurement of Curie temperature and magnetic anisotropy. 4 :DC and broadband measurements of soft magnets ; 5 : Characterization of permanent magnets.

High Fields

Magnetic fields are in most cases generated by means of air-cored windings (solenoids, Helmholtz coils, etc.), but, due to obvious heating problems, the maximum available flux density in water-cooled windings is of the order of 0.1 T. There are two ways to generate higher fields in steady fashion : a : by use of an electromagnet or a permanent magnet ; b : by means of a superconducting solenoid. With magnets one can reach a maximum field around 2.5 T. Much stronger fields are obtained using either NbTi ($B_{max} \approx 9$ T) or Nb3Sn ($B_{max} \approx 20$ T) superconducting wires. Even higher fieldstrengths (up to about 30 T) are obtained by the resistive Bitter coils, actually a stack of copper disks with forced water cooling, which are available in few laboratories only. Hybrid sources, made combining a Bitter coil with a superconducting solenoid can overcome the 40 T barrier. Pulsed fields, obtained by discharging a capacitor bank in a solenoid, are routinely applied in industry for magnetization and demagnetization of permanent magnets. With stored energy of the order of 10-20 kJ, peak fields around 8 T can be reached. With several megajoule stored energies an order of magnitude increase of the peak fieldstrength can eventually be obtained, the ultimate limit being posed by the mechanical strength of the coil. By a pulsed field source one can achieve in a single shot the initial magnetization curve M(H) of a hard magnetic compound. By making the second derivative d^2M / dH^2 of the curve, a cusp is observed in correspondence of $H = H_k$, the anisotropy field, defined in a uniaxial material as $H_k = 2K_u/m_0M_s$. The anisotropy constant K_u is therefore retrieved, independent of the morphological and structural properties of the test specimen.

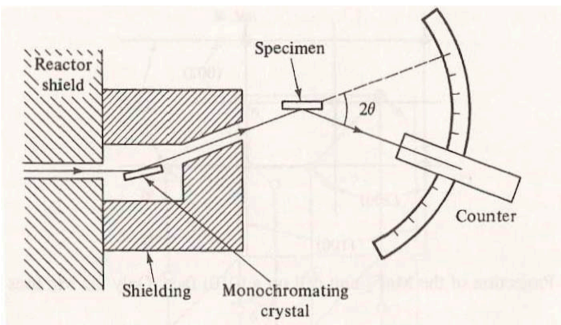

FIGURE 1 – Scheme of a neutron diffractometer. The neutron flux of a monochromatic beam obtained by a high-flux reactor is of the order of 1017 m ^{2}s ^{1}.

Neutron Diffraction

Neutrons have a small magnetic moment, about 10 ^{3} Bohr magnetons, and, being electrically neutral, act as penetrating probes and can be usefully exploited in the study of the intrinsic magnetic properties of bulk materials. Neutron diffraction has therefore become the standard technique for the analysis of the atomic-scale magnetic structure. With a wavelength of the order of 0.1 nm, thermal neutrons can be

1. Istituto Nazionale di Ricerca Metrologica-INRIM, Torino, Italy

diffracted by the atomic planes, according to the same Bragg rule describing X-ray diffraction, the nuclei now being the scattering centres. If the scattering ions have a magnetic moment, the amplitude of the diffracted wave will be affected and a magnetic contribution will add to the nuclear scattering.

Figure 1 shows the scheme of a neutron diffractometer. Either powder specimens or single crystals are investigated by this technique, which permits one to bring to light the magnetic structure at the atomic scale. Fig. 2 shows, for example, how antiferromagnetic order in the compound MnF_2 is revealed by the occurrence of a strong 100 superlattice line in the diffraction pattern below the Néel temperature ($T_N = 67K$).

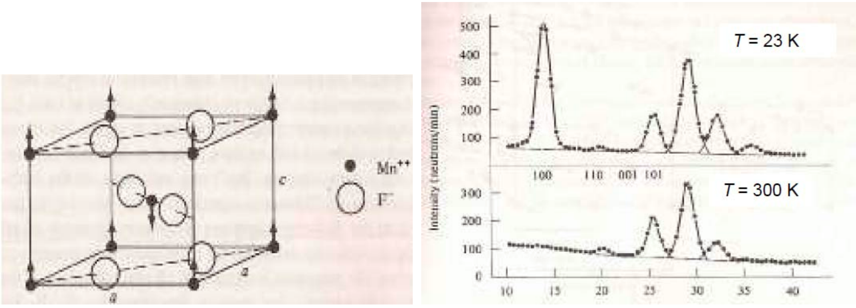

FIGURE 2 – Neutron diffraction pattern in MnF_2. This compound becomes antiferromagnetic below the Néel temperature $T_N = 67$ K.

Neutron diffraction experiments can provide, among other things, information on magnetic ordering around the ferromagnetic Curie temperature T_{cF}, usually distinguishable from the paramagnetic Curie temperature T_p. T_{cF} can also be obtained with a number of other methods, including the measurement of the initial susceptibility (Hopkinson's effect), the isothermal magnetization curves (Arrott plots), the specific heat anomaly by calorimetry.

Measurements of magnetization curve, hysteresis, and the related parameters

Measuring the magnetization curve of a ferromagnetic material requires either vanishing or accurately known demagnetizing field. The first option is most frequently required with *fluxmetric* measurements, where the material behaviour is obtained by detecting the flux variation ensuing from the application of a time-varying magnetic field. It is realized (Fig. 3) either by suitably shaping the test specimen or by resorting to a flux-closing yoke, which can also play the role of magnetizer (e.g. an electromagnet).

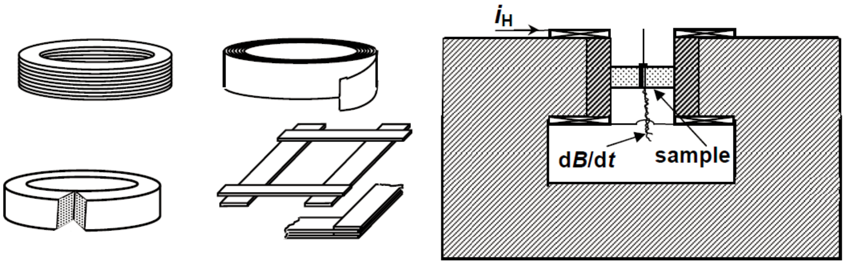

FIGURE 3 – How to form a closed magnetic circuit either shaping the sample or using a soft magnetic yoke. The latter method is typically adopted with permanent magnets.

Measurements on open samples are generally of *magnetometric* type, where the magnetic moment of a small specimen and its dependence on the applied field strength are determined exploiting the reciprocity principle. Fig. 4, where the sample is assimilated to a point-like magnetic dipole located in the midplane of an Helmholtz pair, provides an illustration of this principle. If the magnetic dipole is in the generic point of coordinates (x, y, z)) and has components (mx, my, mz), the general proportionality relationship between the linked flux ϕ_{sm} and the magnetic moment $\boldsymbol{m}$

$$\phi_{sm} = \mathbf{k}(x, y, z).\mathbf{m} = k_x(x, y, z).m_x + k_y(x, y, z).m_y + k_z(x, y, z).m_z$$

holds, where $\mathbf{k}$(x, y, z) is the coil constant. For a magnetic dipole located at the center of a filamentary coil of radius R, we obtain $\phi_{sm} = \mu_0 m/2R$. If the search coil is a Helmholtz pair, it is $\phi_{sm} = 0.1755\mu 0Nm/R$. The reciprocity principle is exploited in the popular Vibrating Sample Magnetometer (VSM) method, the preferred experimental approach to the DC characterization of thin films and recording media.

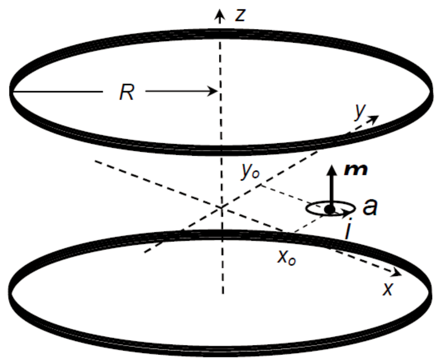

FIGURE 4 – A small sample of magnetic moment m is located in the midplane of a Helmholtz pair of radius R. It is represented as a loop of area a with a current i_m flowing in it ($m = a \cdot i_m$). The flux linked with the search coil is $\phi = k(x_0, y_0) \cdot m$, where $k(x_0, y_0)$ is the value of the coil constant at the loop position. For a moment m located at the center of the pair, each coil having N turns, it is $\phi = 0.1755 \cdot \mu_0 Nm/R$.

Measurements in soft magnetic materials

The applications of soft magnets may call for their characterization from DC to microwave frequencies, a feat made difficult by the correspondingly huge dynamic range, possible parasitic effects, and energy dissipation. These problems further compound with the non-linear response of the material. A suitably developed and calibrated fluxmetric device (the hysteresisgraph, Fig. 5) can permit one to achieve broadband characterization of most available soft magnetic materials. When dealing with industrial materials, the necessary requisite of reproducibility is guaranteed by observance of the recognized international measuring standards (for example, the IEC 60404 standards), which call for sinusoidal induction B(t). The determination of the B(H) hysteresis loops versus peak induction and frequency f is all what is needed for most applications, the property bearing chief technical interest being the magnetic power loss

$$P = f \oint H.dN = f \oint_0^T H(t)\frac{dB(t)}{dt}dt \ , [W/m3]$$

When increasing the testing frequency towards the MHz range, as often required by present-day trends towards device miniaturization, serious limitations arise. They are posed, for example, by the available exciting power, the resolution of the A/D converters, the stray capacitances and inductances, and sample overheating. It is then expedient to identify the material behaviour through the complex permeability $\mu = \mu' \breve{} j\mu''$ and its dependence on frequency. This quantity can be obtained up to the natural frequency limit posed either by relaxation losses or ferromagnetic resonance through characterization in a transmission line. In Fig. 6 a ring sample is tested in a coaxial cell by use of a network analyzer. Fig. 7 provides an example of correspondingly measured broadband (DC – 1GHz) permeability spectrum in a Mn-Zn ferrite, with crossover of μ' and μ'' around the ferromagnetic resonance region.

Measurements in permanent magnets

The characterization of permanent magnets is chiefly directed at the determination of those parameters of the hysteresis loop associated with their property of retaining the magnetization and the related energy in the absence of applied fields : remanent magnetization Jr, coercive fields $H_0 c$J and H_cB, energy product in the second quadrant (BH). The high values of the involved fieldstrengths, besides implying a clear distinction between the (J, H) and the (B, H) curves, makes manageable the correction for the

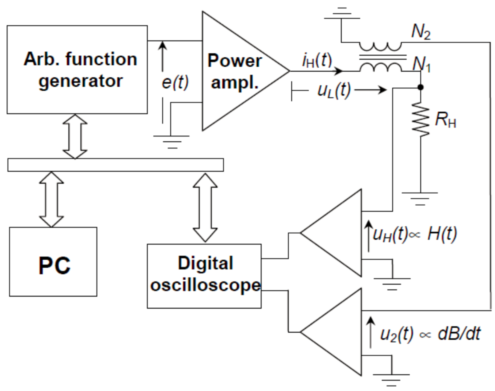

FIGURE 5 – Wattmeter-hysteresisgraph fluxmetric setup implementing digital control by recursive processing of the dB/dt waveform.

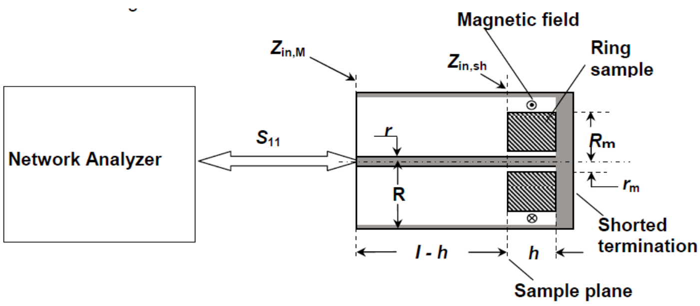

FIGURE 6 – Measurement of the complex permeability of a ring sample and its frequency dependence using the network analyzer. The sample is placed against the shorted termination of a coaxial line and the input impedance at the sample plane $Z_{in,sh}$, directly related to the permeability, is obtained by measurement of the reflection coefficient S_{11}.

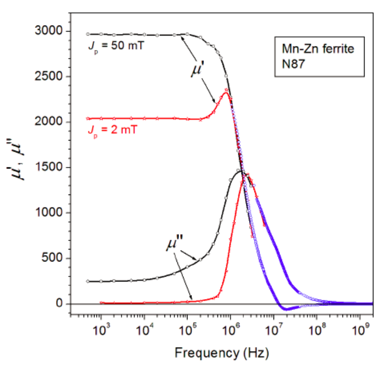

FIGURE 7 – Example of real (μ') and imaginary (μ'') permeability broadband spectrum measured in a Mn-Zn ferrite ring sample. The occurrence of ferromagnetic resonance is apparent in the behaviour of μ'.

demagnetizing field and opens the way to both closed-circuit and open-circuit measuring methods. The closed-circuit configuration with electromagnet was schematically shown in Fig.??. Various open-circuit methods are applied in the literature. Testing by the Vibrating Sample Magnetometer (VSM), frequently applied in industry and research, is based on the measurement of the magnetic moment m of a suitably small specimen by making it to vibrate at the center of a sensing coil assembly. In the example shown in Fig. 8 (transverse vibration) the instantaneous detected signal is $u(z,t) = m\frac{d}{dz}(k_x(0,0,z)).\dot{z}$ where $k_x$is the coil constant . Transverse vibration is adopted when the stepwise changing field Ha(t) is applied by an electromagnet or a permanent magnet source. Longitudinal vibration is adopted with superconducting solenoid sources. Other common open-sample methods are the Extraction Method and the Alternating Gradient Force Magnetometer. The latter is something of a VSM in reverse, where the coils, supplied by an AC current, are used to generate an alternating field gradient at the sample position. The correspondingly generated force on the sample, proportional to m, is revealed by a piezoelectric sensor.

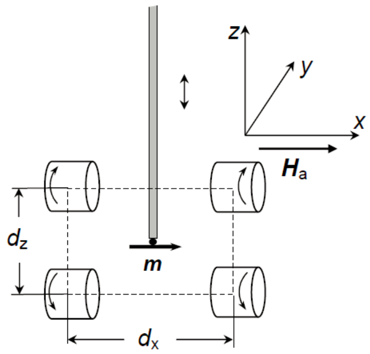

Figure 8 – Coil assembly used with perpendicular (z-axis) sample vibration (Mallinson's set). It is usually $d_z < d_x$. The arrows marked on the coils identify the way in which the signals from the coils are added. The sample is attached to a non-magnetic vibrating rod.

Conclusions

The broad range of properties and operating conditions of magnetic materials require an array of measuring methods, which must satisfy stringent requirements of reproducibility, besides providing solid physical information to fundamental and applied research studies. This lecture will try to convey, under the appropriate physical framework, the basic concepts involved in the realization of present-day measuring systems, aiming at the determination of both intrinsic and technical magnetic properties of the materials.

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MAGNETOCALORIC MATERIALS

Karl G. Sandeman [1]

Adiabatic demagnetisation is a magnetic cooling technology that has been used in research for many years to attain measurement temperatures below the boiling point of liquid ^{4}He (4.2 K). The science of its discovery contributed to the award of a Nobel Prize in Chemistry to William Giauque in 1949[1]. In the past 15 years, research into magnetic cooling at room temperature has grown rapidly due to the promise of appliance efficiencies that could better those of conventional gas-based refrigerators and the prospect of replacing greenhouse gas refrigerants with magnetic solids. Unlike the demagnetisation of paramagnets below 4.2 K, room temperature magnetic cooling uses the entropy change at a *magnetic phase transition.* This lecture will start by describing the classic adiabatic demagnetisation of paramagnets and will then use the material presented in the *Thermodynamics and phase transitions in magnetic systems* lecture to explore further the physics of magnetic phase transitions at room temperature. I will outline the progress towards room temperature magnetic cooling that has been made in the last 15 years and discuss some open questions that remain in the fields of fundamental physics, materials engineering and magnetic refrigerator design – questions that underline the multidisciplinary nature of magnetic cooling research. My starting point will be a discussion of the reported values of two measures of the magnetocaloric effect. These are the adiabatic temperature change, ΔT_{ad}, and the isothermal entropy change, ΔS, caused by the application of an applied magnetic field. The vast majority of experimental research literature reports estimates of ΔS but there is sufficient ΔT_{ad} data available to plot the two quantities together on a so-called Ashby plot of material performance (Figure 1).

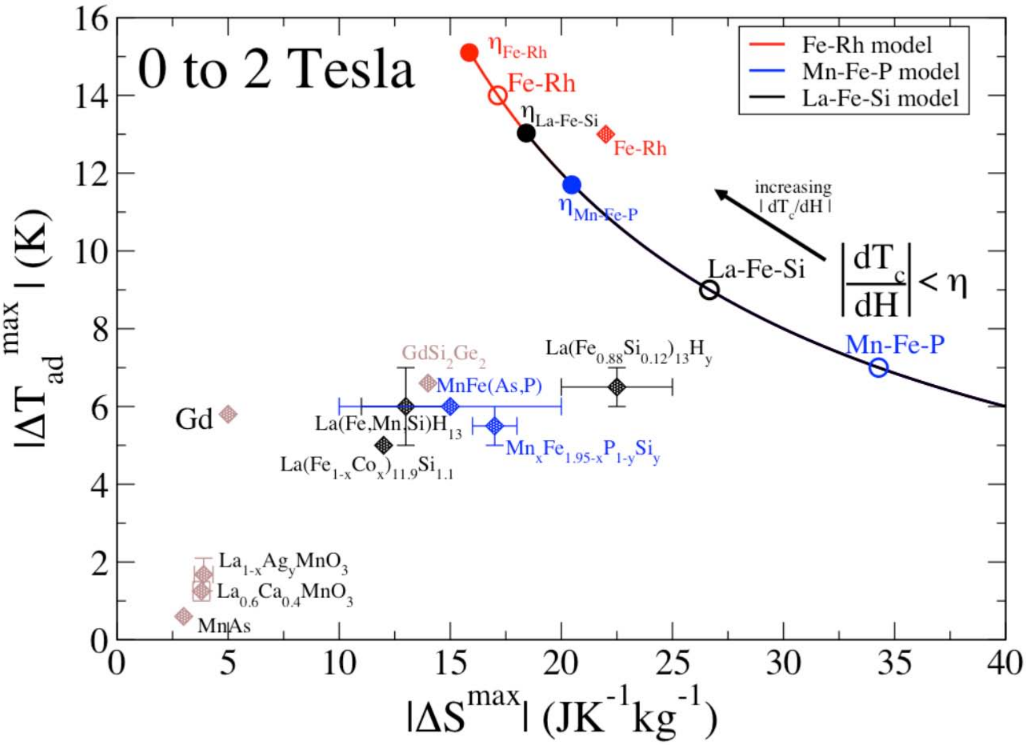

FIGURE 1 – An Ashby plot of magnetocaloric material performance around room temperature in an applied field of 2 Tesla (after Sandeman[2]). The diamonds are experimental data. Error bars arise from the variation in magnetothermal properties across a series of compositions. The circles are theoretical maxima while the solid line is a limit on the combined values of ΔS and ΔT_{ad} for a maximum magnetic field of 2 Tesla, assuming an approximate saturation magnetisation value for Fe-Rh, $(Mn,Fe)_2P$-based and La-Fe-Si-based compounds.

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Of the materials that possess appreciable values of both ΔS and ΔT_{ad}, there are three $3d$-metal based compounds that are being trialled in magnetic cooling devices : $(Mn,Fe)_2P$-based[3] and La(Fe,Si)13-based[4] compounds, and manganites.[5] A common feature that they possess (which is not shown) is a line of first order phase transitions in (field vs. temperature) phase space that terminates in a critical point close to room temperature.
I will explore why such critical or tricritical features in phase space are of interest in magnetocaloric materials, and why the search for room temperature (tri)critical points at moderate fields (1 Tesla) leads to the development of several areas, including

- novel methods of comparative material characterisation[6]
- finite temperature material modelling[7]
- the use of experimental and theoretical techniques to examine the role material structure at all length scales, from the atomic scale[8] to the microstructural scale[4]
- feedback between final device design and the engineering and magnetothermal performance of magnetocaloric materials[9,10]

Any presentation of magnetocaloric materials physics leads naturally to a discussion of other methods of solid-state cooling.[11] I will conclude with a brief overview of the progress and challenges in two related fields : electrocaloric[12] and elastocaloric materials.[13]

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MAGNETIC IMAGING TECHNIQUES.

Laura Heyderman [1]

In order to fully understand the behaviour of magnetic materials, it is very important to know how the magnetic configurations look at the microscopic scale. There are several microscope techniques that have been developed to observe magnetic domains, which have evolved hand-in-hand with techniques developed to, for example, measure material microstructure or determine surface properties. These techniques can be based in the laboratory or at large scale facilities. Laboratory based techniques include magnetic force microscopy, Kerr microscopy and transmission electron microscopy. At synchrotron X-ray facilities, photoemission electron microscopy and transmission x-ray microscopy are available.

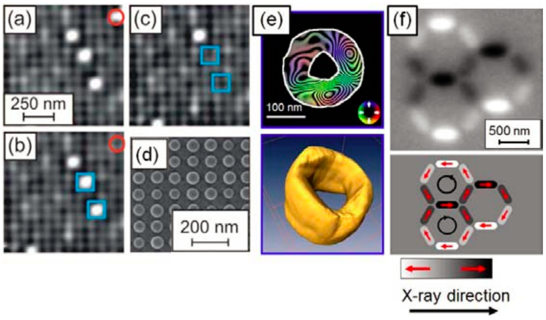

FIGURE 1 – Images demonstrating the usefulness of using different imaging techniques for the understanding of microscopic magnetic phenomena (a-c) MFM images of switching events in Co/Pt multilayer caps [1] coated on polystyrene nanospheres (d). (e) Electron holography image of the magnetic flux lines in a nanoscale magnetite ring depicted together with an electron tomography image of the same ring [2]. (f) Synchrotron x-ray photoemission electron microscopy image of the magnetic configuration in a so-called 'artificial spin ice' made up of interacting single domain nanomagnets [3].

Magnetic imaging techniques come with their own advantages and disadvantages, and are often complementary. Depending on the scientific or technological question that needs to be answered, there are several factors that should be taken into account in order to decide which technique to use. For example, some magnetic imaging techniques give a measure of the magnetization (Fig.1f), while others record the magnetic induction (Fig.1e) or are sensitive to magnetic stray fields (Fig.1a-c). Certain techniques are more suitable for measuring the magnetic configurations in materials with in-plane magnetic anisotropy, while others are better for the measurement of materials with strong out-of-plane magnetic components. Some techniques are more quantitative than others and some provide very high spatial resolution of a few nm's, which is particularly interesting when probing magnetism in systems confined to the nanoscale. One should also consider the depth sensitivity since some imaging techniques provide information from the full thickness of the film, whereas others are only sensitive to the surface. In terms of the sample environment, certain imaging methods require ultrahigh vacuum or other special requirements for the samples in terms of sample thickness, surface roughness, surface cleanliness, and material conductivity. For in-situ experiments, it is useful to know the maximum possible applied magnetic field or current, and whether the setup allows, for example, heating/cooling or application of strain to the samples. More advanced techniques provide not only magnetic information but also information about the crystallography, topography, chemical species, and/or electronic properties in parallel. Finally it is important to consider whether one would like to perform static or dynamic measurements and, if dynamic, what temporal resolution is required to capture the details of the evolving magnetic process.

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Some Useful Books

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3. J. Stöhr and H. C. Siegmann *Magnetism : From Fundamentals to Nanoscale Dynamics.*
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SIMPLE CONCEPTS OF MAGNETIZATION PROCESSES - fROM MACROSPINS TO MATERIALS

Olivier Fruchart [1]

Slides and lecture notes online : http ://perso.neel.cnrs.fr/olivier.fruchart/slides.html

Magnetic materials have various uses in applications, depending on how their magnetization reverses against applied fields or other stimuli. This behavior may be grasped in the form of hysteresis loops, from which global quantities are extracted such as coercivity, remanence, susceptibility, losses ; and the thermal and frequency dependence of these quantities. For example permanent magnets and data storage rely on remanence and coercivity, sensors and shielding on susceptibility, transformers on susceptibility and low losses. Therefore understanding magnetization reversal, with a view to further engineering it, is a major task in applied magnetism.

Magnetization reversal is often a complex process as a huge number of degrees of freedom is at play with multiscale and non-linear effects, not speaking of microscopic details (microstructure and defects) of real systems which often are not known precisely. Real systems can therefore be handled analytically only at the expense of simplifying assumptions. Grasping the essential aspects of magnetization reversal is crucial for selecting the assumptions to be made and retaining only the parameters most relevant in a given situation. Only this allows one to deliver accurate understanding and predictions using simple models.

Magnetization reversal is determined by the several sources of energy characterizing magnetic materials : exchange, anisotropy, Zeeman, dipolar. As always in physics, the competition between different energies yields characteristic length scales. Nanomagnetism may have been called mesomagnetism, i.e. the scale where macroscopic (schematically magnetic domains) and microscopic (schematically sizes of a few nanometers where exchange dominates) scales meet. Following this idea the lecture will be divided in three parts.
The first part considers macrospins (single-domains), strictly speaking applicable only in the limit of very small sizes (circa 10nm), however also suitable to introduce many phenomena applicable to all materials
The second part deals with micromagnetism, considering well-defined elements at a mesoscale.
The third part considers magnetization processes at play in extended systems.
The fourth part is a practical guide on what to do with hysteresis loops in order to better understand the magnetization processes at play in your system.

Single-domain concepts

The basic ingredients of magnetization reversal are magnetic anisotropy and Zeeman energies. The first one sets energy minima separated by energy barriers, responsible for metastability underlying coercivity, while the latter helps overcoming these energy barriers. Therefore the simplest and earliest models of magnetization reversal consider these two ingredients only. Setting aside exchange energy implies that magnetization is assumed to be uniform in the systems considered. This yields so-called coherent rotation models, as first outlined by Stoner and Wohlfarth [STO48], and the famous astroid first drawn and geometrical constructions discussed to infer various informations by Slonczewski [SLO56]. In a simple case we will derive energy barriers preventing magnetization reversal, and infer the dependence of coercivity on temperature and time scales, and introduce the effect of superparamagnetism. Relevance for real small magnetic elements will be discussed based on examples.

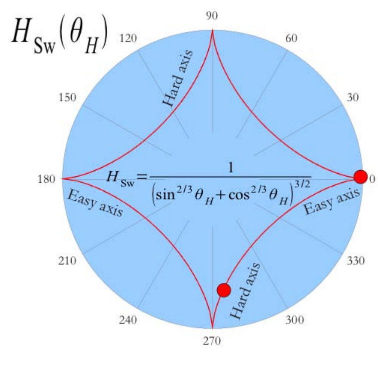

FIGURE 1 – The Stoner-Wohlfarth astroid : the polar plot of the reversal field under the assumption of coherent reversal.

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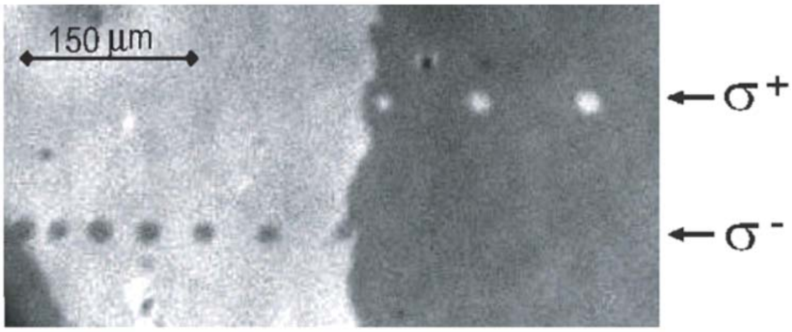


FIGURE 2 – All-optical magntization reversal using the inverse Faraday effect [STA2007].

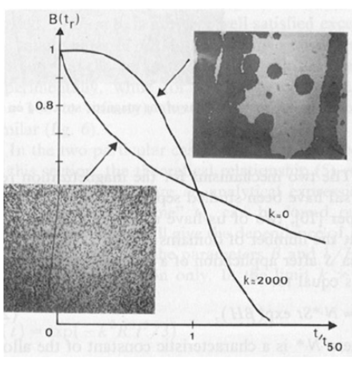
In the past decade, new ways of reversing magnetization have emerged. These open new fundamental fields, as well as potential applications. We will shortly discuss thermally-assisted reversal (decrease the coercivity with heating), precessional dynamics and switching [BAC1999] (typical time scale 1ns), spin transfer torque [SLO1996,BER1996] (reversal using spin-polarized currents as a mean to bring the momentum required to reverse magnetization), electric fields [WEI2007] (direct through charge transfer, or through induced stress), all-optics [STA2007] (so-called inverse Faraday and Kerr effects).

Micromagnetism

Micromagnetism describes magnetization arrangements and processes at the mesoscale, beyond macrospins however at a length scale where phenomena may still be described analytically or numerically, possibly based on suitable assumptions. It typically covers the range 10nm to one micrometer. Flat thin film magnetic elements patterned by e.g. lithography are model systems for micromagnetism, owing to their relative simplicity (two-dimensional magnetization configurations), and our ability to essentially characterize them fully using plane view magnetic microscopies. There are also obviously objects of prime importance for technology. As a consequence their study is extremely well documented, and we will base our description of micromagnetism on such elements. Characteristic length scales of nanomagnetism will be introduced : dipolar and anisotropy exchange length, quality factor. Well below these length scales systems are mostly uniformly-magnetized. Upon increasing their size deviations from strictly- speaking single-domain appear (e.g. flower and leaf states associated with configurational anisotropy [SCH1988,COW1998]). Above these sizes flat elements may retain an essentially single-domain magnetization configuration owing to the shorter range of dipolar field in two dimensions. Then end domains may occur leading to so-called C and S states ; engineering of the coercivity with end geometries (e. g. flat or pointed) will be outlined. Non-single-domain states will finally be described, with the vortex state, and more generally the Van den Berg construction [VAN1984], and Bryant and Suhl model for flux-closure domains.
We will also introduce basics about domain walls : The Bloch domain wall, domain walls in thin films (Bloch versus Néel [NEE1955], energetics of domains versus their angle, its consequences such as cross-tie walls, domain walls and magnetic vortices [SHI2000] in stripes and wires. Various reviews are available on micromagnetism : [HUB1999], [MAR2003], [SLO2003], [FRU2005], [FRU2012].

Coercivity in materials

In real extended systems the assumption of uniform magnetization is obviously not valid, and coherent rotation models usually fail.
In particular the experimental value of coercivity is often much smaller than the one expected from the value of anisotropy. This discrepancy has long been known as Brown paradox. This 'paradox' is lifted by the fact that in reality magnetization reversal instead proceeds via nucleation of small reversed domains, and possibly the



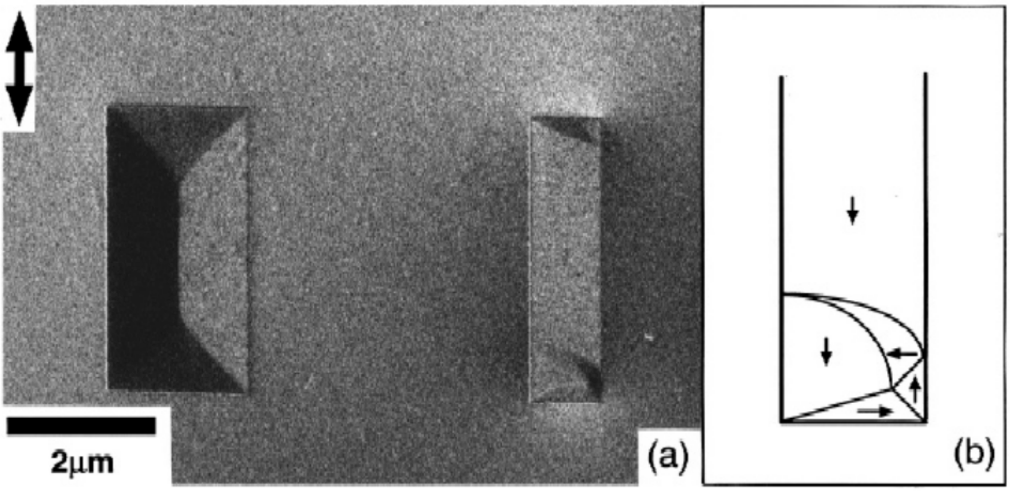


FIGURE 3 – Flux-closure (so-called Landau state, left) and essentially single-domain state with end domains (right) [KIR1997].

propagation of the associated domain walls [GIV2003]. This stresses that the engineering of microstructure is of particular importance to hinder or ease these processes to yield application-oriented materials, such as highly-coercive materials (permanent magnets). Simple models to account for these processes will be presented, including microscpic models such as the Kondorski model for model relevant for thin films.

What do you learn from hysteresis loops ?

Hysteresis loops, also called magnetization curves, are the most widespread means of characterizing a magnetic material. We will present a practical guide on what to do with hysteresis loop to gain knowledge on your system. Some issues covered will be : extract magnetic moments, magnetic anisotropy, consider interactions and distributions such as with FORC diagrams [PIK1999], signatures for various magnetization processes (eg nucleation versus propagation), temperature effects.

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SOFT MAGNETIC MATERIALS, FROM STATICS TO RADIOFREQUENCIES

Victorino Franco [1]

There are multiple ways in which magnetic materials can contribute to saving electric power and reducing CO2 emissions. For example, the conversion of electrical energy into mechanical work and vice versa is done using electric motors and generators, respectively, which imply the use of hard and soft magnetic materials. For electric vehicles, magnetic materials which retain their properties up to moderately high temperatures are needed. Advanced amorphous and nanocrystalline soft magnetic materials are also of interest for inductors/transformers in high frequency power electronics components and power conditioning systems. Thus, optimizing soft magnetic materials and extending the temperature span in which they are applicable can imply a notable enhancement in the energy efficiency of these devices. In this lecture we will overview the different families of soft magnetic materials with current technological interest, ranging from those which represent the largest volume in the global market (non-oriented and grain oriented electrical steels) to those with the lowest coercivity (amorphous and nanocrystalline alloys). We will focus on the mechanisms by which low coercivity values can be achieved, as well as on the different properties which should be optimized for a material to be suitable for its application as a soft magnet in the quasistatic frequency range or up to radiofrequencies.

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PERMANENT MAGNETS FOR ENERGY – FROM FUNDAMENTALS TO APPLICATIONS

Oliver Gutfleisch [1]

Due to their ubiquity, magnetic materials play an important role in improving the efficiency and performance of devices in electric power generation, conversion and transportation. Permanent magnets are essential components in motors and generators of hybrid and electric cars, wind turbines, etc., and improvements in magnetic materials will have a significant impact in this area, on par with many "hot" energy materials efforts (e.g. hydrogen storage, batteries, thermoelectrics, etc.). An increase in the magnetic energy density (BH)max, increases the efficiency of the device making it smaller and lighter.

The lecture focuses on the state-of-the-art of permanent magnet concepts and materials with an emphasis on their optimization for energy applications. The synthesis, characterization, and property evaluation of the materials will be examined having in mind the critical micromagnetic length scales of the 3d-4f compounds. The principle processing routes for various types of magnets will be elucidated. Especially the structure-property relationships impacting on coercivity will be discussed. Considering future bottle-necks in the rare earths and in the supply chain concepts for reduction and substitution will be explored. Using this example, the analysis of criticality of metals and their life cycle will be briefly introduced. Finally, options for recycling of rare-earth metals will be discussed ("from urban mine to magnet").

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MAGNETOELASTIC MATERIALS

Sebastian Fähler [1]

Introduction

In magnetoelastic materials an external magnetic field can change the elastic properties and the extension of a magnetic material. This can be used either directly for actuation or the reverse effect allows for sensing and energy harvesting. Goal of this lecture is to explain the different underlying physical concepts of magnetostrictive materials and magnetic shape memory (MSM) alloys. This includes a short excursion to diffusionless phase transformations, which is also needed to understand magnetocaloric materials. With some examples it will be illustrated how these materials can be implemented in devices. Most of the following is taken from 1), which gives a state of the art summary of magnetic shape memory alloys.

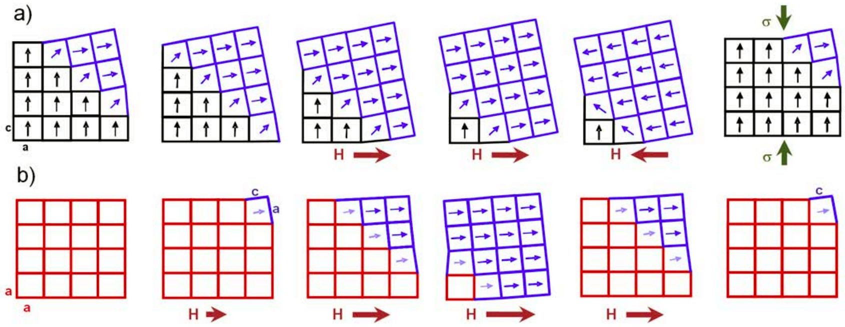

Figure 1 – Controlling microstructure (a) and structure (b) of magnetic shape memory alloys by magnetic fields. a) During Magnetically Induced Reorientation (MIR) the magnetic field H moves twin boundaries in a way that variants with their easy magnetization axis parallel to the external field (blue) are favored compared to those aligned perpendicularly (blue). Since the easy axis coincides with the short c-axis the sample shrinks along the field direction. Using negative field direction does not affect variant orientation. However, for reversible actuation with strains up to 10% the original state can be restored by mechanical stress σ, which aligns the short c-axis. b) During a Magnetically Induced Martensite (MIM) transition the magnetic field induces the martensitic phase, exhibiting a higher magnetization. The sketch illustrates the movement of the austenite(red)/martensite(blue) phase boundary. When removing the magnetic field the original austenitic state is restored.

In magnetoelastic materials there are different ways of coupling between magnetism and crystal lattice. In magnetostrictive material spin-orbit coupling allows to change the orbits and thus the distance between the atoms when changing the direction of the magnetic field. This allows obtaining strains up to 0.24% in low magnetic fields and with reasonable forces.

Magnetic shape memory (MSM) alloys can reach strains of up to 10%, which are about two orders of magnitude more than common magnetostrictive materials and the piezoelectric materials applied today. Since MSM materials can be driven with frequencies up to the kHz regime, the unique combination with very large strain and high energy density allows for novel applications, which are not feasible using other adaptive materials. Due to the large strain MSM actuators often can be used directly, without any complex mechanical amplification. This is of particular importance for micro actuators and sensors, where things have to be kept simple.

MSM alloys are one of the rare materials where a relatively small energy input supplied by moderate magnetic fields is sufficient to control the sample's microstructure. The underlying mechanism, Magnetically Induced Reorientation (MIR) of martensitic variants, is sketched in fig. 1.a. Starting point is a twinned martensitic microstructure, which had been formed by a diffusionless transformation. This microstructure consists of variants with different crystal orientation, which are connected by twin boundaries. In case of materials with large magnetocrystalline anisotropy it can be energetically favorable to move

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these twin boundaries in order to orient variants with their easy magnetic axis towards the direction of the external field. During MIR the crystal structure remains the same since only the orientation of the unit cell is affected. As the crystallographic axes differ in length, the extension of the sample is changed by the magnetic field. MIR requires highly mobile twin boundaries. Indeed in the best samples twin boundaries can be moved by a fraction of a MPa. This means that you can deform these samples with your fingers like rubber − though they are a metal. This is in strong difference to steel – another ferromagnetic material, where martensite formation is used for hardening.

Also the sample structure can be controlled by a magnetic field. The Magnetically Induced Martensite (MIM) effect is sketched in fig.1b. In case that the martensite exhibits a higher magnetization compared to the austenite, an external magnetic field favors the martensite phase by thermodynamics. Though this structural transformation may also be used for high force actuation, it is more promising to use the associated latent heat of this first order transformation for magnetocaloric refrigeration. For this type of application so-called metamagnetic martensites are of particular interest. In these materials the magnetic state changes with the structure such that the austenitic phase exhibits a substantially higher magnetization compared to the martensite, hence one obtains a Magnetically Induced Austenite (MIA) effect.

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APPLICATION ORIENTED DEVELOPMENT OF AMORPHOUS AND NANOCRYSTALLINE SOFT MAGNETIC MATERIALS.

Giselher Herzer [1]

Introduction and Basic Features

The talk surveys characteristic features of amorphous and nanocrystalline alloys particularly relevant for soft magnetic applications. Both materials have much in common starting from their way of production by rapid solidification as a thin ribbon and ranging over to the key factors which determine their magnetic properties. Thus, their structural correlation length, D, is much smaller than the exchange length L_{ex} (domain wall width). This results in a virtually negligibly magneto-crystalline anisotropy contribution (Fig.1) the prerequisite for good soft magnetic behaviour.

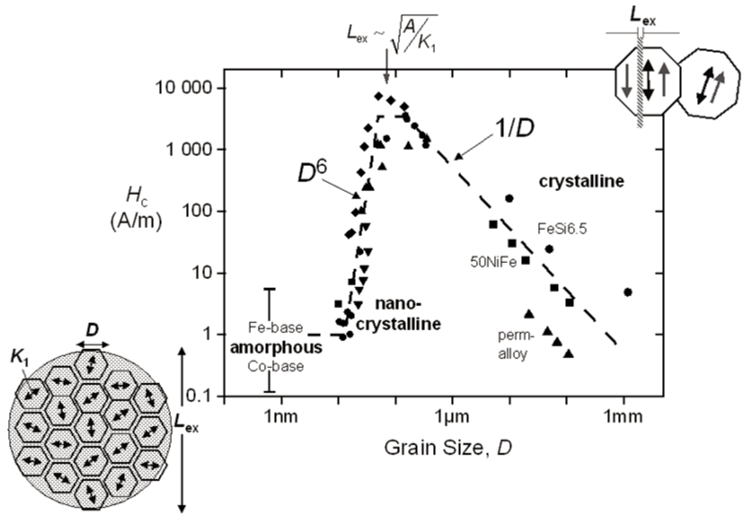

FIGURE 1 – Coercivity, Hc, versus structural correlation length (grain size), D, for various soft magnetic metallic alloys. In amorphous and nanocrystalline systems the randomly oriented magnetocrystalline anisotropy, K_1, is averaged out due to the smoothing effect of exchange interaction A.

Superior soft magnetic properties additionally require a low magnetostriction (Fig.2). This is realized for amorphous Co-based alloys and for nanocrystalline Fe-base alloys on which we will focus. An important point to stress is that for both amorphous and nanocrystalline materials a vanishing saturation magnetostriction λ_s really results in stress insensitivity of the soft magnetic properties. This is again a consequence of the small structural correlation length. The situation, thus, contrasts with that for large grained crystalline systems, where an average zero saturation magnetostriction does generally not imply stress-insensitivity of the hysteresis loop.

Due to their production inherent low thickness and relatively high electrical resistivity, finally, rapidly solidified materials additionally reveal a favourable high frequency behaviour making them even competitive with MnZn ferrites (Fig.3). This is ultimately a most important issue for their success in application.

Tailoring the Soft Magnetic Properties

Soft magnetic applications typically require a well defined shape of the hysteresis loop with a specific level of permeability. This is accomplished by annealing induced uniaxial anisotropies. In particular, magnetic field induced anisotropies are of tremendous practical relevance. Their orientation relative to the

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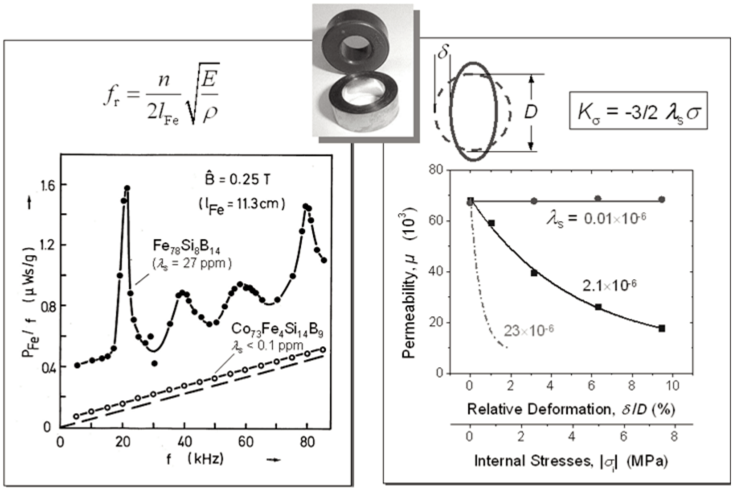

FIGURE 2 – Effect of magnetostriction on losses P_{Fe} and permeability.

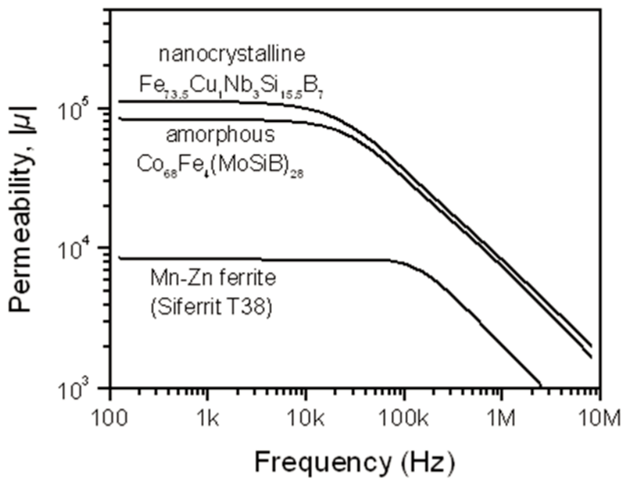

FIGURE 3 – Permeability as a function of frequency for an amorphous and nanocrystalline alloy in comparison with a ferrite core.

magnetic path controls the shape of the hysteresis loop (Fig.4a). The magnitude of the induced anisotropy constant, K_u, controls the level of the permeability (Fig.4b) and, particularly for square loops, it is a decisive factor for excess eddy current losses (Fig.5). Appropriate choice of the alloy composition and the annealing conditions allows to vary K_u by about three orders of magnitude.

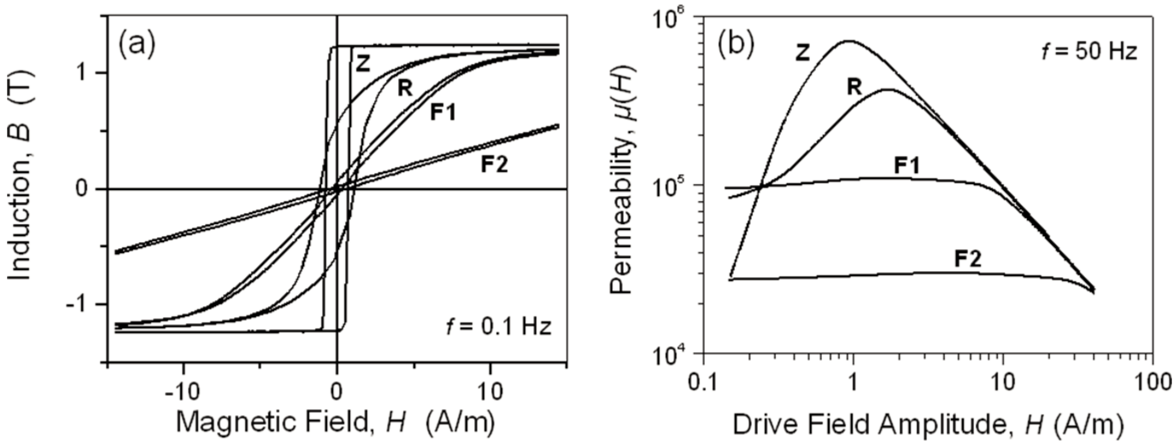

FIGURE 4 – Typical dc hysteresis loops and 50 Hz permeability of nanocrystalline $Fe_{73.5}Cu_1Nb_3Si_{15.5}B_7$ (VITROPERM® 800) annealed without magnetic field (R), with a magnetic field oriented parallel (Z) and transverse (F1, F2) to the magnetic path (F1 and F2 refer to different temperature time profiles ref).

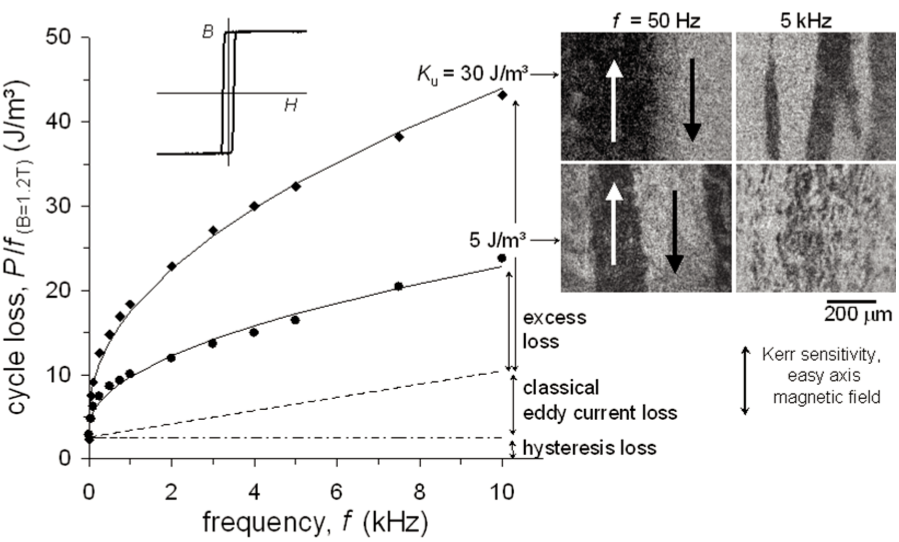

FIGURE 5 – Power loss and dynamic domain structure of nanocrystalline $Fe_7 3.5Cu_1Nb_3Si_1 5.5B_7$ (VITROPERM® 800) with a square loop achieved by inducing a weak and strong longitudinal anisotropy Ku, respectively.

Conclusions

Amorphous Co-base and nanocrystalline Fe-base alloys presently offer the best available static and dynamic soft magnetic properties. Both alloy systems reveal isotropic near-zero magnetostriction. The advantages of the nanocrystalline material are its higher saturation induction of at least 1.2 T and a significantly better thermal stability of the soft magnetic properties. The combination of high saturation magnetization, high permeability, good frequency behaviour, low losses and the good thermal stability allows the reduction of size and weight of magnetic components used in, for example, switched mode power supplies or telecommunication. Apart from its technical performance the material is based on the inexpensive raw materials iron and silicon. Accordingly, nanocrystalline alloys are found in a steadily increasing number of applications previously served by amorphous Co-based alloys or MnZn ferrites. Yet, the variability of their soft magnetic properties as well as their form of delivery so far is still restricted compared to amorphous or other soft magnetic materials. Thus, amorphous alloys may reveal good soft magnetic properties already in the as quenched state or after moderate annealing. They, hence, can be delivered as a semi-finished, ductile product useful for e.g. flexible magnetic screening or for sensor applications, most noticeably in electronic article surveillance. Accordingly, the major draw-back of the nanocrystalline materials is the severe embrittlement upon crystallization which requires final shape annealing and restricts their application mainly to toroidally wound cores.

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SPIN TORQUES IN SPIN VALVES AND DOMAIN WALLS

Michel Viret [1]

Spintronics traditionally relies on a basic device called a 'spin valve' composed of two ferromagnetic layers separated by a nonferromagnetic one. Depending on the relative magnetic orientation of the ferromagnetic layers, the resistance of the stack switches between low and high values, thus demonstrating the influence of charge carriers' spins (controlled via the magnetization) on the electrical properties of the device. The non magnetic spacer layer can also be a tunneling barrier which leads to very large magnetoresistance (over 500%) effects are obtained in Fe/MgO/Fe). These have been commercialized as magnetic fields sensors and memory elements where the information is stored in the magnetization. This has triggered an impressive increase in the density of data storage which largely contributed to the revolution of information technologies.

A more recent advance relies on the effect of a spin polarized current on ferromagnetic layers [1] . It has indeed been demonstrated that the angular momentum lost by spin carriers as their polarization changes direction passing through differently magnetized layers is given to the local magnetization and is able to switch it. This is an important new addition to spintronics as it opens the way to a pure electrical control of magnetization in spin valves. Furthermore, spin currents can also affect the magnetization dynamics and even induce ferromagnetic resonance. Specially designed spin valves can therefore be used as integrable and agile and nano radio-frequency sources (a clear dependence of the emitted frequency with the input current intensity) much in demand for applications. The early prediction [2] and subsequent confirmation that domain walls, the regions separating different magnetic domains, can also be moved by (spin-polarized) electrical currents offers an attractive alternative in designing novel devices such as sensors and magnetic random-access memories. Indeed, domain walls are now considered as possible objects for high-speed logic, where each wall represents a single bit. In IBM's racetrack memory [3] project, the walls can be moved with a current and the information read, either with optical techniques or electrically. Driven by these enormous prospects for technological applications, active studies of domain walls are underway worldwide.

In this lecture, the different spin-transfer torques, often studied independently will be addressed. I will cover theory and experiments on magnetization reversal, domain-wall displacement and nano-oscillators. Indeed, since the first theoretical proposal on spin-transfer torque—reported by Berger and Slonczewski independently—spin-transfer torque has been experimentally demonstrated in vertical magnetoresistive nano-pillars and lateral ferromagnetic nano-wires. In the former structures, an electrical current flowing vertically in the nano-pillar exerts spin torque onto the thinner ferromagnetic layer, which can be used to either reverse magnetization or generate radio-frequency. In the latter structures, an electrical current flowing laterally in the nano-wire exerts torque onto a domain wall and moves its position by rotating local magnetic moments within the wall, i.e., domain wall displacement.

The theoretical understanding of magnetization dynamics during reversal as well as domain wall displacement can be understood using the conventional Landau-Lifshitz–Gilbert (LLG) equation, adding a spin-torque term. Basic analytical models will be introduced which can explain the details of the spin current induced magnetization dynamics and domain wall motion mechanisms. A short overview on materials and potential applications will conclude the lecture.

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CHALLENGES FOR BULK HARD AND SOFT MAGNETIC MATERIALS IN HIGH PERFORMANCE ELECTROMAGNETICAL DEVICES

Geraint Jewell [1]

This lecture will discuss the many properties of bulk hard and soft magnetic materials which determine their suitability for the most demanding future applications for electrical machines and actuators. The range of properties offered by commercially produced and latest state-of-the-art development grades of hard and soft magnetic materials will be reviewed within the context of their practical deployment in electrical machines and drives for applications ranging from high power density drives for aerospace through to multi-MW scale offshore wind generators. Many of the key properties used as figures of merit in magnetic material development to will be discussed in terms of their impact on the ultimate performance of the electromechanical devices into which they will be incorporated. This will include discussion of some often overlooked properties such as electrical conductivity, thermal conductivity and the coefficient of thermal expansion. A particular focus of the lecture will be the challenges in terms of material requirements, characterisation and modelling for applications in which the magnetic components are exposed to temperatures in excess of 300°C, as might encountered for example in aircraft engines, process equipment, nuclear power generation and bore-hole drilling. In many such applications, some of the magnetic components may also be subjected to high levels of mechanical stress and extreme level of internally generated losses. Within the context of high temperature applications, on-going research on the performance of Cobalt-Iron alloys at elevated temperatures will be discussed in detail, including the effects of extended ageing (e.g. 1000s of hours at 400°C) on core loss and means by which such ageing effects can be accommodated into the device design process, including extensive material characterisation. The trade-offs which must be made between enhancing mechanical and magnetic properties of Cobalt-Iron alloys will be illustrated by a case studies on a high-performance switched reluctance machine and a high temperature linear actuator. The lecture will conclude by drawing together a 'wish-list' of improvements in properties of both hard and soft magnetic materials which would have significant impact on the performance of electrical machines.

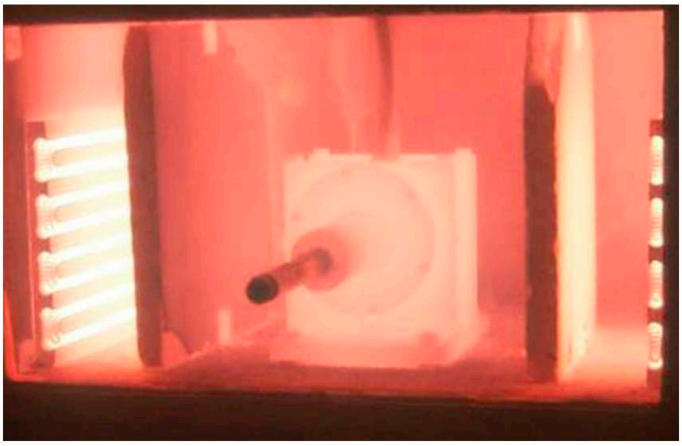

FIGURE 1 – Cobalt Iron linear actuator operating at 800°C.

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1. The University of Sheffield, United Kingdom

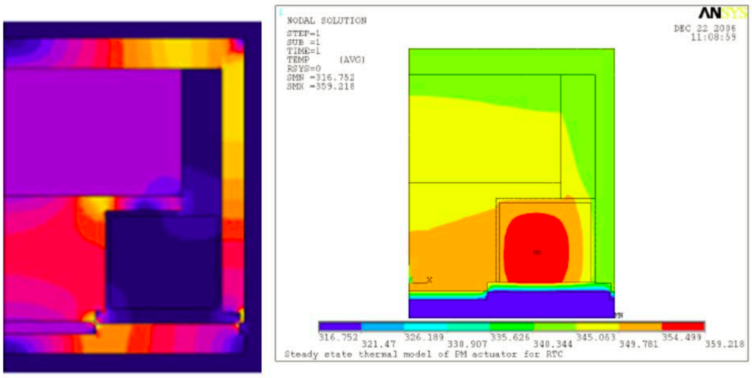

FIGURE 2 – Electromagnetic and thermal modelling of a high temperature linear permanent magnet actuator.

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SPIN CURRENT AND SPIN CALORITRONICS

Sergio O. Valenzuela [1]

The coupling between spin and charge transport is studied in the field referred as spin-electronics or spintronics. The field of spin caloritronics focuses on the interaction of spins with heat currents and combines spintronics with thermoelectrics and magnetism [1]. Spin caloritronics is as old as spintronics ; it started in the 1980's with the work of Johnson and Silsbee, who applied the methods of nonequilibrium thermodynamics to study the transport of charge, heat, and nonequilibrium magnetization in metallic heterostructures [2]. The field remained largely unexplored for many years and has been stimulated by newly unveiled physical effects that may lead to the development of novel thermoelectric devices [3-6]. These new phenomena include collective effects caused by spin waves that can be observed in both metals and insulators, such as the spin Seebeck effect [4], and effects that can be modeled by two parallel spin-transport channels with distinctive thermoelectric properties that can only be observed in metals, such as the thermal spin-transfer torque [5]. In this lecture, I will give an overview of our understanding and the experimental state-of-the-art of spin caloritronics.

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1. Institució Catalana de Recerca i Estudis Avançats (ICREA), and Catalan Institut of Nanoscience and Nanotechnology (ICN2), Barcelona, Spain.

MULTIFERROICS AND MAGNETOELECTRIC FIELDS

Silvia Picozzi [1]

Introduction

Multifunctionality is one of the keywords in modern materials science, with a star role featured by ***multiferroics*** (i.e. compounds showing more than one of the following long-range orders : magnetic order, dipolar order or spontaneous deformation). Indeed, their many active and competing degrees of freedom give rise to a plethora of phenomena, ranging from exotic magnetic/charge/spin/orbital orders to colossal responses to external fields, thus offering a huge potential for both rich basic physics as well as unprecedented technological applications. In this lesson, I will give an overview on the vaste phenomenology offered by multiferroics and magnetoelectrics [i.e. compounds where a magnetic (electric) field can control ferroelectric (magnetic) properties], both in the bulk phase as well as at (oxides-based) junctions, focusing on the microscopic mechanisms driving multiferroicity and magnetoelectricity. In addition, we will briefly discuss how these complex materials can be modelled, also showing some recent examples where theory and experiments gave a successful interpretation of the physics at play in relevant multiferroics.

Main Topics

- Multiferroics : What are they ? Why are they useful ? Why are they “complex” ? Are they “many” or “few” ?
- How to achieve ferroelectricity in transition-metal oxides :
  1. Proper ferroelectricity : the physics of lone-pair
  2. (Electronically driven) Improper ferroelectricity :
     - Spin-ordering driven (spin-spirals, collinear antiferromagnets)
     - Charge-ordering driven
     - Combination of spin and charge-ordering
     - Examples of prototypical improper multiferroics
- Novel candidates and new mechanisms : manganites layered materials, ferrites, organic crystals, metal organic frameworks
- Magnetoellectricity : how to control magnetic properties via an electric field and ferroelectric properties via a magnetic field.
- Composites : Magnetoelectricity at ferroelectri/ferromagnetic interfaces
- Bref review on the physics of domain and domain walls in ferroic materials (if time permits)
- Challenges and perspectives

1. Consiglio Nazionale della Ricerche (CNR-SPIN L’Aquila, IT)

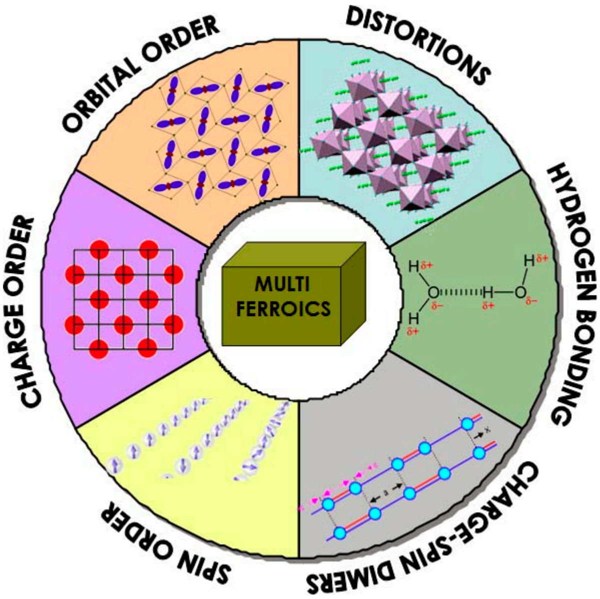

FIGURE 1 – Pictorial representation of the different microscopic mechanisms that can lead to multiferroicity (adapted from Ref. 6).

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MAGNETIC MEMS FOR ENERGY

Orphée Cugat [1]

Introduction

This course will introduce the benefits of exploiting magnetism for MEMS, and illustrate applications of magnetic MEMS to the global field of Energy.

Part 1

How and why homothetic downscaling of magnetic systems are generally favourable to magnetic interactions, between magnets and/or conductors, as well as admissible current density. Integration of active elements into MEMS : - conducting coils, permanent magnets and active materials.

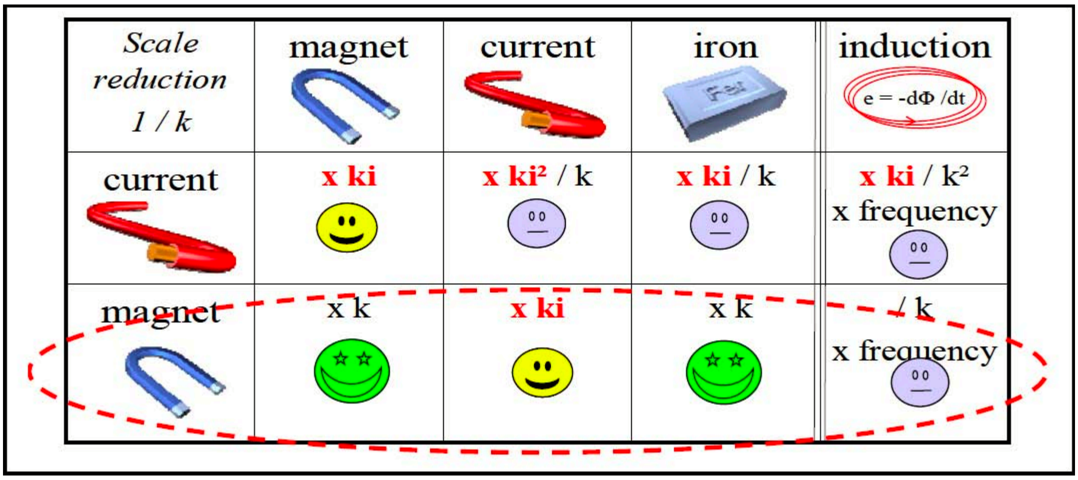

FIGURE 1 – Effect of homothetic scale reduction on force density for various magnetic interactions.

Part 2

Several illustrated examples of application of Mag-MEMS to Energy : - magnetic micro-actuators, - micro-sources and harvesters of energy, exploiting magnetism, - MEMS for energy network supervision.

Conclusion

1. Scale reduction laws are mostly beneficial to magnetic interactions in MEMS
2. Mag-MEMS offer high energy density actuation and/or electrical generation
3. Autonomous MEMS sensors can improve global Energy management

References

1. Scale reduction laws : Cugat et al., *IEEE Trans Mag* 2003
2. Applications : conference proceedings Power-MEMS, Transducers, MEMS

1. G2Elab Grenoble, France

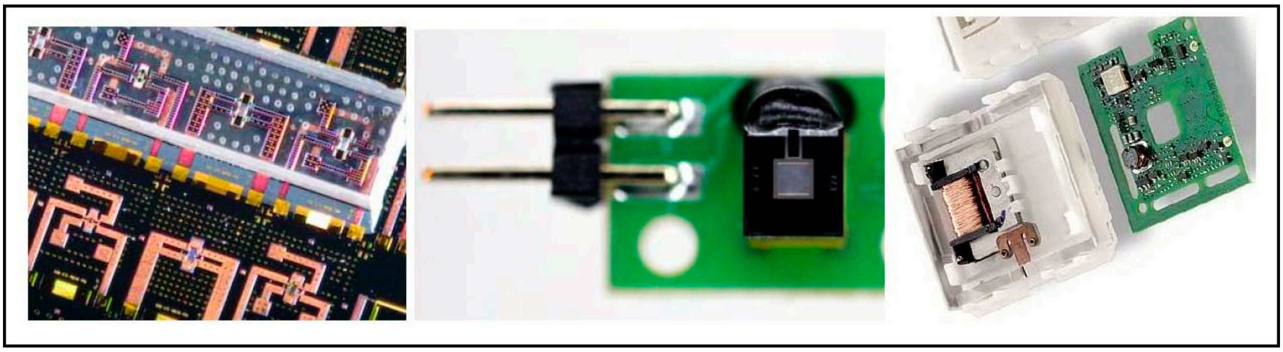

FIGURE 2 – Left : Si-integrated bistable micro-switches ($1\,mm^2$ each. G2ELab + CEA/LETI). Centre : 2D Si-integrated scanner for pico-projectors (2x2 mm^2. LEMOPTIX). Right : Energy harvester for autonomous remote switch (EnOcean).

FROM PHYSICS TO PRODUCT FROM MRAM TO MAGNETIC LOGIC UNIT (MLU)

Lucien Lombard [1]

Introduction

Since the discovery of Giant Magnetoresistance, spin-electronics has been a steadily expanding field of research and development which mainly benefited so far to the magnetic recording industry. More recently, magnetic tunnel junctions (MTJ) and the associated phenomena of tunnel magnetoresistance have been widely studied in order to produce non-volatile magnetic random access memories (MRAM) which offers significantly improved cyclability and access time compared to Flash memories.

The basic MRAM cell is the so-called Magnetic Tunnel Junction (MTJ) which consists of two magnetic layers sandwiching a thin (sub-nm) insulating layer (see Fig. 1). The magnetization of one of the layers, acting as a reference layer, is fixed and kept rigid in one given direction. The other layer, acting as the storage layer, can be switched under an applied magnetic field from parallel to antiparallel to the reference layer, therein inducing a change in the cell resistance. The corresponding logic state ("0" or "1") of the memory is hence defined by its resistance state (low or high), monitored by a small read current.

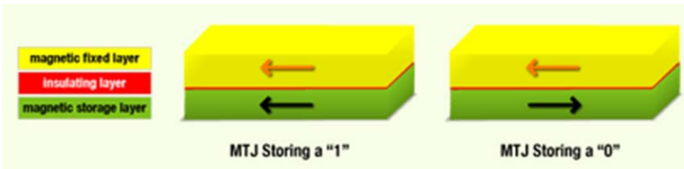

FIGURE 1 – Stored data follows the magnetization direction (parallel or anti-parallel) of the magnetic layers in the MTJ

A fully functional MRAM memory is based on a 2D array of individual cells, which can be addressed individually. In traditional architectures, each memory cell combines a CMOS selection transistor with a magnetic tunnel junction and three line levels, two of which are positioned in a cross point architecture.

Founded in 2006, Crocus-Technology [1] first developed Thermally Assisted Switching MRAM (TAS-MRAM) [2], using a thermal assistance during write to temporarily ease the pinned magnetization of a storage layer while applying magnetic field to switch its direction, thus changing the bit cell information. With pinning of the reference and storage layers being obtained by interfacial exchange coupling with an antiferromagnetic materials (AF) and heating of the storage layer produced by a pulse of current through the tunnel barrier, this TAS-MRAM provides both high thermal stability of the information within a large temperature operating range low power consumption.
In addition to TAS-RAM, Crocus has developed a new concept named Self-Reference (SR) [3] which is the heart of Magnetic Logic Unit (MLU) architecture. SR goes much further in resolving additional challenges and enabling new functionality and capability. The structure of SR MTJ is modified by the substitution of the base AF (that served to pin the reference layer in the fixed reference MTJ structure) with a magnetically free layer. As a result, the magnetization of this free layer is variable and subject to the magnetic field applied via the field line, and this layer is renamed as the sense layer.

In the SR case, read is achieved by measuring the MTJ resistance twice. The first measurement is performed with the sense layer aligned in one direction and the second measurement in the opposite direction. The alternative alignment of the sense layer is achieved by first driving a "north" current in the corresponding filed line followed immediately by a "south" current, which can be achieved in a 5 to 10ns time lapse [3].

1. Crocus-Technology Grenoble, FRANCE

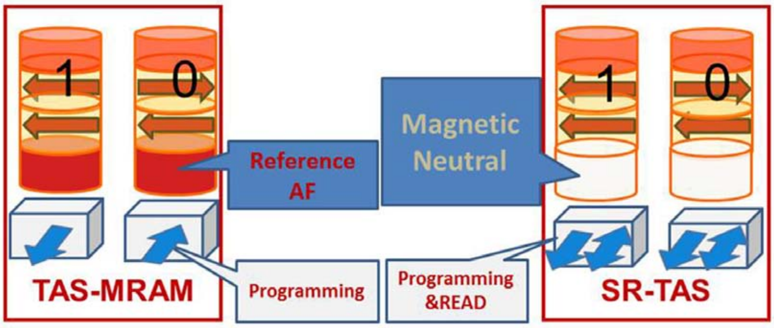

FIGURE 2 – TAS-MRAM with fixed reference (FR) vs SR-TAS with sense reference (SR)

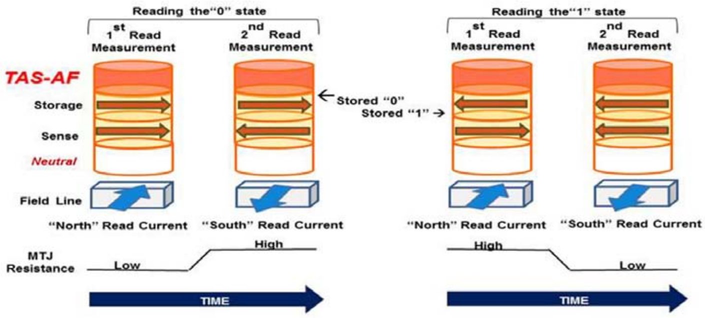

FIGURE 3 – MLU Read Sequence

Crocus is developing solutions based on its Magnetic Logic Unit^{TM} (MLU). Crocus' MLUs read and write faster than Flash memory and have a smaller footprint. The company's Magnetic Logic Unit^{TM} (MLU) architecture, based on its patented self-reference Thermally Assisted Switching^{TM} (TAS) technology, enables a number of previously unachievable breakthroughs in magnetic memory implementation, including highly robust secure embedded memory, order-of-magnitude higher density hardware-based table searches (e.g., content addressable memory), high density multi-bit storage, and scaling to sub-20nm manufacturing. This enables Crocus' MLUs to offer significant advantages in performance, security and cost-effectiveness, making them ideal for use in mobile devices, smart cards, secure data servers and other embedded memory products. In addition, Crocus' MLU^{TM} architecture offers a highly reliable approach for building non-volatile memory (NVM) capable of operating at 250°C or higher, in comparison to Flash and other technologies that are effectively limited to 150°C or lower, making it ideal for extreme environment such as automotive, aerospace, energy exploration and defense.

This Talk will cover the description of Crocus as a start-up company within its academic and industrial eco-system. After the description of TAS-MRAM technology and its place in the quest for the universal memory, the technical and manufacturing challenges will be discussed in order to understand how to transform laboratory innovation on into a product ready for market. Then, the discussion will continue with the description of the Self-Referenced Bit-cell description the range of new applications it opens. The presentation will then be concluded with a discussion on the future of MTJ based devices.

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List of Posters

1. Afid Raja 'Magnetostatic interactions in arrays of cylindrical nanowires'
2. Aghte Michael 'Nucleation and growth of self-assembled arrays of iron oxide nanocubes'
3. Akmaldinov Kamil 'Blocking temperature distributions in F/AF bilayers'
4. Almanza Morgan 'Magnetic refrigeration at room temperature'
5. Banerjee Rudra 'An ab-initio theoretical approach to tune the magnetocaloric effect in magnetic metals.'
6. Barati Ehsan 'Calculation of Gilbert damping in magnetic multilayers'
7. Batley Joseph 'Pure spin transport in metalic nanostructures.'
8. Bersweiler Mathias 'Tunnel magneto-resistance and magnetic configuration in [Co/Pt]- based Magnetic Tunnel Junctions.'
9. Birenbaum Yael 'Aurivillius Phases : Examples of Layered Perovskite Related Compounds and Potential Multiferroic'
10. Buijnsters Frank 'Multiscale magnetization dynamics : unified atomistic–coarse-grained simulation'
11. Cascales Sandov Juan Pedro 'Magnetization dynamics and noise in magnetic tunnel junctions'
12. Chaudhuri Debpriya 'Spin-orbit coupling in the Breit equation for Ni dimers in thermodynamic spin engines.'
13. Cuchet Léa 'Development of magnetic tunnel junctions with perpendicular anisotropy.'
14. Dejena Fasil Kidane 'Magnetic control of heat transport in nanopillar spin valve devices.'
15. Delczeg Ema Krisztini'Microscopic theory of magnetism in magnetocaloric material Fe2P(1_x)Tx (T=B and Si).'
16. Di Sante Domenico 'Electric Control of Giant Rashba Effect in Bulk GeTe.'
17. Djeghoul Fatima Zohra 'Electron spin motion at the interface between an organic film and a ferromagnetic surface.'
18. Dobkowska Sylwia 'Magnetic properties of (Ga,Mn)N layers with Mn concentration up to 10%.'
19. Fang Weiging 'Composite Materials Based on Co Nanowires for the fabrication of Rare-earthfree permanent magnets.'
20. Gluba Tukasz 'Electronic and Band Structure Analysis in Low and Ultra Low Doped (Ga,Mn)As Epitaxial Layers.'
21. Gottschall Tino 'Giant magnetocaloric effect of Heusler alloys in experiment and simulation.'
22. Granados Cecilia 'Time-resolved synchrotron studies of particle size and morphology dependence with reaction temperature of Sr-Hexaferrite.'
23. Grois Andreas 'Dilute and condensed transition-metal-doped GaN : phase diagrams and magnetic interactions.'
24. Hahn Christian 'Generation and Detection of Pure Spin Currents.'
25. Hamadeh Abbass 'Spin-Torque nano-oscillators.'
26. Hellsén Ann-Cathrin 'Soft Magnetic Composite Materials - Different Somaloy® Products.'
27. Inglot Michal 'Thermoelectric and thermomagnetoelectric properties of graphene.'
28. Izydorzak-Wozniak Marta 'Effect of nanocrystallite size distribution on magnetic behavior of Ni#C beads.'
29. Janda Tomas 'Observation of the Optical Spin Transfer Torque and Optical Spin-Orbit Torque in GaMnAs.'
30. Kamantesev Alexander 'Thermodynamic and relaxation precesses near phase transitions in advanced caloric materials.'
31. Kataja Mikko 'Magnetoplasmonic nanostructures for manipulation of magneto-optical effects.'
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33. Levatic Ivana 'Electric-field control of the skyrmion lattice in Cu_2OSeO_3.'
34. Liébana Sara
35. Lottini Elisabetta 'Novel Rare-Earth Free Nanostructured Magnetic Materials.'
36. Merodio Pablo 'Spin dependent transport and STT on antiferromagnets.'
37. Miao Xuefei 'Origin of the thermal history dependence of first-order magneto-elastic transition in magnetic refrigerant MnFePSi.'
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39. Nadvomik Lukas 'Study of Spin Hall Effect in high mobility regime.'
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41. Niemann Robert 'The role of adaptive martensite in magnetic shape memory alloys.'
42. Nikilshin Yasha '
43. Parchenko Sergii 'Light-induced dynamics in magnetophotonic structures.'
44. Patissier Amaury 'Tunning properties of magnetocaloric Materials : La(Fe,Si)13.'
45. Pedreira Bueno Thiago Eduardo ' Magnetic damping in spin valves investigated by ferromagnetic resonance.'
46. Porcari Giacomo 'Experimental setup for the simulation of real magnetothermal cycles through adiabatic characterization.'
47. Marc Pousthomis 'Synthesis and characterization of core-shell anisotropic magnetic nanoparticles.'
48. Regaieg Yassine 'Structure and magnetocaloric properties of $La_{0.67}Ca_{0.33-x}Sr_xMnO_3$ perovskites produced by reactive Spark Plasma Sintering route.'
49. Reichel Ludwig 'Enhancement of magnetocrystalline anisotropy in $Fe_xCo_{(1-x)}$ thin films due to tetragonal distortion.'
50. Reznicek Richard 'NMR in Substituted Magnetite.'
51. Ridier Karl 'Photomagnetism in copper octacyanomolybdate molecular compounds : a neutron diffraction investigation.'
52. Rousseau Jérémie 'Nano-gap device for single-cluster transport properties measurements.'
53. Saloaro Minnamari 'The effect of film thickness on the magnetic and magneto-transport properties of Sr_2FeMoO_6 thin films.'
54. Saura Matilde 'Supercritical flow synthesis of Sr-hexaferrite.'
55. Savero Torres Williams Fernando
56. Sazanovich Andrei 'Synthesis and ferroelectric properties of layered heterostructures (FM/PZT/FM)n where FM - Co, $Ni_{78}Fe_{22}$.'
57. Schoerling Daniel 'Normal-conducting accelerator magnets at CERN, Research & Development.'
58. Schöppner Christian 'Magnetic correlations in single crystalline magnetic shape memory alloy NiMnInCo.'
59. Schumacher Stefan 'Magnetism of Cobalt Nanoclusters and Intercalated Europium at Supported Graphene.'
60. Shokr Yasser 'The role of magnetic coupling across ultrathin epitaxial antiferromagnetic layers in exchange bias.'
61. Sieczkowska Ewalina 'The dependence of magnetization reversal of nanodots on their size, shape and occurring defects.'
62. Silva Catia 'Substrate induced anisotropy in Co-N thin films'
63. Stern Taulats Enric 'Calorimetric study of materials exhibiting first-order magnetic transitions : large entropy changes and their reproducibility'
64. Telesio Francesca 'Electrical spin injection in all-oxides crystalline heterostructures.'
65. Turcaud Jeremy 'Microstructural control and tuning of thermal conductivity in $La_{0.67}Ca_0.33MnO_3$'

66. Ukleev Victor 'Polarized neutron reflectometry and SQUID complementary study of Giant Injection Magnetoresistive granular films'
67. Wakamura Taro 'Spin Injection into Superconducting Nb by Quasiparticle Excitations'
68. Yamane Yuta 'Theory of Spinmotvie Force in Ferromagnetic Nanostrucutures'
69. Yibole Yibole 'Determination of magnetocaloric effect of (Mn,Fe)1.95(P,Si) compounds'
70. Yildirim Oguz 'Defects in magnetic TiO_2'
71. Zsurzsa Sandor 'Investigation of structural and magnetic properties of rare earth-transitional metal thin films'

Timetable of the European School on Magnetism ESM2013 - Updated 29 Jan 2013

	Mo 25/02	Tue 26/02	We 27/02	Th 28/02	Fr 01/03	Sa 02/03	Su 03/03	Mo 04/03	Tu 05/03	We 06/03	Th 07/03	Fr 08/03	
9h-9h30		Opening / Intro.	Kuzmin (2/3)	Kuzmin (3/3)	Sandeman (2/3)	Fruchart (1/2)	Excursion	Fruchart (2/2)	Fähler	Jewell	Cugat	Transfer to Ajaccio airport / harbour	9h-9h30
9h30-10h													9h30-10h
10h-10h30													10h-10h30
10h30-11h		Coffee	Coffee	Coffee	Coffee	Coffee + Posters		Coffee	Coffee	Coffee + Posters	Coffee		10h30-11h
11h-11h30		Wulfhekel (1/3)	Wulfhekel (3/3)	Tutorials / Library	Heyderman			Franco	Herzer		Tutorials / Library		11h-11h30
11h30-12h						Questions				Questions			11h30-12h
12h-12h30	Transfer from Ajaccio airport / harbour and registration		Clips poster										12h-12h30
12h30-13h										Fill-in evaluation			12h30-13h
13h-13h30		Lunch	Lunch	Lunch	Lunch	Lunch		Lunch	Lunch	Lunch	Lunch		13h-13h30
13h30-14h													13h30-14h
14h-14h30					Sports								14h-14h30
14h30-15h		Wulfhekel (2/3)	Lacroix	Sandeman (1/3)		Gutfleisch		Sandeman (3/3)	Viret	Valenzuela	Lombard		14h30-15h
15h-15h30													15h-15h30
15h30-16h													15h30-16h
16h-16-30		Coffee	Coffee + Posters	Coffee		Coffee		Coffee	Coffee	Coffee	Coffee		16h-16-30
16h30-17h		Kuzmin (1/3)		Fiorillo		Tutorials / Library		Questions	Tutorials / Library	Picozzi	Questions, evaluation and closing		16h30-17h
17h-17h30			Questions										17h-17h30
17h30-18h													17h30-18h
18h-18h30													18h-18h30
18h30-19h		Welcome party											18h30-19h
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