Multifunctional (magnetic) nanostructures

Denys Makarov

Manipulation of the magnetic order parameter using external means

Multifunctional nanostructures with a focus on functions, devices, MEMS, sensors and actuators, energy harvesting etc.

Duration: 1.5h

Dr. Denys Makarov I E-Mail: d.makarov@hzdr.de I Intelligent Materials and Systems

Dresden, Germany

Dresden (~800 years old & ~500.000 inhabitants):

Capital of the Free State of Saxony

Scientific landscape:

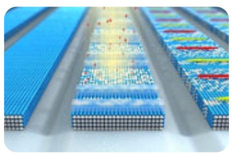
Technical University of Dresden: about 40.000 students

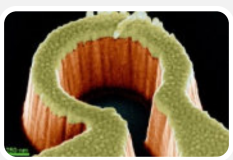
Max Planck Institutes: 3 | Leibniz Institutes: 3
Fraunhofer Institutes: 8 | Helmholtz Center: 1

Helmholtz-Zentrum Dresden-Rossendorf (HZDR)

Research for the World of Tomorrow

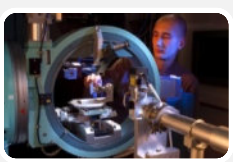
Established	1992 (1955)
Member of Helmholtz Association	2011
Base Budget	~ 120 Mio. €/a
Employees	~ 1400





10 Institutes

11 Junior Research Groups

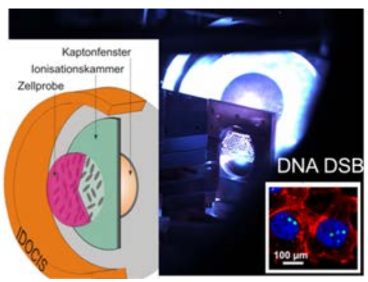


Sites: Dresden, Leipzig, Freiberg, Grenoble (FR), Hamburg, Görlitz

RESEARCH AREAS

ENERGY

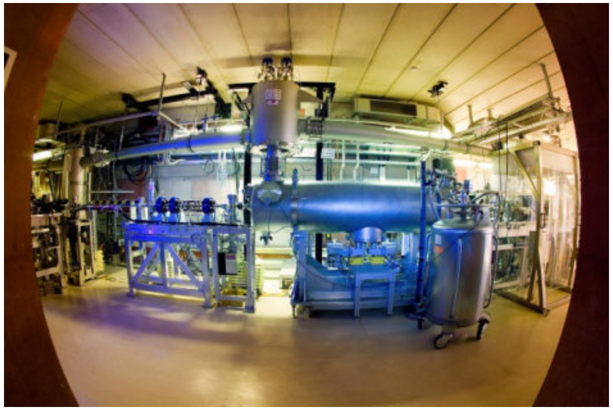
HEALTH (→ Oncology)



MATTER (→ Materials)

HZDR Facilities

- User Facilities



ELBE.

Center for High-Power Radiation Sources

IBC.

Ion Beam Center

Industry Services via

HZDR INNOVATION

HLD.

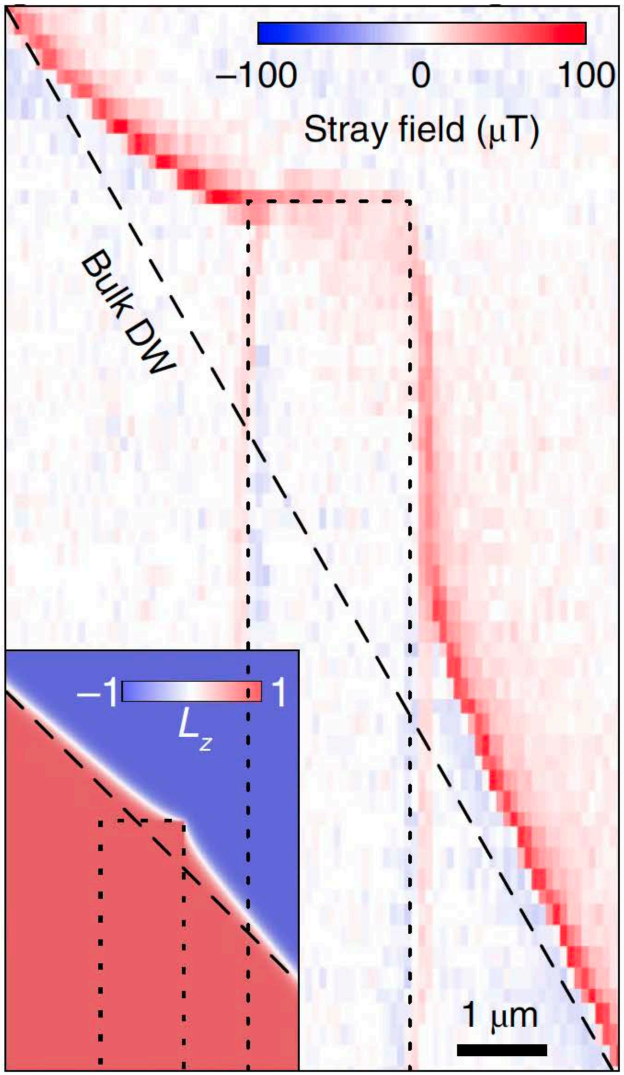
High-Magnetic Field Laboratory

PET Center

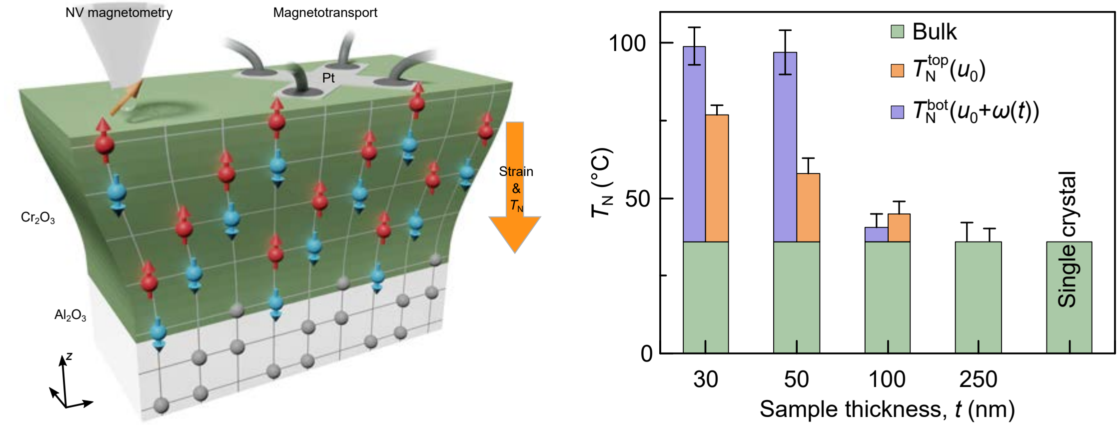
DRESDEN concept

HZDR

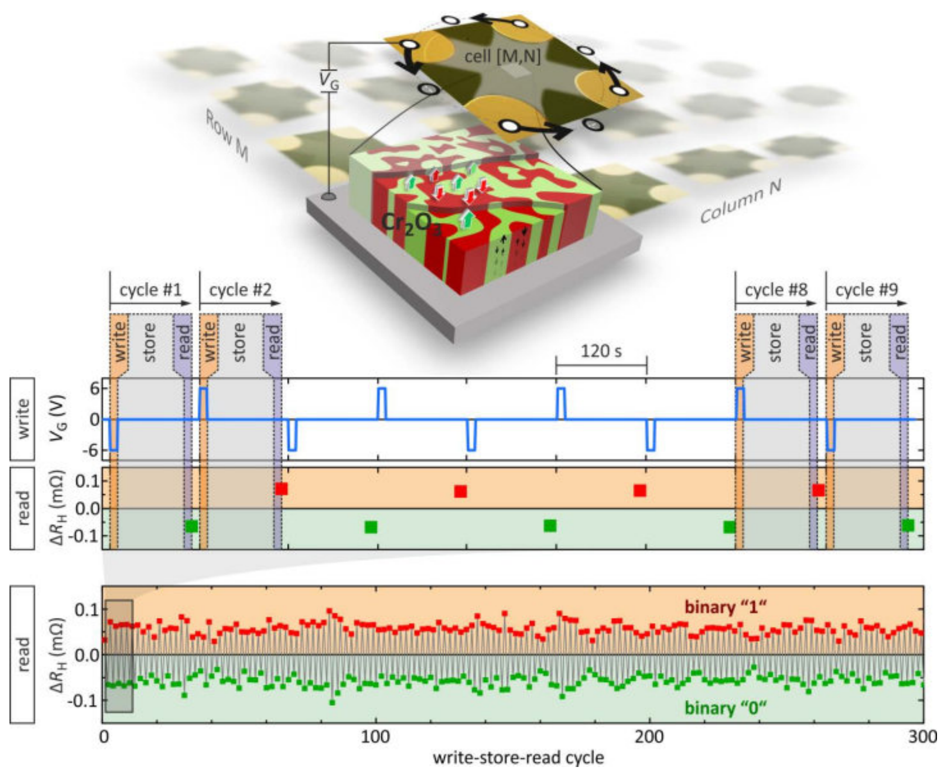
Activities on (magnetoelectric) antiferromagnets



N. Hedrich et al., *Nature Physics* (2021)



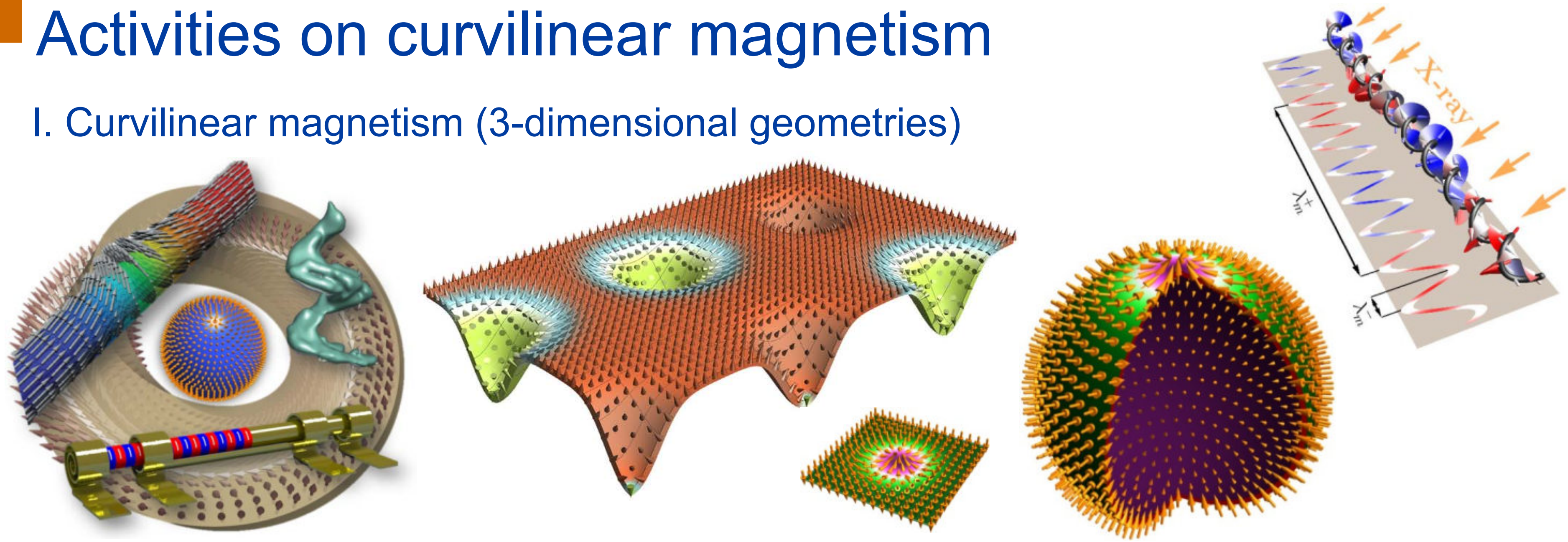
P. Makushko et al., *Nature Commun*. (2022)



T. Kosub et al., *Nature Commun*. (2017)

Activities on curvilinear magnetism

I. Curvilinear magnetism (3-dimensional geometries)



Nature Physics & *Nature Electronics* & *Nature Communications* & *Phys. Rev. Lett.* & *Nano Letters* & *Advanced Materials*

Review: DM et al., *Advanced Materials* **34**, 2101758 (2022)

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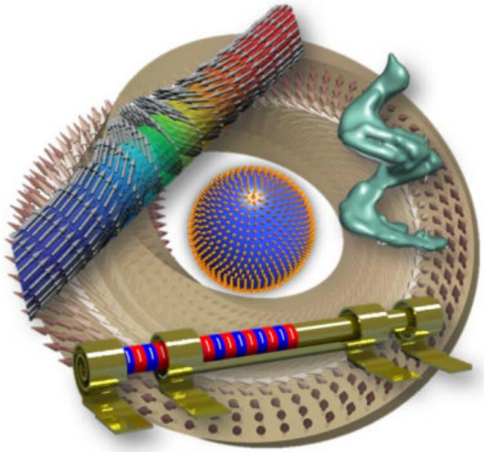
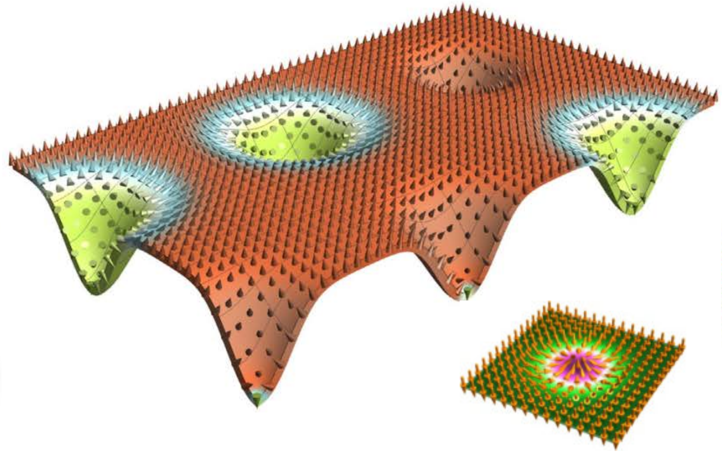
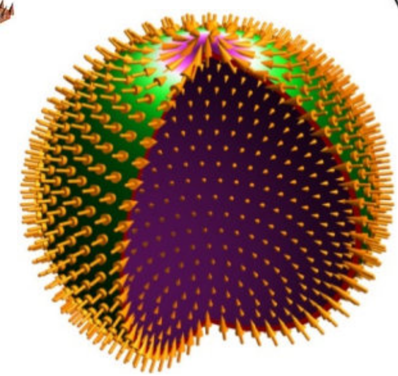
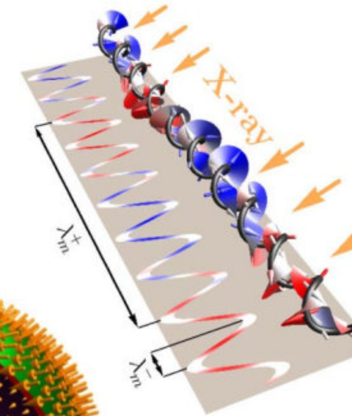




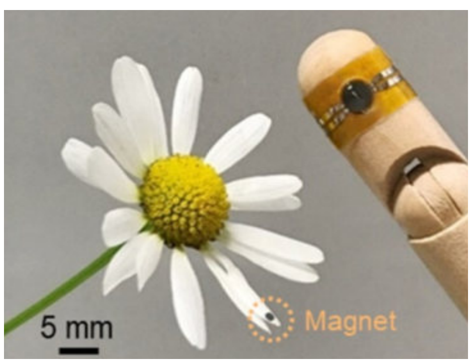


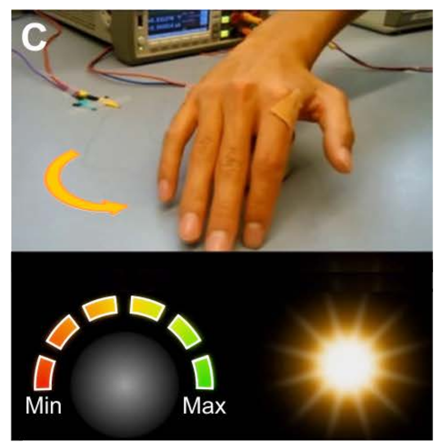


Nature Physics & *Nature Electronics* & *Nature Communications* & *Phys. Rev. Lett.* & *Nano Letters* & *Advanced Materials*

<u>Review:</u> DM et al., *Advanced Materials* **34**, 2101758 (2022)

II. Flexible sensors & Flexible actuators





Science Advances & *Nature Electronics* & *Nano Letters* & *Advanced Materials* & *npj Flexible Electronics* & *Nature Commun.*

<u>Review:</u> Santiago Canon et al., *Adv. Funct. Mater.* **31**, 2007788 (2021)

DRESDEN concept HZDR

Definition

What is multifunctional material?

Multifunctional material is defined to be any material or material-based system which integrally combines two [or possibly more] properties, one of which is normally structural and the other functional, e.g. optical, electrical, magnetic, thermal etc...

https://www.scitechnol.com/scholarly/multifunctional-materials-journals-articles-ppts-list.php

Definition

Multifunctional materials are the materials that perform multiple functions in a system due to their specific properties

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The applications of such new "smart" materials include energy, medicine, nanoelectronics, aerospace, defence, semiconductor, and other industries

Multifunctional materials can be both naturally existing and specially engineered

https://www.e-education.psu.edu/eme807/node/698

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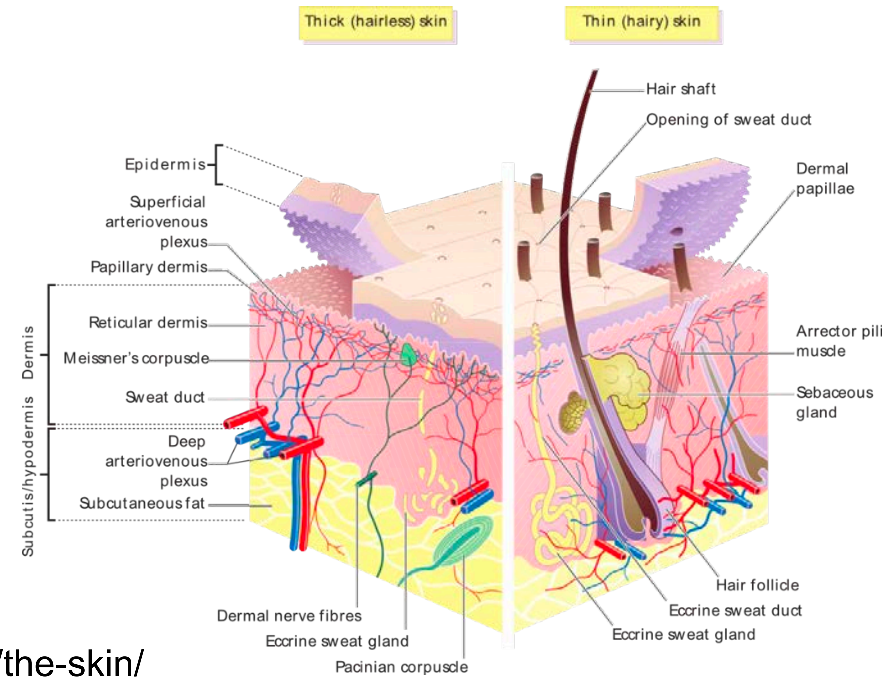

https://www.e-education.psu.edu/eme807/node/698

https://courses.lumenlearning.com/boundless-ap/chapter/the-skin/

Do you know <u>not</u> multifunctional materials?

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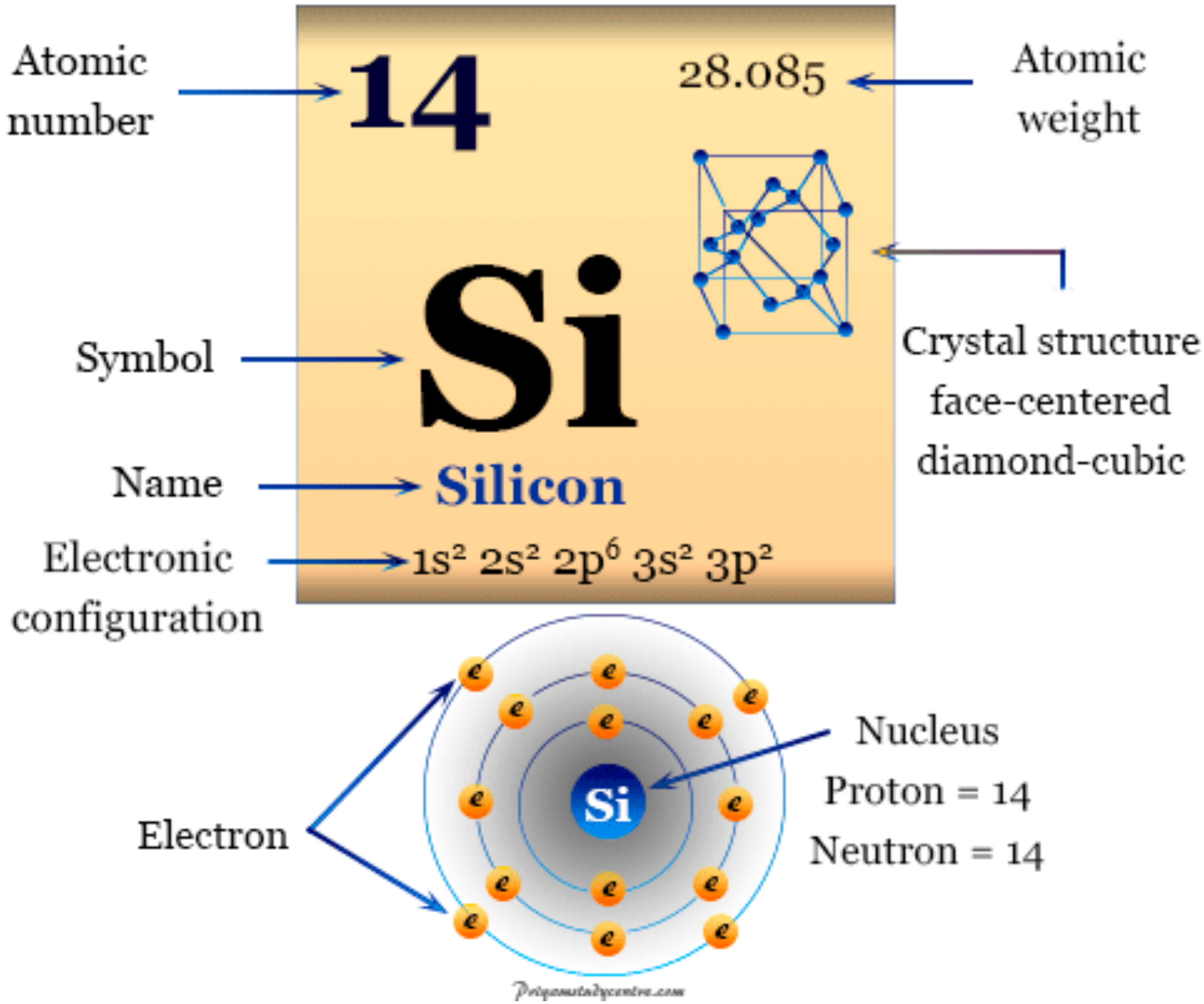
Is every material multifunctional?



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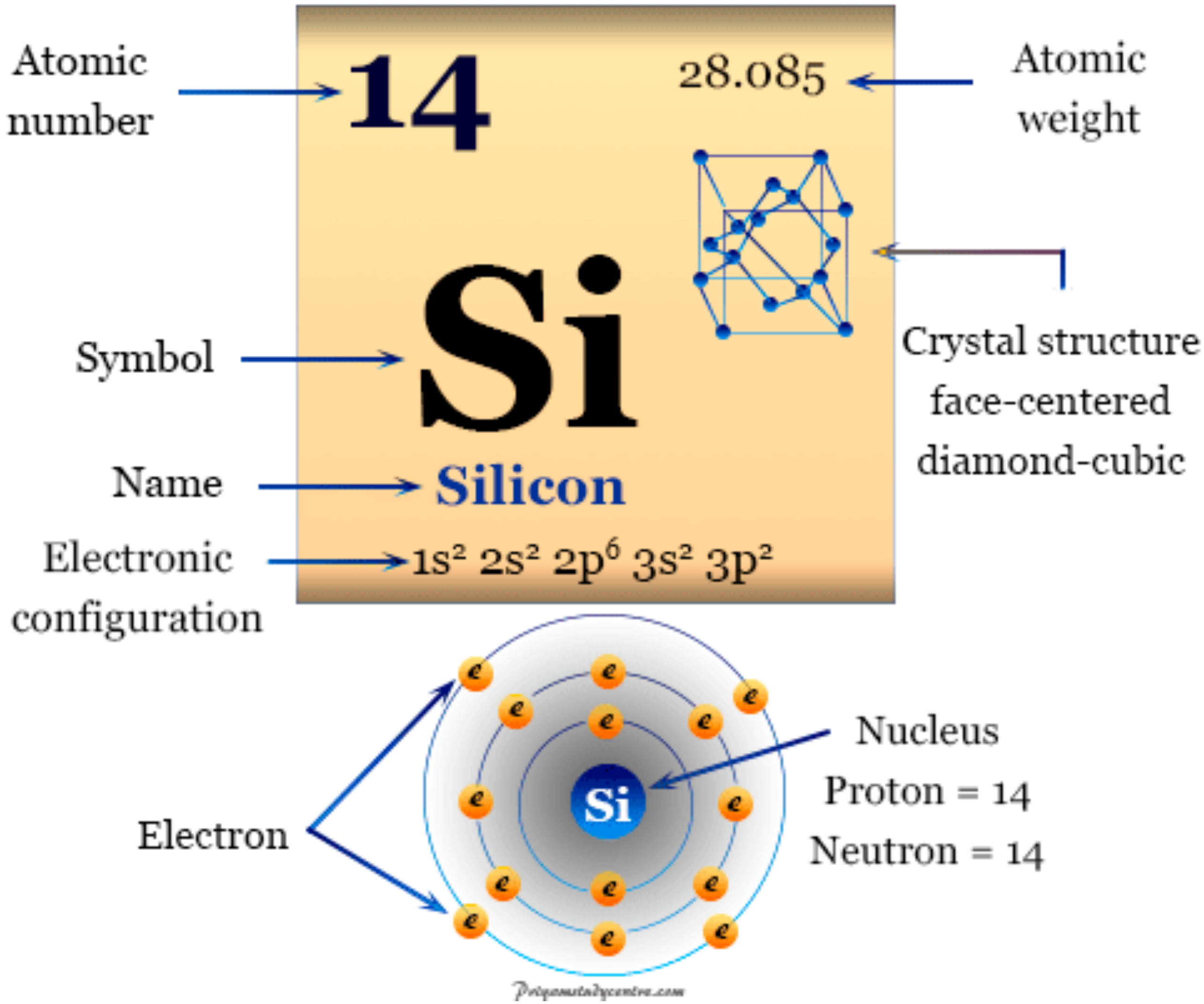

Semiconductor => electronics   Suitable band gap => optics (detectors), communication

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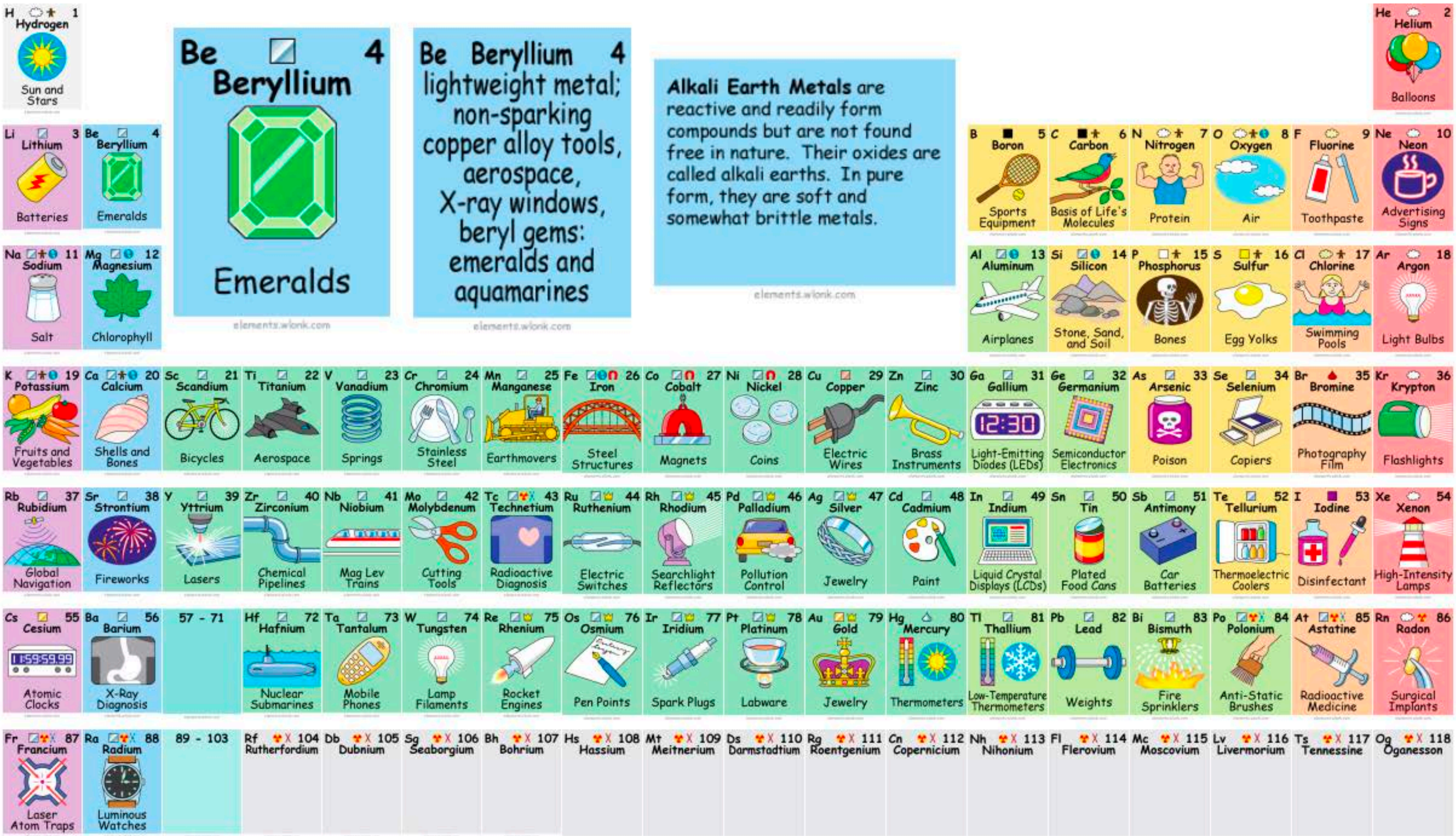

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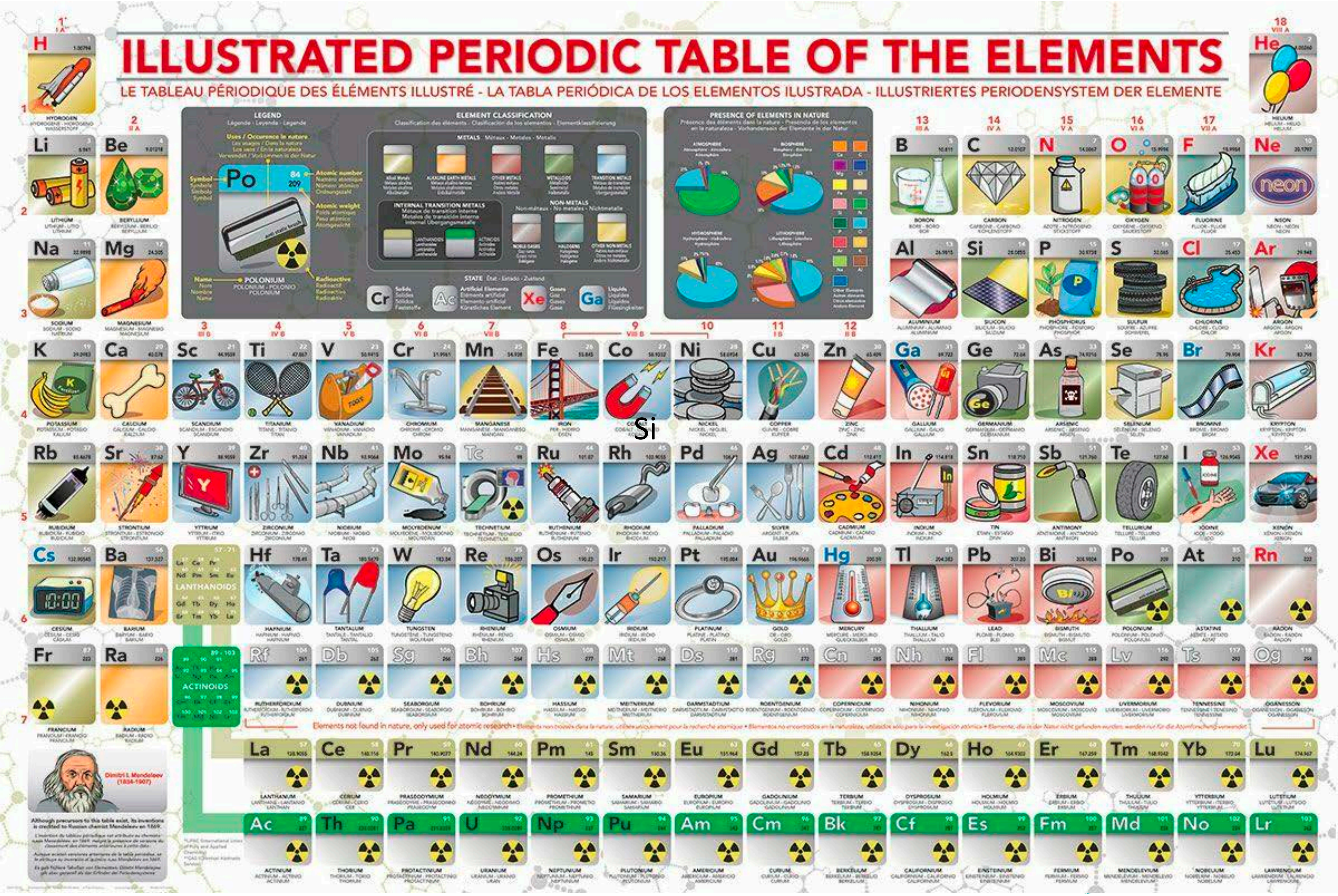


Definition / Semantics

Multifunctional materials

Definition / Semantics

Smart materials

Multifunctional materials

Definition / Semantics

Smart materials

Intelligent materials

Advanced Materials

Multifunctional materials

Definition / Semantics

Smart materials   Intelligent materials   Advanced Materials

Multifunctional materials   Advanced functional materials

Multiferroic materials   Magnetoelectric materials

Magnetic composites

Definition / Semantics

Smart materials Intelligent materials Advanced Materials

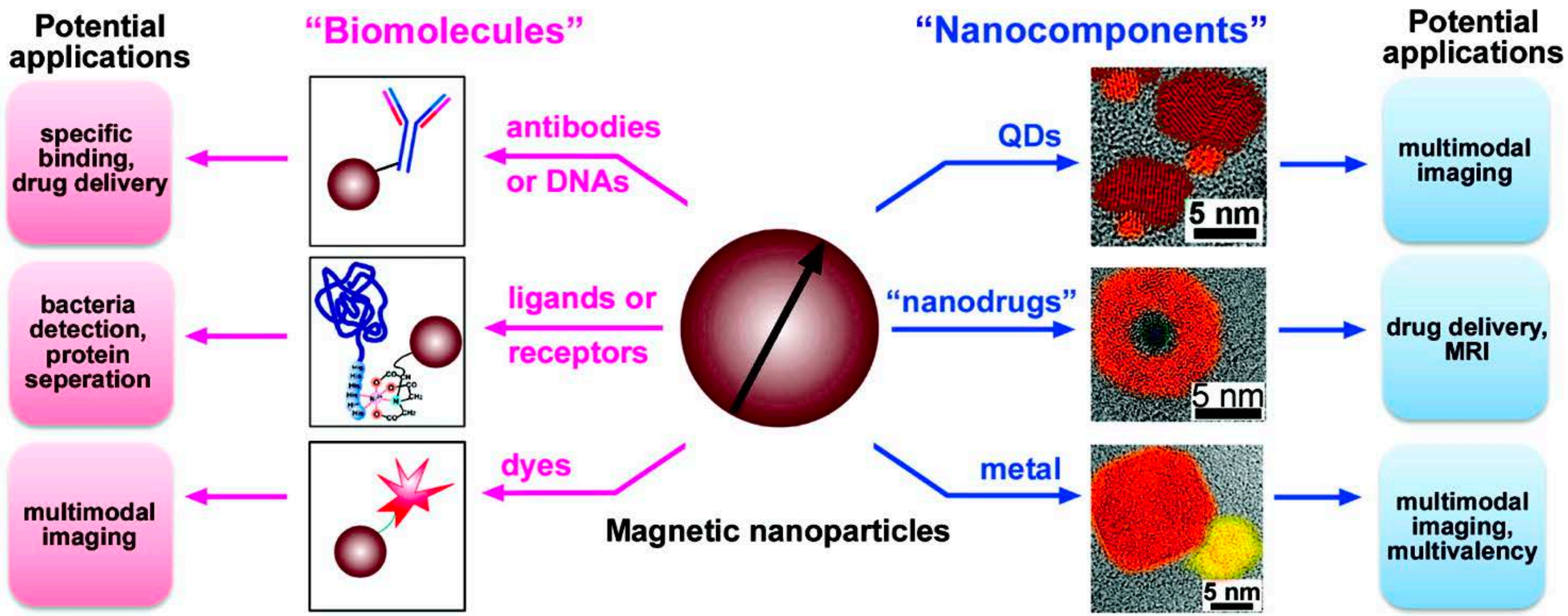
Multifunctional materials Advanced functional materials

Multiferroic materials Magnetoelectric materials

Magnetic composites

Most probably, these are (in some sense) synonyms

Multifunctional magnetic nanoparticles

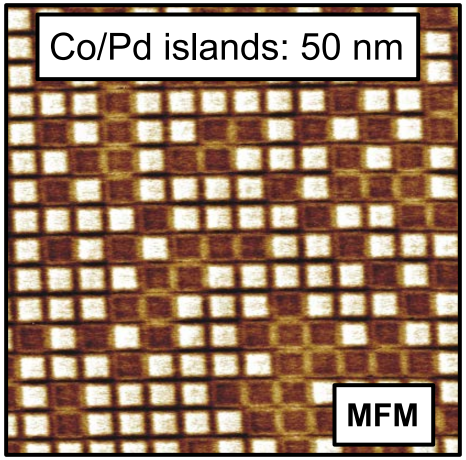


Medical applications: hyperthermia (pre-clinical)

J. Gao et al., *Acc. Chem. Res.* **42**, 1097 (2009)

Nanosized magnetic objects

Electron beam lithography



Hu et al., *J. Appl. Phys.* **95** (2004) 7013

Challenges

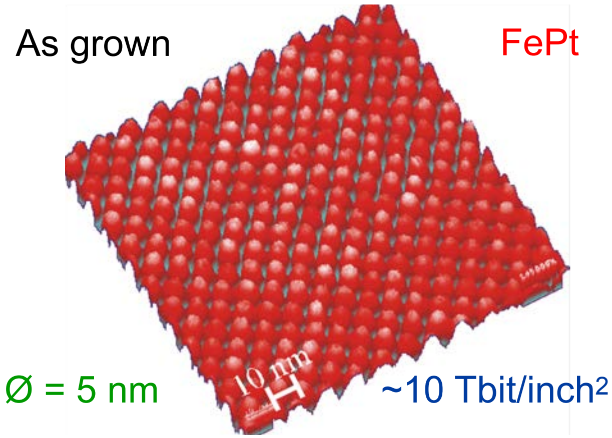
i. Expensive
ii. Time consuming
iii. Size limited

X-ray/nanoimprint lithography

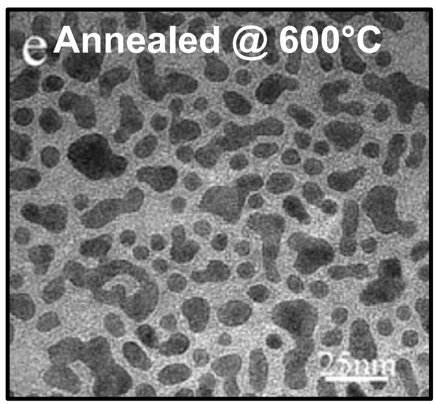
Ross, *An. Rev. Mat. Res.* **31** ('01) 203;

Chou et al., *J. Appl. Phys.* **76** ('94) 6673

Magnetic particles self-assembly



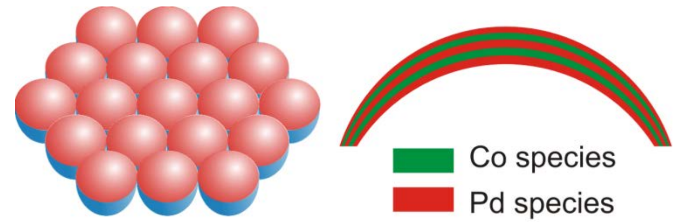
Sun et al., *Science* **287** (2000) 1989

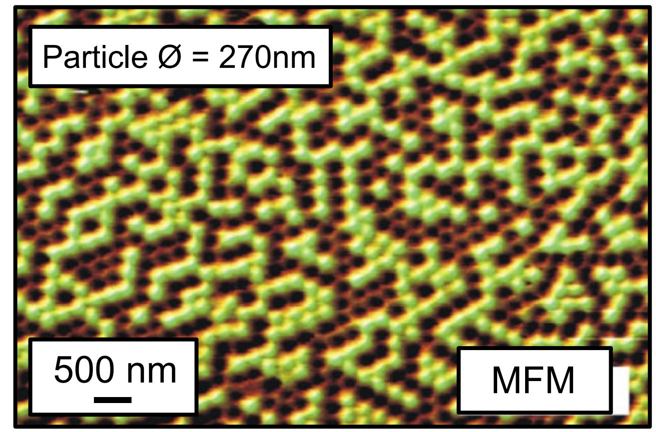


!!! Agglomeration !!!

Dai et al., *NanoLett.* **1** (2001) 443

Magnetic films on nanospheres





Magnetic properties

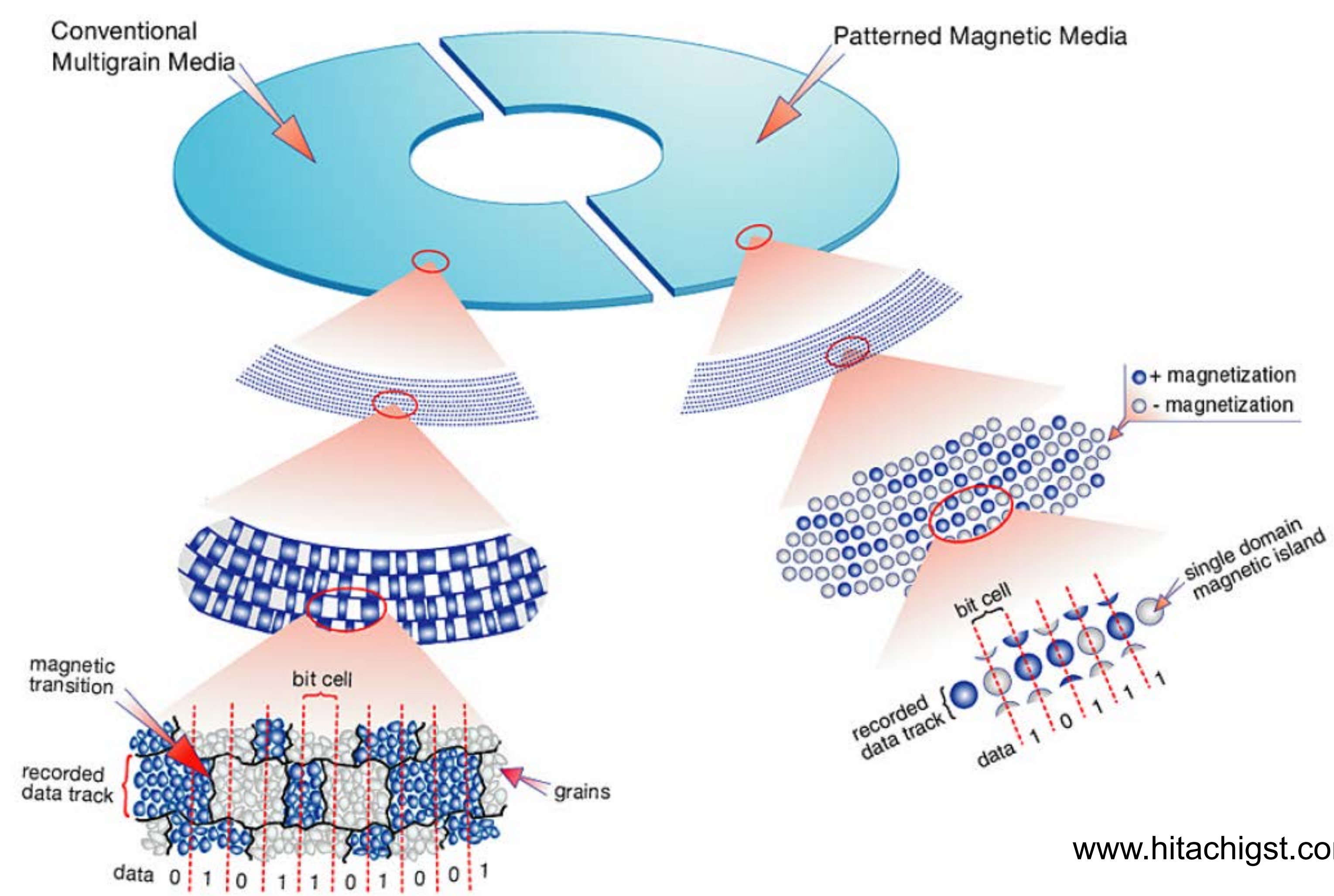
- Perpendicular anisotropy
- Single-domain state
- Exchange isolated caps

Albrecht et al., *Nature Materials* **4** (2005) 203

Driving force: magnetic recording and spintronics

$L1_0$ chemically ordered FePt alloy allows thermal stability for 3-nm-large grains

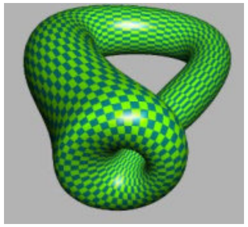
Single grain ⇔ Single bit => Patterned Magnetic Media



www.hitachigst.com

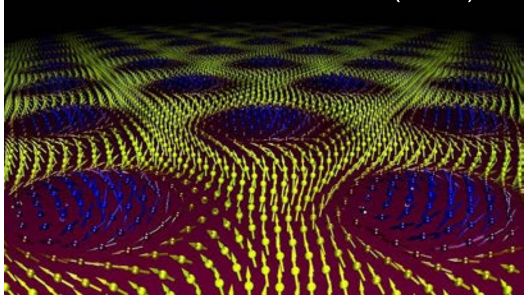
Manipulation of the (magnetic) order parameter

Effects of topology



wikipedia

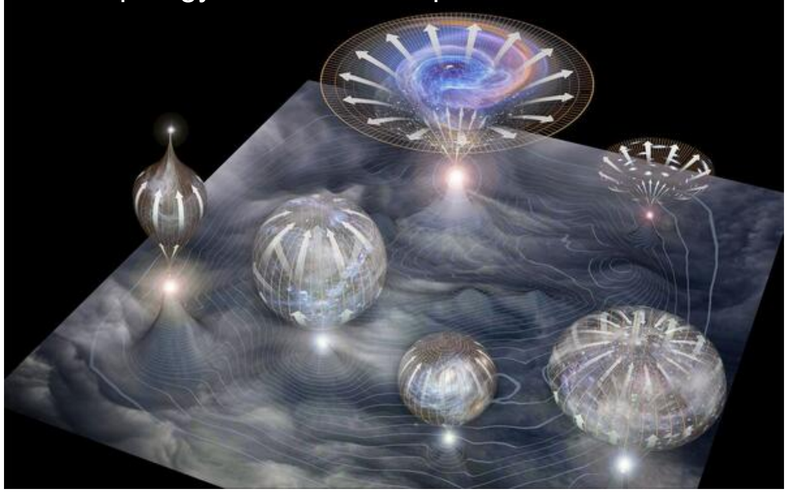
pngkit.com



Mühlbauer et al., *Science* (2009)

- **Geometry**
  - Symmetric boundary conditions (tubes and spheres)
  - Antisymmetric boundary conditions (Möbius rings and Klein bottles)
  - Shells with perforations…

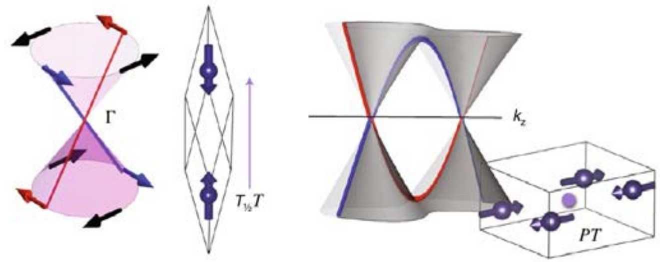
- **Texture**
  - Domain walls, skyrmions, vortices
  - Dislocations and disklinations (antiferromagnetic textures)



Topology of the curved space-time universe

https://tallbloke.wordpress.com/2014/03/21/p-a-semi-topology-of-the-curved-space-time-universe/

- **Band structure**
  - Topological insulators, Weyls…
  - 2D materials and heterostructures



Smeikal et al., *Nat. Phys.* (2018)

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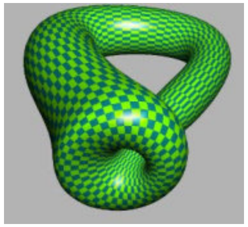

wikipedia

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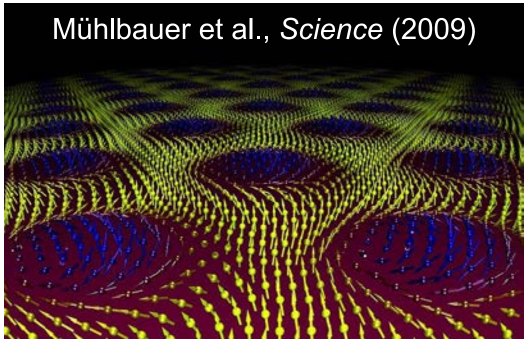

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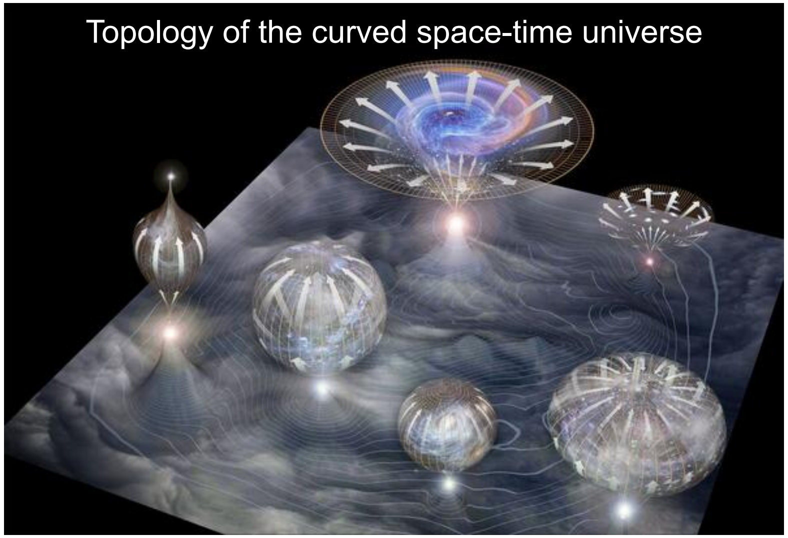

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Flexomagnetism, Magnetostriction…

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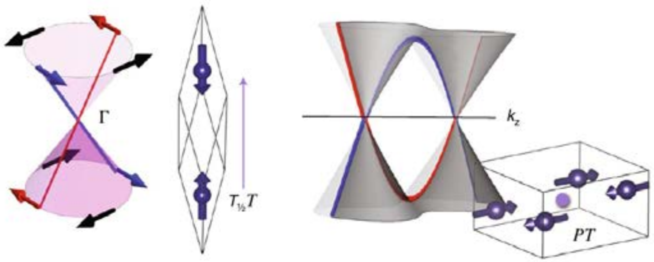

Smeikal et al., *Nat. Phys.* (2018)

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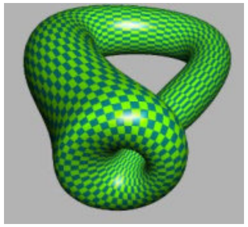

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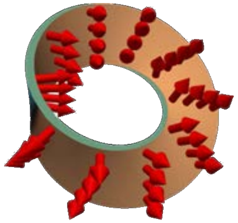
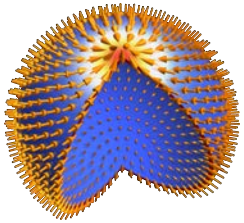
pngkit.com

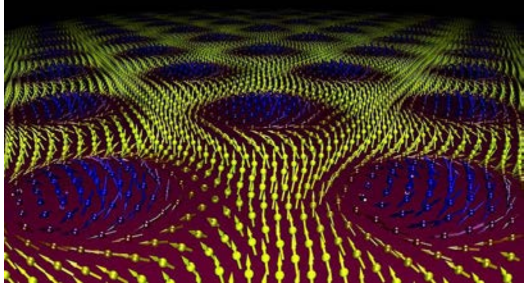


Pylypovskyi et al., *PRL* (2015)



Kravchuk et al., *PRB* (2016)

Mühlbauer et al., *Science* (2009)



Curvilinear magnetism

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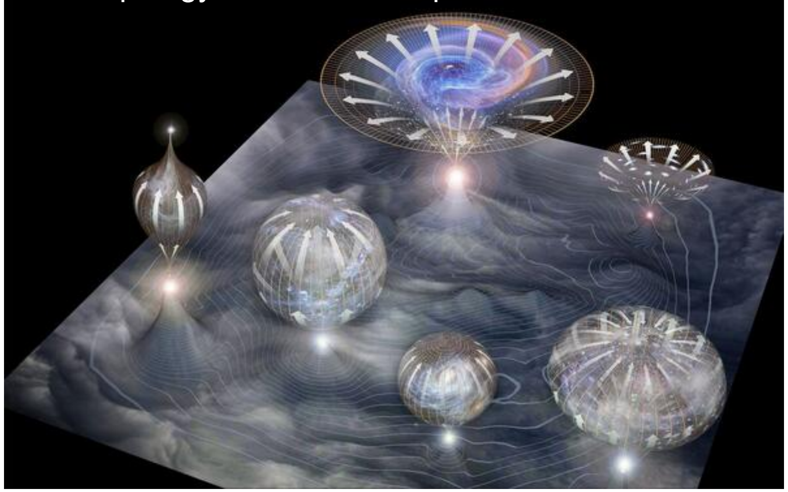

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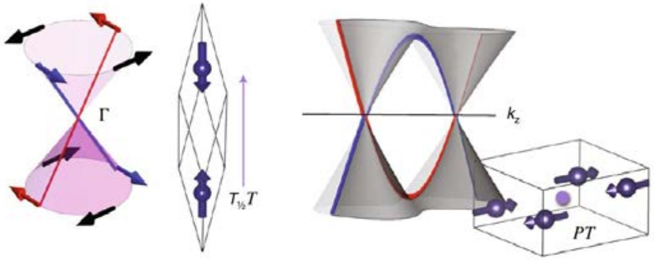
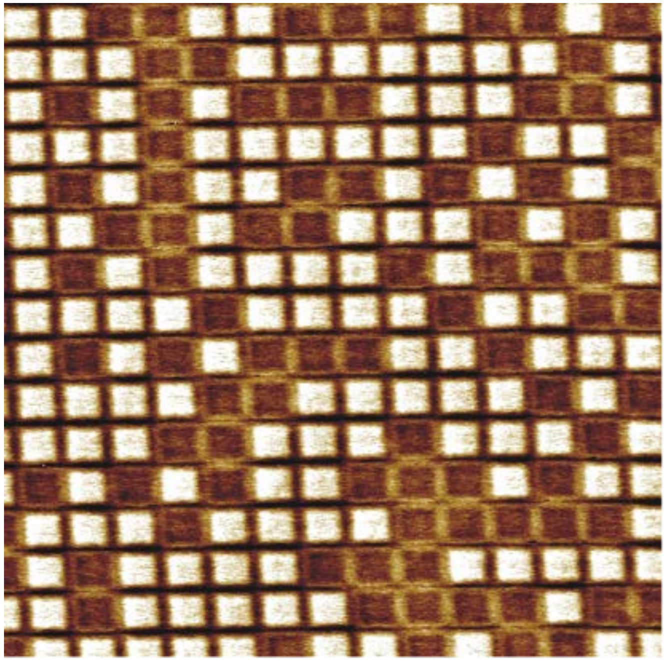


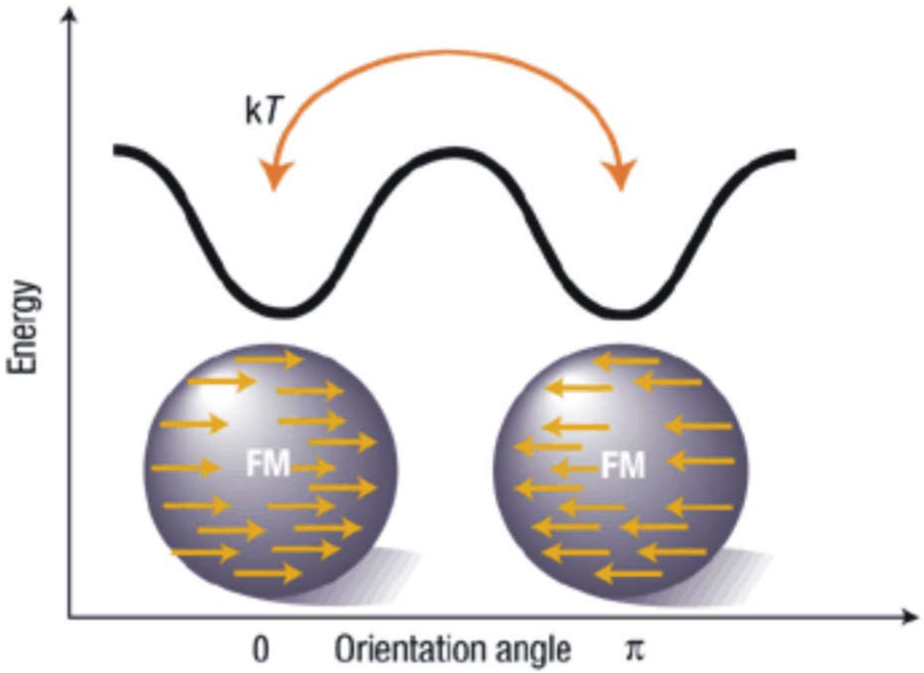
Smeikal et al., *Nat. Phys.* (2018)

Planar vs 3D magnetic nanostructures

Information bits in perpendicular recording media



Higher areal density <=> Reduce the bit size



Bit size: 50 nm

A: 10^{-11} J/m

M_S: 0.6 T

K_U: 1 MJ/m^3

Criteria: Long time stability (~10 years)

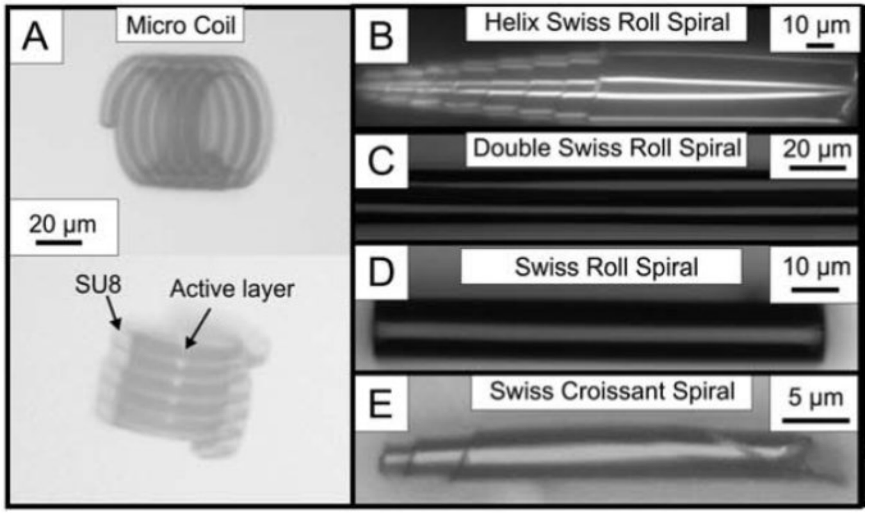
[Anisotropy Energy] = 60 x [Thermal Energy]

$$K_U \cdot V = 60 \cdot k_B \cdot T$$

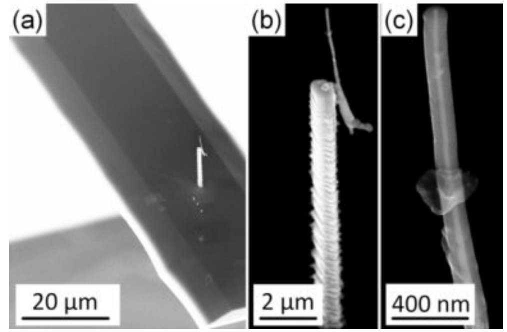
Piramanayagam, *J. Appl. Phys.* **102** (2007) 011301

Eisenmenger et al., *Nature Mater.* **2** (2003) 437

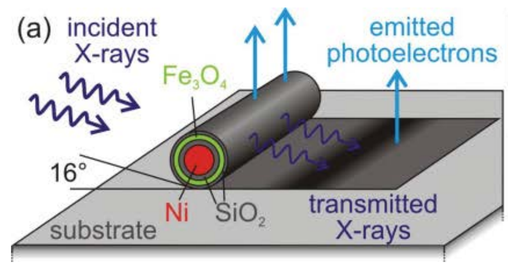
Experimental realizations



Smith, DM et al., *Phys. Rev. Lett.* (2011) & *Soft Mat.* (2011)



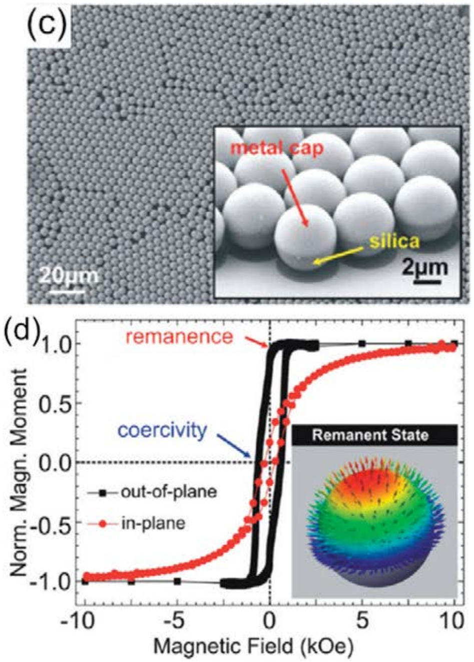
Mühl et al., *APL* (2012)



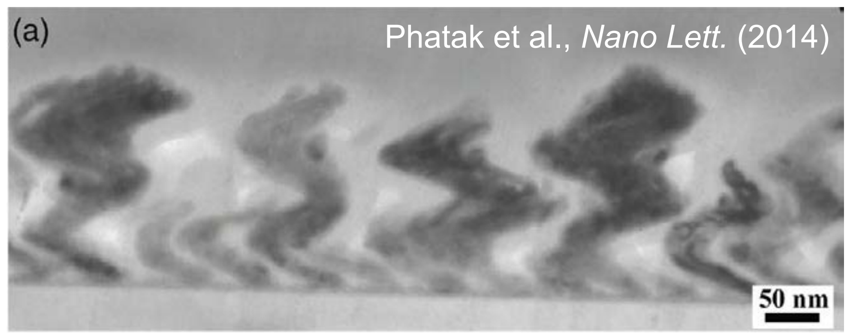
Kimling et al., *PRB* (2011)

Magnetic soft x-ray tomography

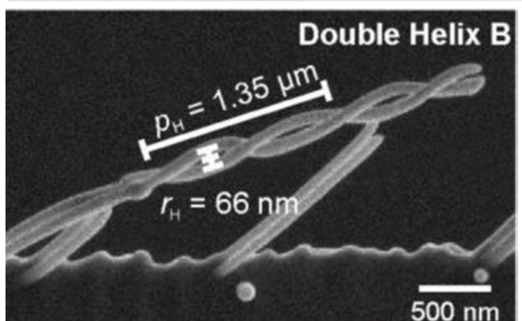
Streubel, DM et al., *Nature Commun.* (2015)



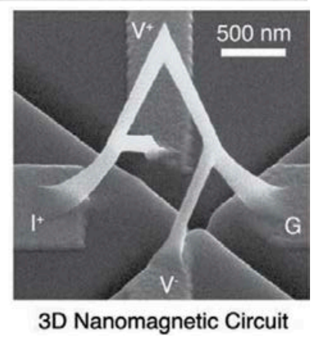
Baraban, DM et al., *ACS Nano* (2012)



Phatak et al., *Nano Lett.* (2014)

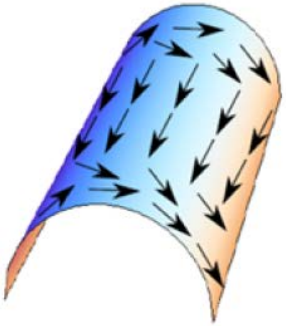


Donnelly et al., *Nature Nano* (2022)

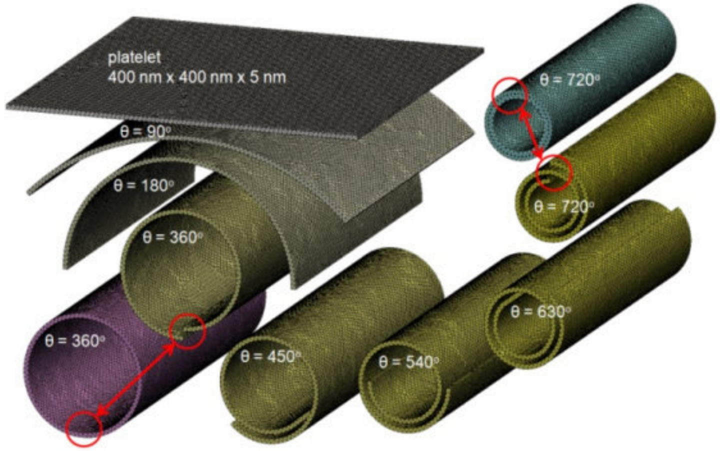


Meng et al., *ACS Nano* (2021)

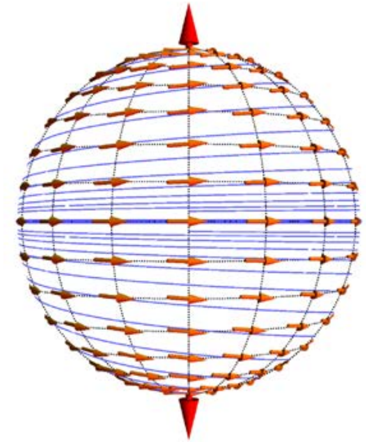
3D curved magnetic shell structures

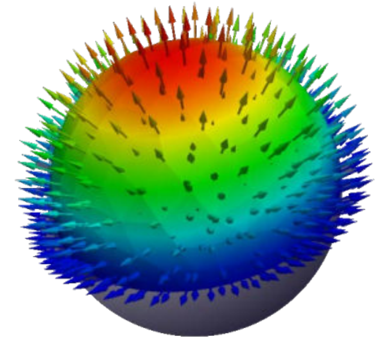


Cylindrical surfaces



Streubel et al., *Nano Lett.* (2012) & (2014) & *Adv. Mat.* (2014)

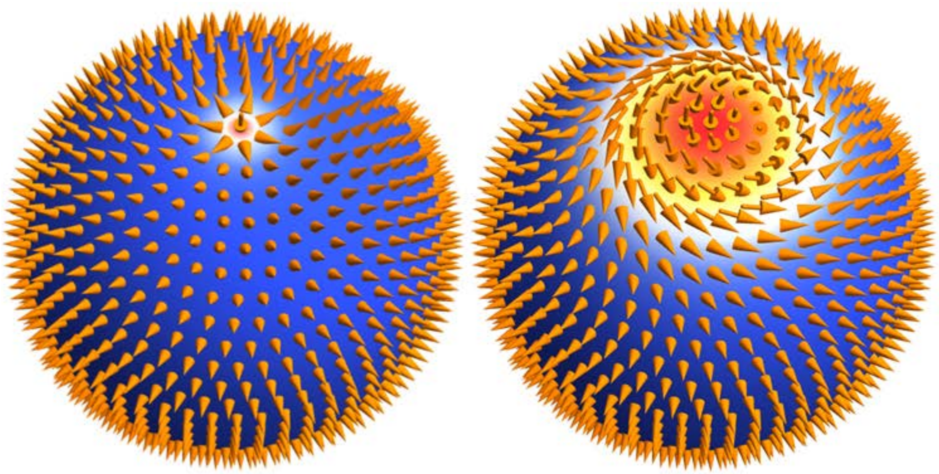




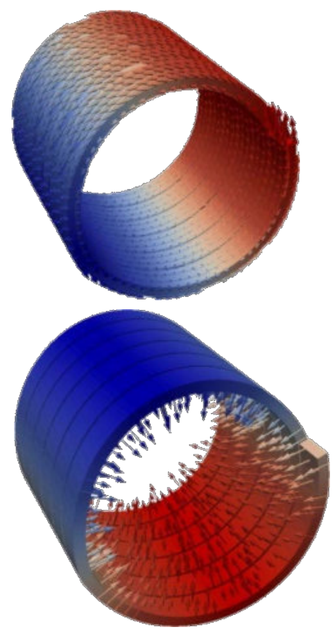
Spherical surfaces

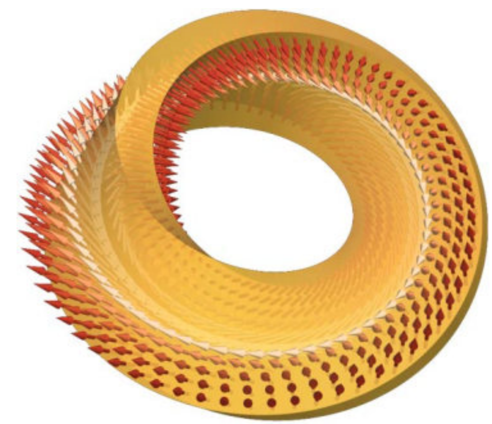
Albrecht et al., *Nat. Mater.* **4**, 203 (2005)
Ulbrich et al., *PRL* (2006); DM et al., *APL* (2007)…
Kravchuk et al., *PRB* **85**, 144433 (2012)

Curvature induced skyrmions on a sphere



Kravchuk et al., *PRB* (2016); *PRL* (2018)





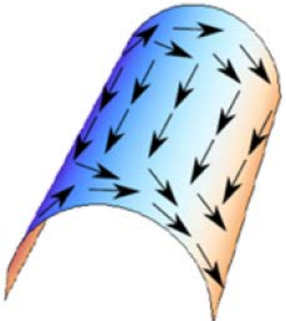
Pylypovskyi et al., *PRL* ('15)

Smith et al.,
PRL **107**, 097204 (2011)

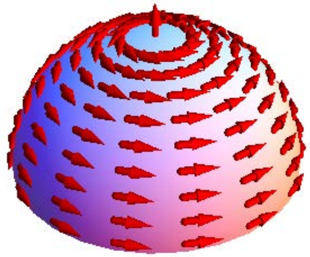
DRESDEN concept HZDR

Dr. Denys Makarov I E-Mail: d.makarov@hzdr.de I Intelligent Materials and Systems

Impact of curvature on a magnetic system



Cylindrical surfaces



Spherical surfaces

Magnetic interactions in the anisotropic Heisenberg ferromagnet:

$$E = L \int_{\mathcal{S}} \left[A \sum_{i=x,y,z} (\nabla m_i)^2 + K(\boldsymbol{m} \cdot \boldsymbol{n})^2 \right] \mathrm{d}\mathcal{S}$$

Exchange energy Anisotropy energy

In a curvilinear basis, micromagnetic energy can be rewritten:

$$\mathscr{E}_{ex} = [\boldsymbol{\nabla}\theta - \boldsymbol{\Gamma}(\varphi)]^2 + \left[\sin\theta\,(\boldsymbol{\nabla}\varphi - \boldsymbol{\Omega}) - \cos\theta \frac{\partial \boldsymbol{\Gamma}(\varphi)}{\partial\varphi}\right]^2$$

$$\mathscr{E}_{ex} = \mathscr{E}_{ex}^0 + \mathscr{E}_{ex}^A + \mathscr{E}_{ex}^D \qquad \mathscr{E}_{ex}^0 = (\boldsymbol{\nabla}\theta)^2 + \sin^2\theta(\boldsymbol{\nabla}\varphi)^2$$

Induced anisotropy responses:

$$\mathscr{E}_{ex}^A = \boldsymbol{\Gamma}^2 + \sin^2\theta \boldsymbol{\Omega}^2 + \cos^2\theta(\partial_\varphi \boldsymbol{\Gamma})^2$$

Quadratic in curvature

Induced chiral responses:

$$\mathscr{E}_{ex}^D = D_{\alpha\beta\gamma} m_\beta \nabla_\gamma m_\alpha, \quad D_{\alpha\beta\gamma} = -D_{\beta\alpha\gamma}$$

$$\mathscr{E}_{ex}^D = -2\left[(\boldsymbol{\nabla}\theta \cdot \boldsymbol{\Gamma}) + \sin\theta \boldsymbol{\nabla}\varphi \cdot (\boldsymbol{\Omega} + \cos\theta \partial_\varphi \boldsymbol{\Gamma})\right]$$

Linear in curvature

Gaididei et al., *PRL* (‘14); Pylypovskyi, DM et al., *PRL* (‘15); Kravchuk, DM et al., *PRL* (‘18); Volkov, DM et al., *PRL* (‘19)…

Impact of curvature on a magnetic system

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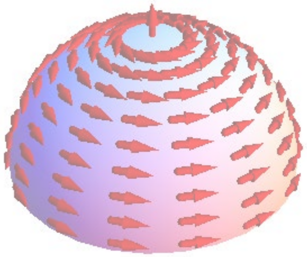

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Exchange energy   Anisotropy energy

New approach to material science

designing magnetic responses by tailoring the geometry of thin films

Induced anisotropy responses: $\mathscr{E}^A_{ex} = \boldsymbol{\Gamma}^2 + \sin^2\theta\boldsymbol{\Omega}^2 + \cos^2\theta(\partial_\varphi\boldsymbol{\Gamma})^2$ Quadratic in curvature

Induced chiral responses: $\mathscr{E}^D_{ex} = D_{\alpha\beta\gamma} m_\beta \nabla_\gamma m_\alpha, \quad D_{\alpha\beta\gamma} = -D_{\beta\alpha\gamma}$

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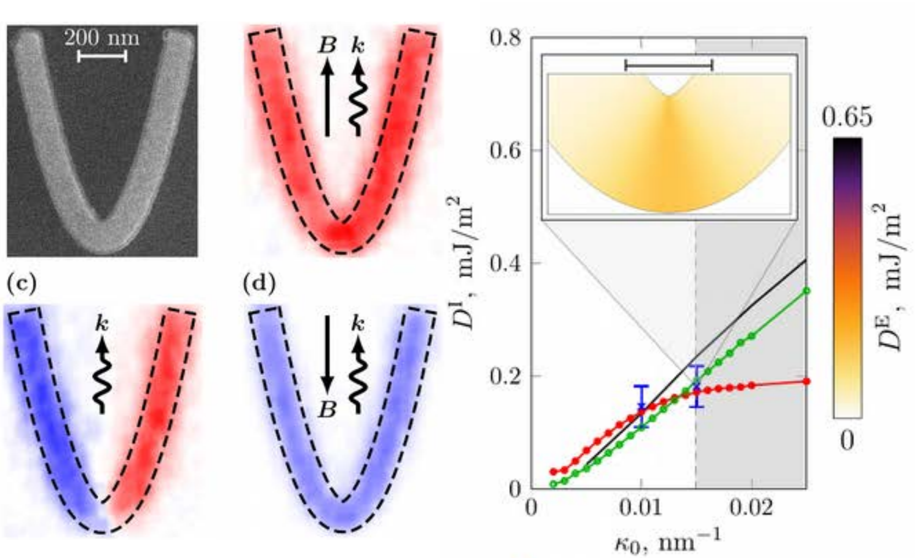
Linear in curvature

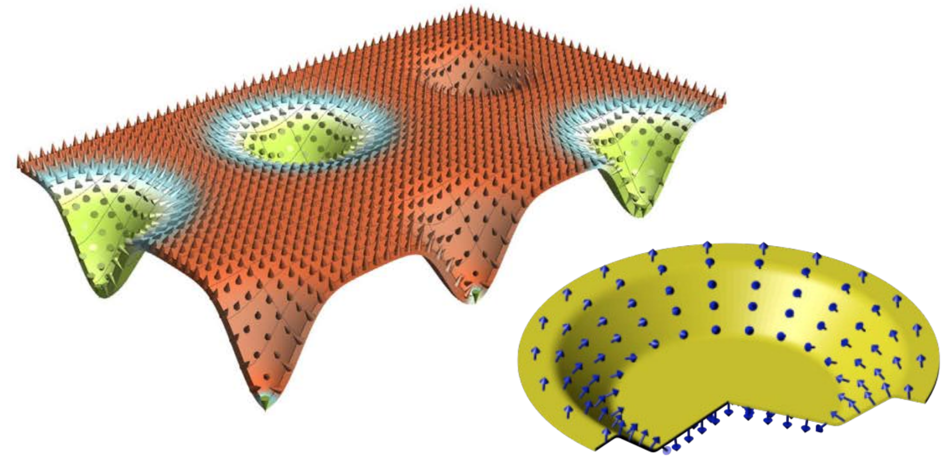
Gaididei et al., *PRL* (‘14); Pylypovskyi, DM et al., *PRL* (‘15); Kravchuk, DM et al., *PRL* (‘18); Volkov, DM et al., *PRL* (‘19)…

Experimental confirmation of curvature effects



Volkov et al., *Phys. Rev. Lett.* **123**, 077201 (2019)

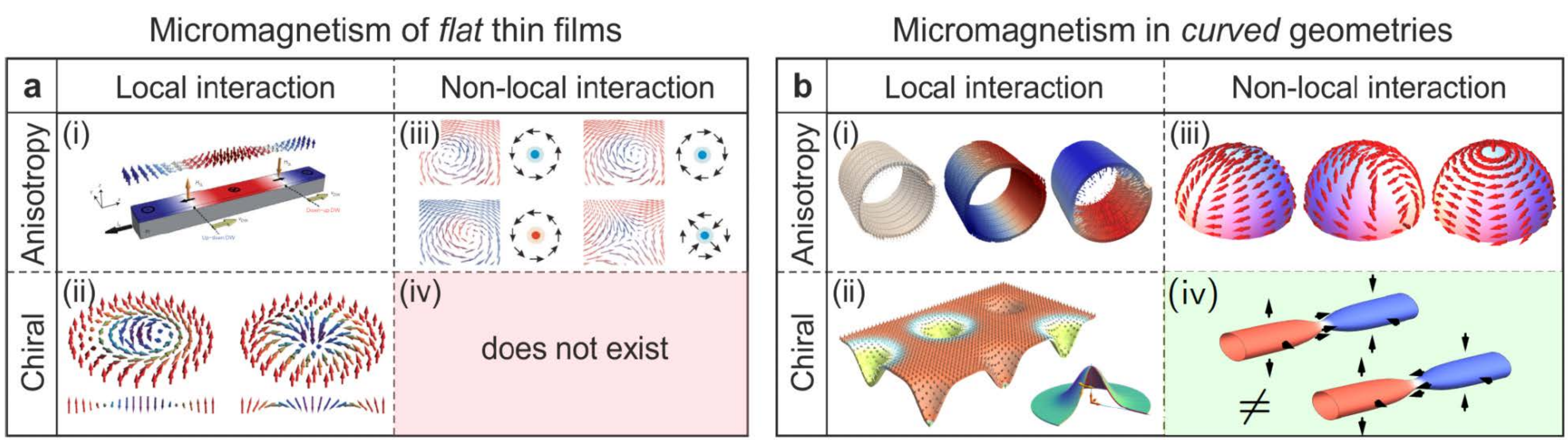
Magnetic Skyrmion states on a curvilinear defect



Kravchuk et al., *Phys. Rev. Lett.* **120**, 067201 (2018)

Pylypovskyi et al., *Phys. Rev. Appl.* **10**, 064057 (2018)

Discovery of a non-local chiral effect in curvilinear ferromagnetic shells



Sheka et al., *Communications Physics* **3**, 128 (2020)

Multiferroic materials

Ferroic materials / Order parameter

The behavior of any physical system from cosmological objects in field theories through living organisms in biology up to synthetic objects in condensed and soft matter is determined by the order parameter that lives in spacetime

Dr. Denys Makarov I E-Mail: d.makarov@hzdr.de I Intelligent Materials and Systems

Ferroic materials / Order parameter

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Order parameter of magnetic materials: magnetization

In ferromagnets, order parameter brakes the time reversal symmetry

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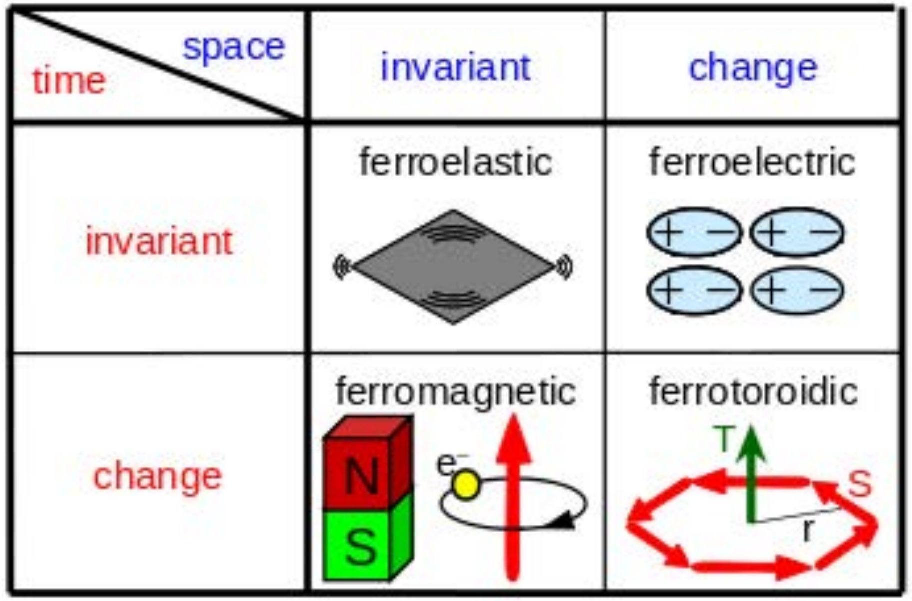
Order parameter of magnetic materials: magnetization

In ferromagnets, order parameter brakes the time reversal symmetry

There are 4 ferroic order parameters

Ferroic materials / Order parameter



Type	Micro. property	Macro. property	Force field
Ferroelastic	Deformation	Strain	Stress
Ferromagnetic	Magnetic moment	Magnetization	Magnetic field
Ferroelectric	El. dipole moment	Polarization	Electric field
Ferrotoroidic	Magnetic vortex	Toroidization	Toroidal field

N. A. Spaldin, M. Fiebig & M. Mostovoy
The toroidal moment in condensed-matter physics and its relation to the magnetoelectric effect
J. Phys.: Condens. Matter **20**, 434203 (2008)

Manfred Fiebig: https://www.hikari.uni-bonn.de/research/multiferroics/new-forms-of-ferroic-order

Ferroic materials / Order parameter

A material is termed as ferroic if there is a spontaneous property, called the order parameter, that arises in uniform alignment of some microscopic property of the unit cell throughout macroscopic regions of a crystal

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The order parameter O can be switched into at least two different directions by some external field A

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This works because a ferroic contributes a term

$$F = -OA$$

to the free energy so that an alignment of O parallel to A minimizes this energy

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Regions with different orientation of the order parameter can coexist.
They are called domains

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They are called domains

Long-range ordering is present below a critical temperature only

Manfred Fiebig: https://www.hikari.uni-bonn.de/research/multiferroics/new-forms-of-ferroic-order

Ferroelectric barium titanate: $BaTiO_3$

parent phase: ideal cubic ABO_3 perovskite structure => no electric polarisation

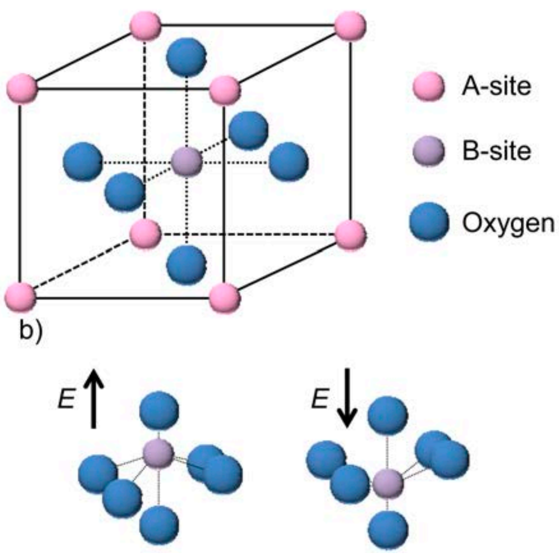
ferroelectric phase: the Ti^{4+} ion is shifted away from the center of the octahedron causing a polarization (only one ferroic order; no magnetism; empty *d* shell)

https://blogs.hrz.tu-freiberg.de/pyro/pyroelektrizitaet/

Mutiferroic $BiFeO_3$ (BFO)

In BFO, the ferroelectric displacement is driven by the A-site cation, and the magnetism arises from a partially filled *d* shell on the B site

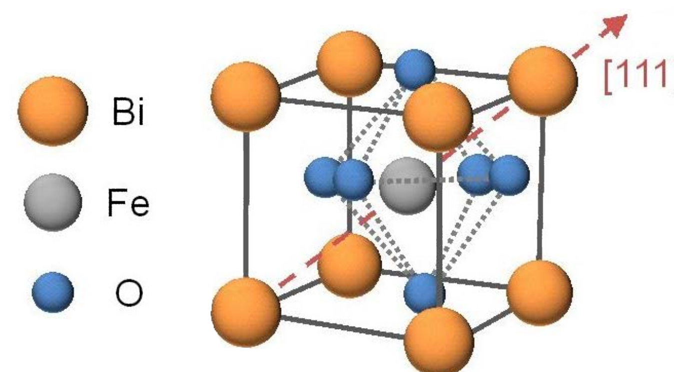
In BFO, the A-site cation (Bi^{3+}) has a so-called stereochemically active *6s²* lone-pair of electrons, and off-centering of the A-site cation is favoured by an energy-lowering electron sharing between the formally empty A-site *6p* orbitals and the filled O *2p* orbitals



J. B. Neaton et al., *Phys. Rev. B*. **71**, 014113 (2005)

cubic phase

rhombohedrally distorted perovskite structure



$BiFeO_3$

https://www.intechopen.com/chapters/44929

BFO based ultralow power electronics

Spin transfer torque magnetic random access memory (STT-MRAM) is among the most promising spintronic memory for computing

Still, it suffers from resistance scalability (resistance scales inversely proportional to the area and drive current densities) and intrinsically high energy/bit operation (>100 fJ/bit)

https://onlinelibrary.wiley.com/doi/full/10.1002/adma.202001943

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Magneto-electric memory can operate with capacitive displacement charge and potentially reach 1-10 aJ/switching operation

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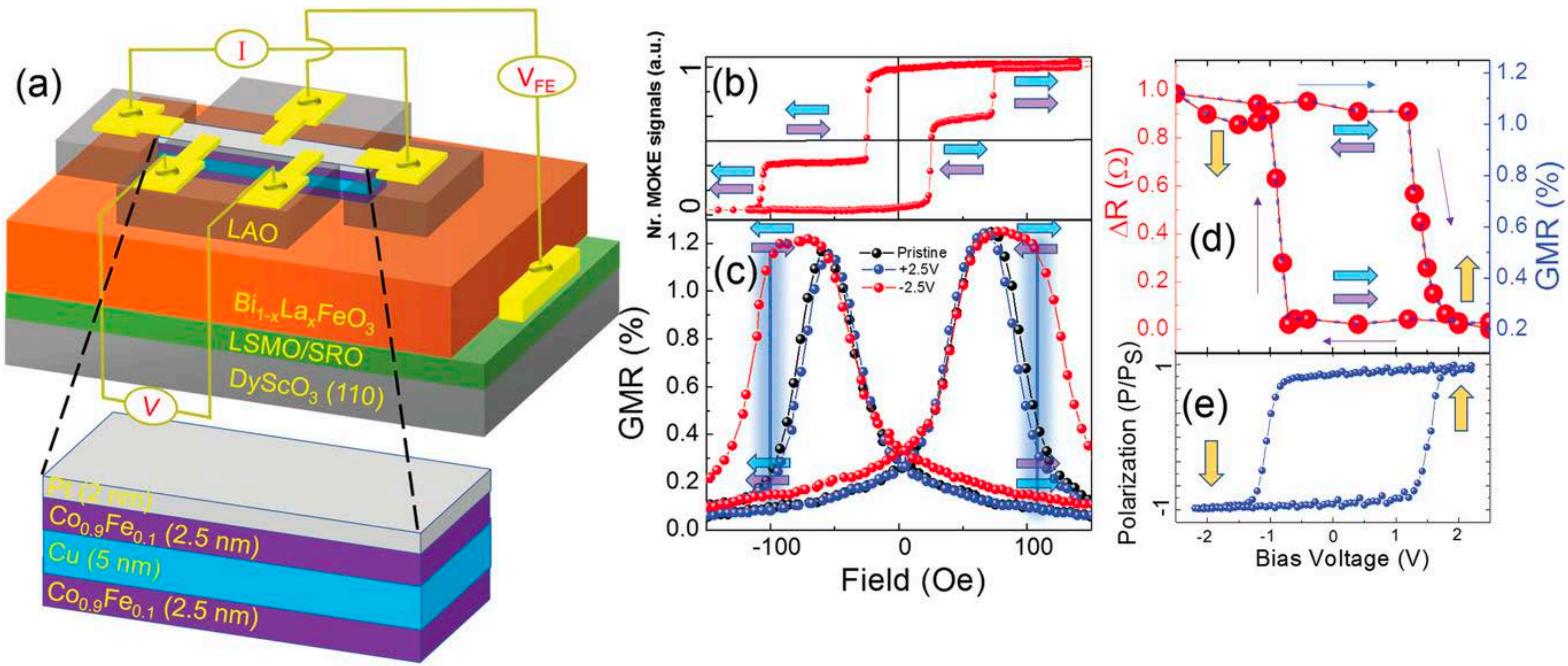

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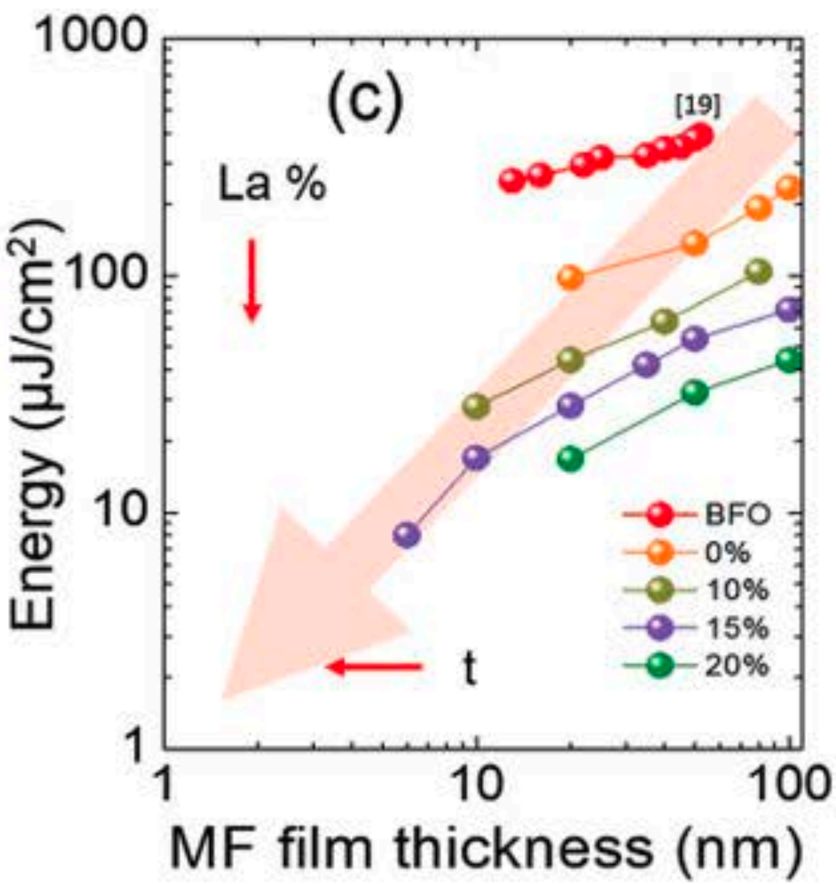
BFO based ultralow power electronics

Magneto-electric memory can operate with capacitive displacement charge and potentially reach 1-10 aJ/switching operation

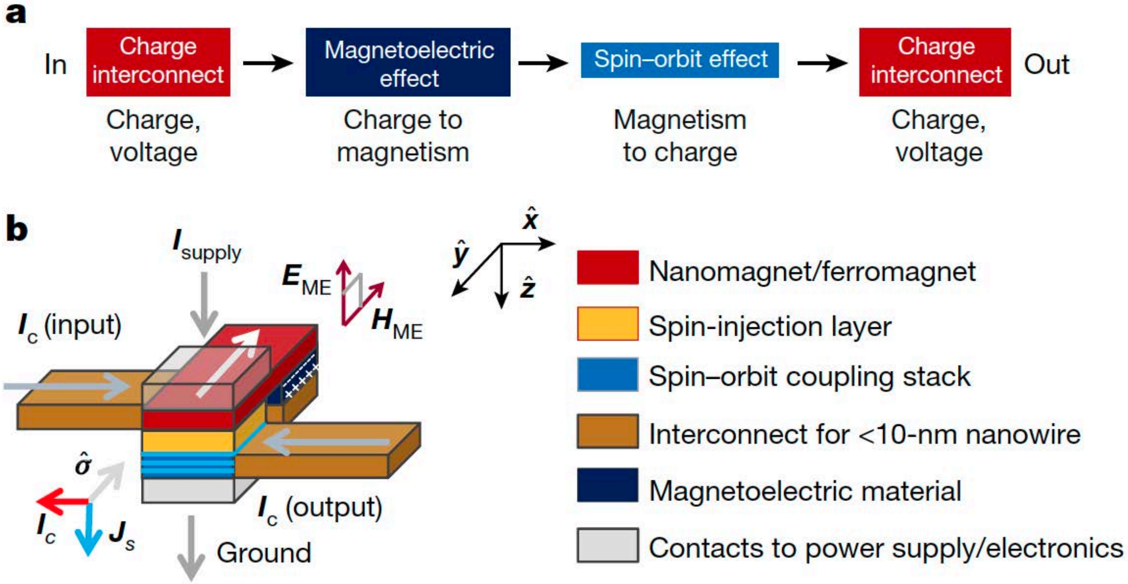
$Bi_{1-x}La_xFeO_3$ thin films



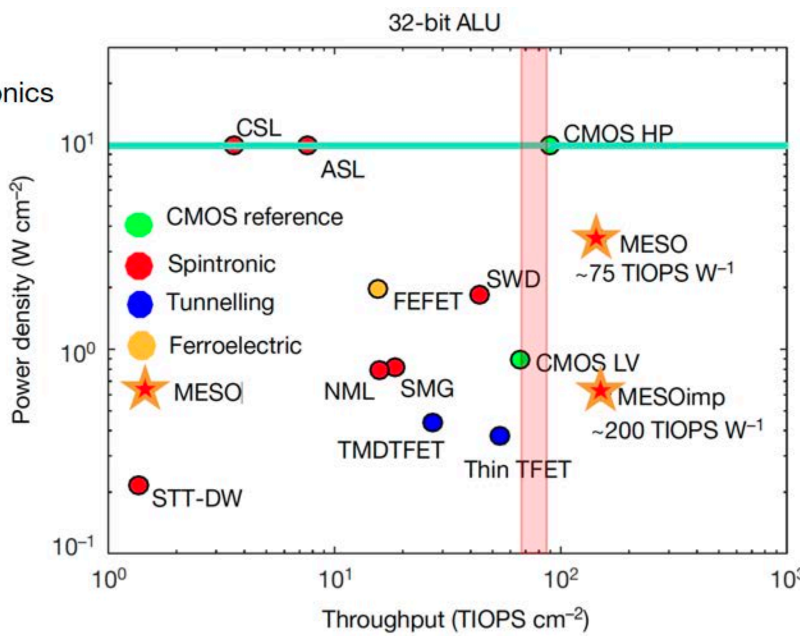
https://onlinelibrary.wiley.com/doi/full/10.1002/adma.202001943

>60 years of material science research

Only 1 mutiferroic which is <u>potentially</u> relevant for spintronic applications: $BiFeO_3$ (BFO)

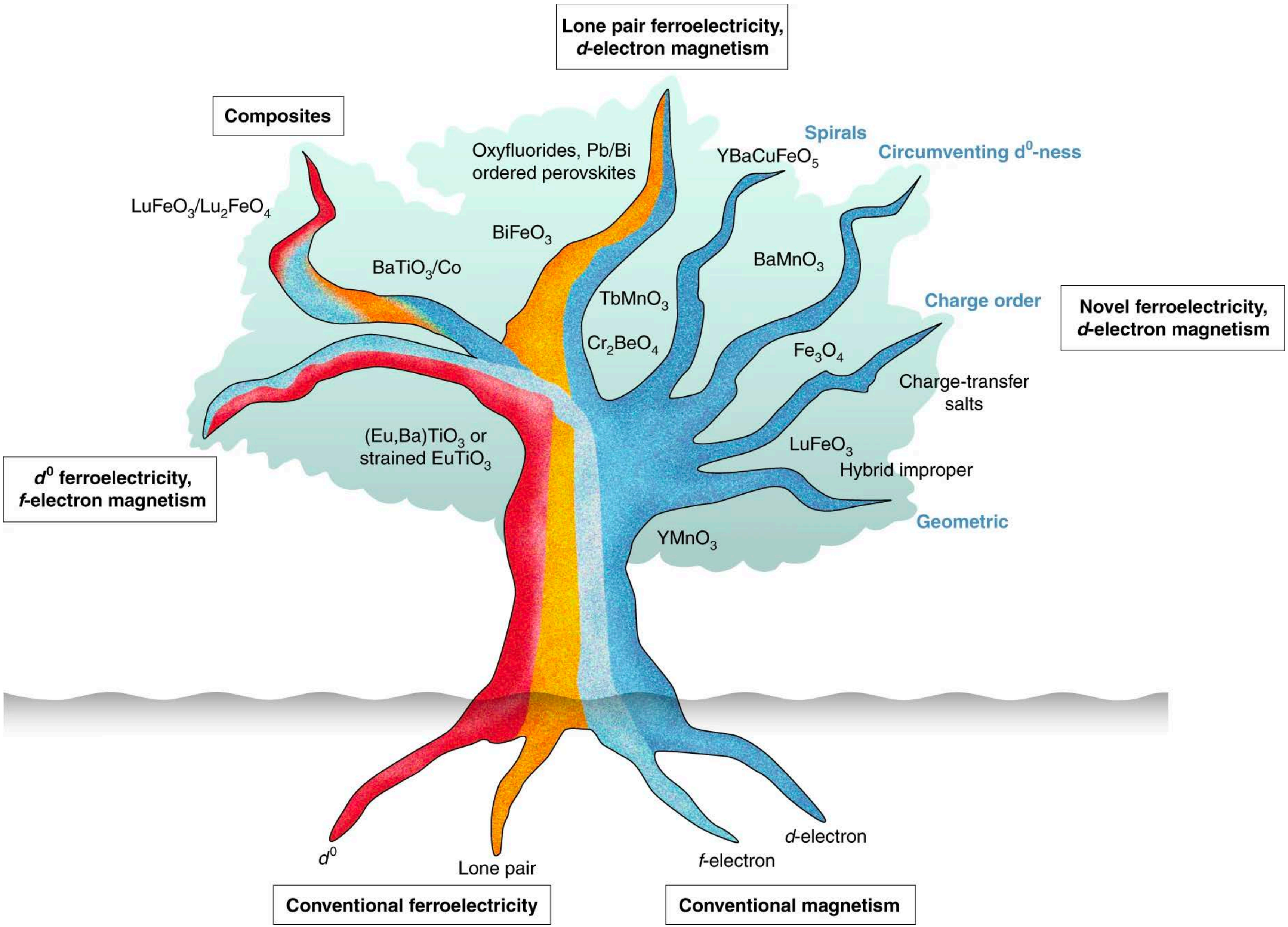


Spin transfer torque magnetic random access memory (STT-MRAM)
><u>100 fJ</u> per switching



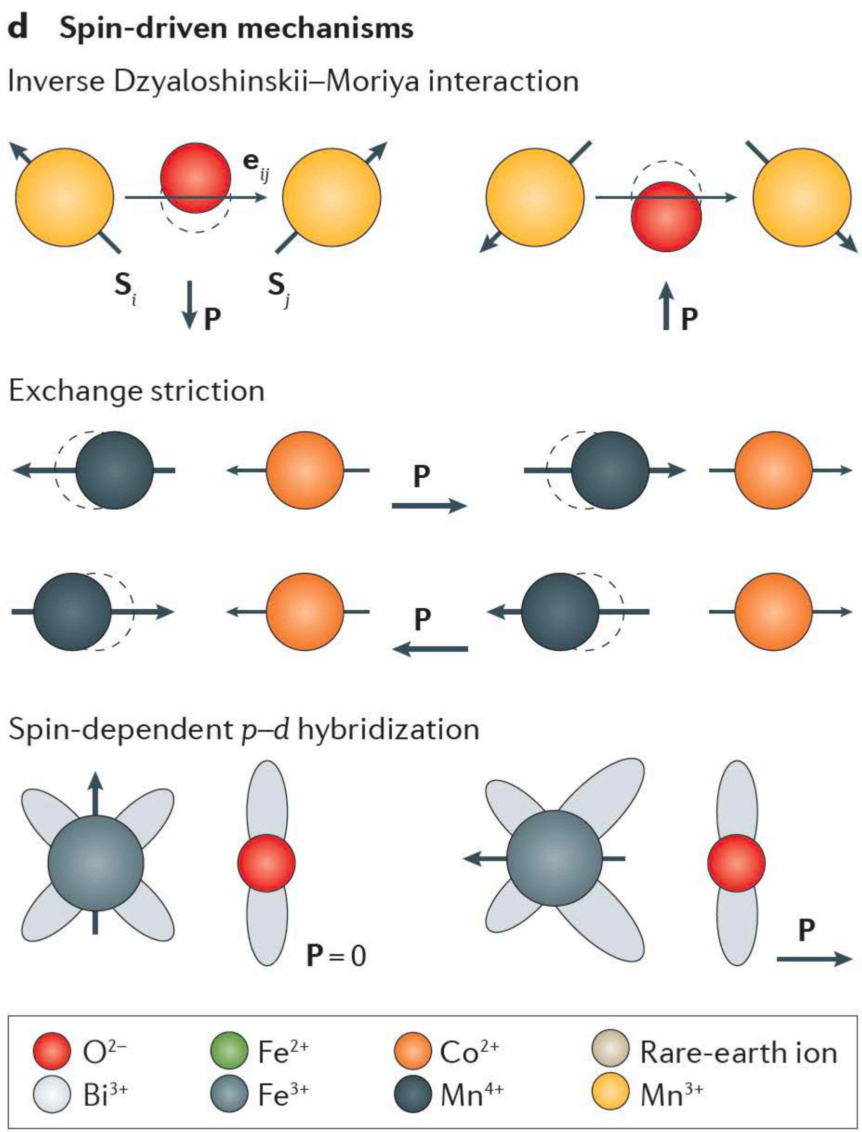
Magnetoelectric memory can operate with capacitive displacement charge and *potentially* reach <u>1-10 aJ</u> per switching operation

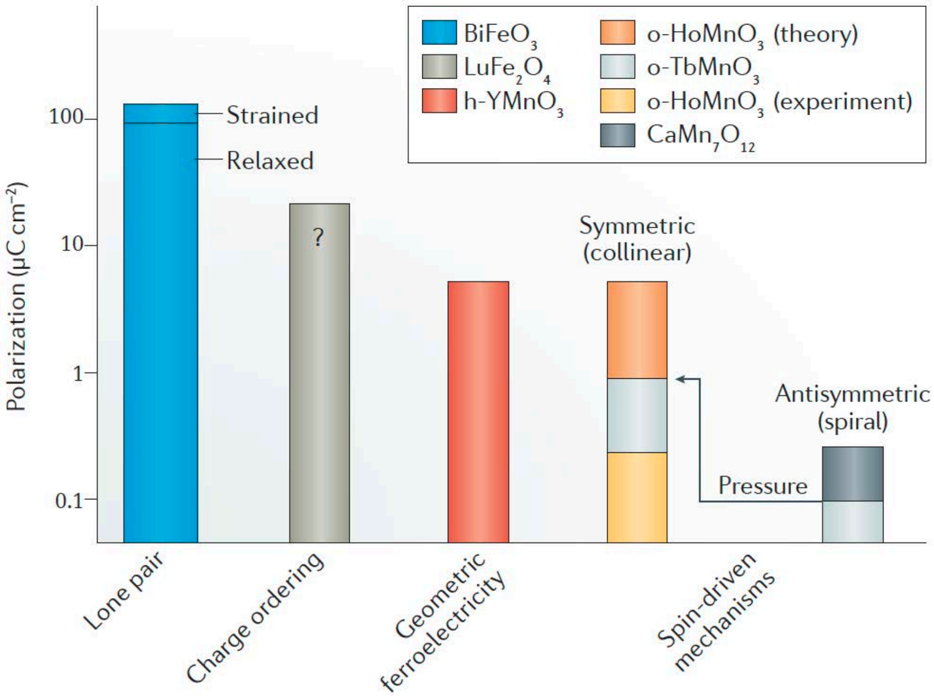
S. Manipatruni, D. E. Nikonov, C. C. Lin et al.
Scalable energy-efficient magnetoelectric spin–orbit logic
Nature 565, 35 (2019)



Nature Materials 18, 203 (2019)

Multiferroics based on magnetic materials





M. Fiebig, T. Lottermoser, D. Meier et al.:

The evolution of multiferroics

Nature Rev. Mater. 1, 16046 (2016)

Magnetoelectric composites

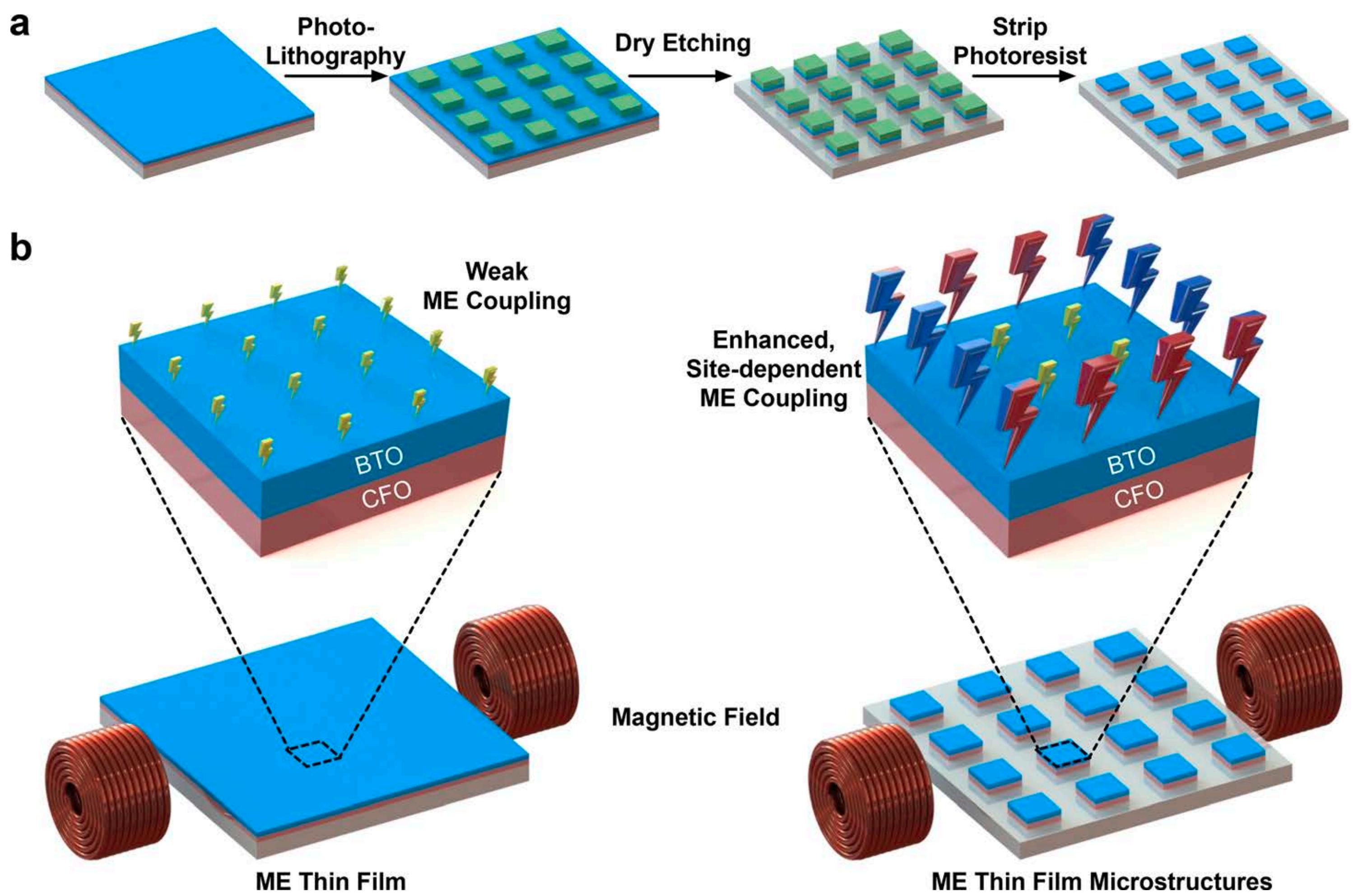
$BaTiO_3$ (BTO) & $CoFe_2O_4$ (CFO): ferroelectric and ferrimagnetic layers

Magnetoelectric composites

$BaTiO_3$ (BTO) & $CoFe_2O_4$ (CFO): ferroelectric and ferrimagnetic layers

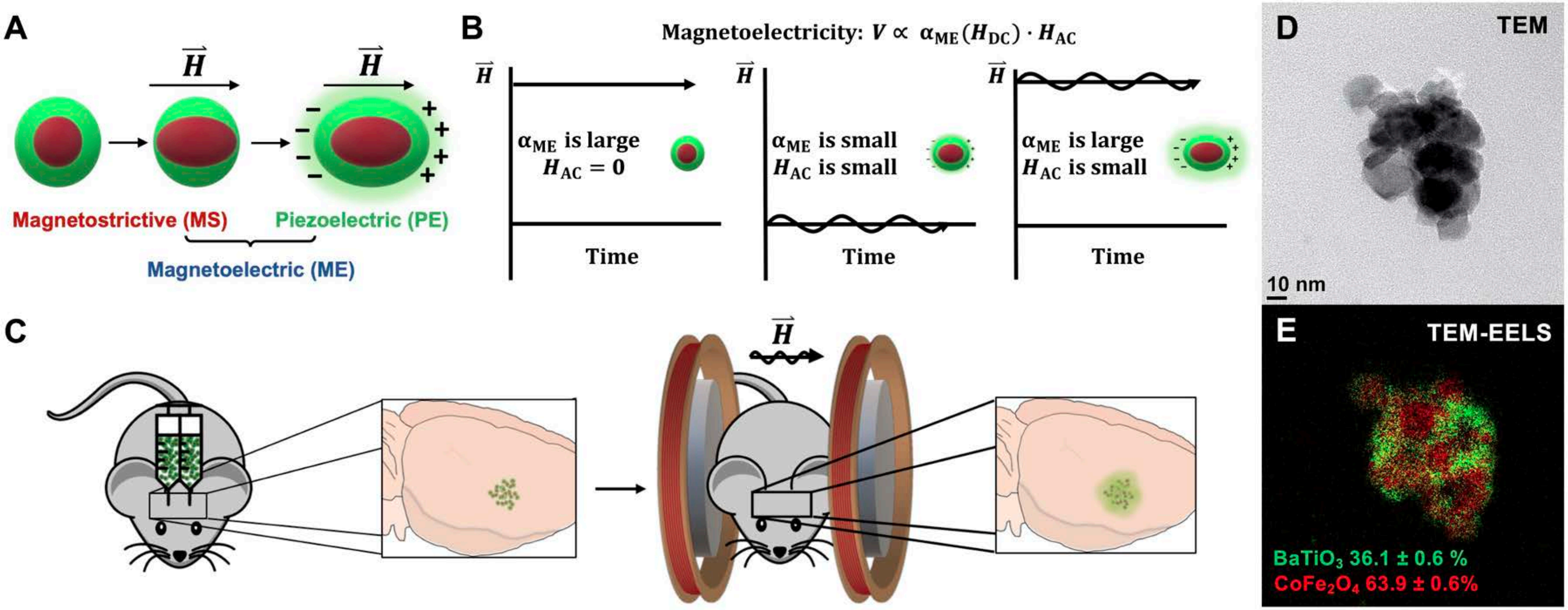
CFO: large magnetostriction | CFO and BTO: high Curie temperatures

BTO/CFO composite gives large strain-mediated ME response



Appl. Phys. Lett. 119, 012901 (2021)

Wireless deep brain stimulation in freely moving mice



Kozielski et al., Science Advances 7, eabc4189 (2021)

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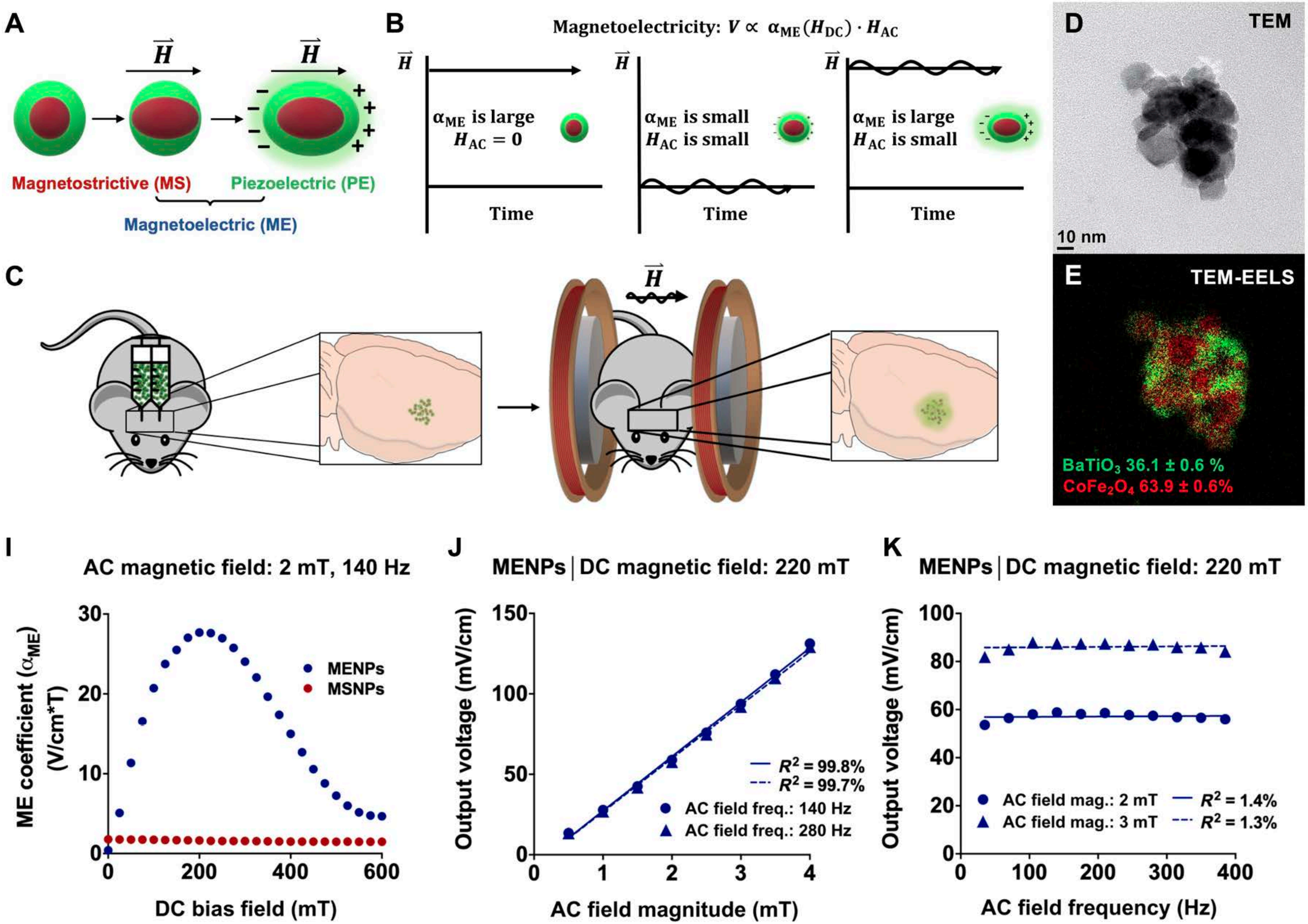
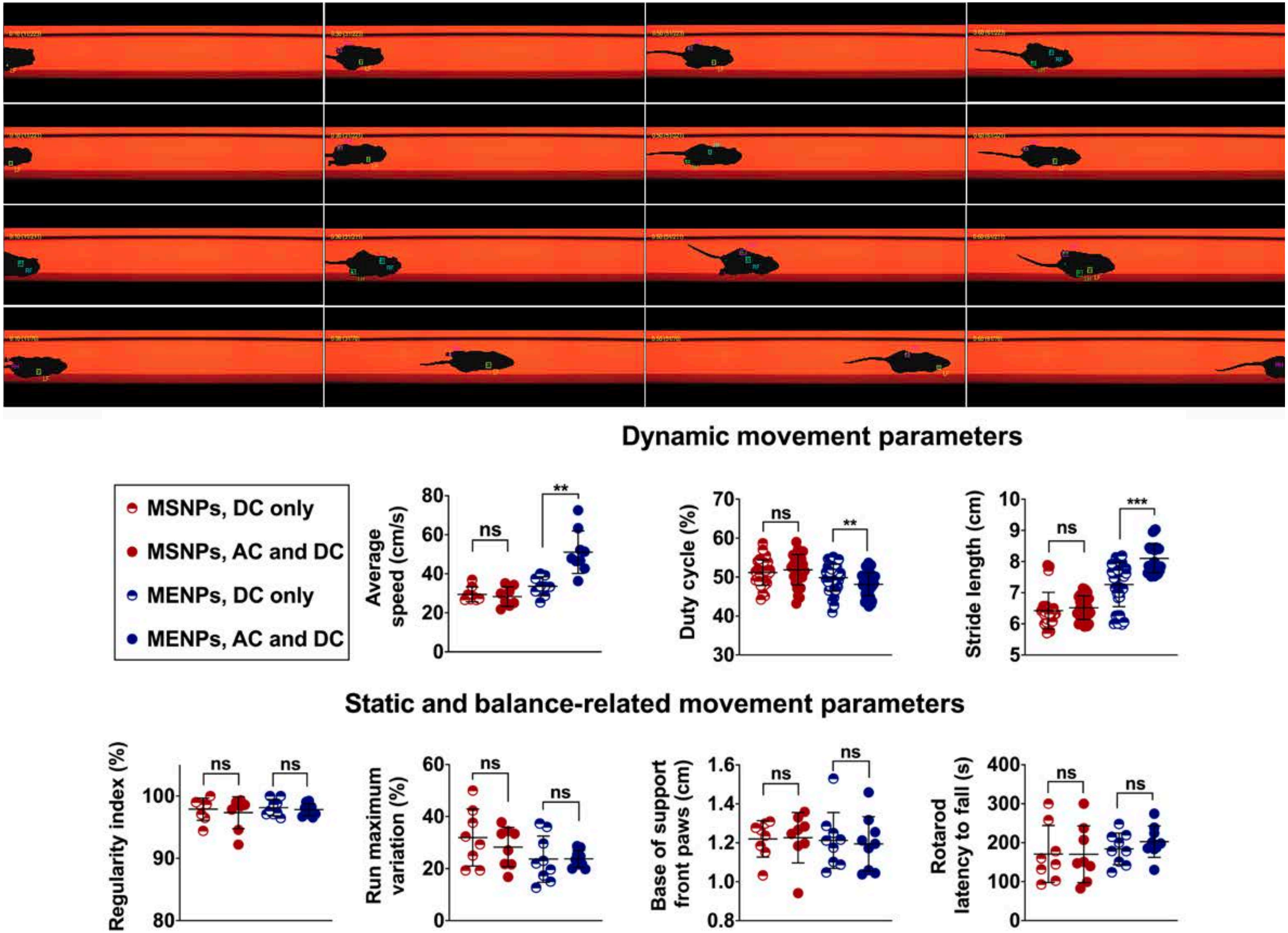


Kozielski et al., Science Advances 7, eabc4189 (2021)

Magnetic stimulation modulates neural activity in mice



Kozielski et al., Science Advances 7, eabc4189 (2021)

Mutiferroic vs Magnetoelectric materials

Multiferroics are defined as materials that exhibit more than one of the primary ferroic properties in the same phase

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Multiferroics are defined as materials that exhibit more than one of the primary ferroic properties in the same phase

In magnetoelectric materials electric field modifies the magnetic properties and vice versa

All ferromagnetic ferroelectric multiferroics are linear magnetoelectrics

Magnetoelectric materials are not necessarily multiferroic

Magnetoelectric Cr_2O_3

Free energy expansion in powers of *E* and *H* according to Landau & Lifshitz (1958):

$$F(E,H) = F_0 - \frac{\varepsilon_{ij}E_iE_j}{8\pi} - \frac{\mu_{ij}H_iH_j}{8\pi} - \alpha_{ij}E_iH_j - \cdots$$

Electric response to electric field

Magnetic response to magnetic field

Magnetoelectric Cr_2O_3

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Electric response to electric field

Magnetic response to magnetic field

Linear magnetoelectric effect

➡ Only allowed if time- & space inversion symmetries individually broken

α_{ij}

Magnetoelectric tensor

Magnetoelectric Cr_2O_3

I. Dzyaloshinskii, *ZETF* **37**, 881 (1959)

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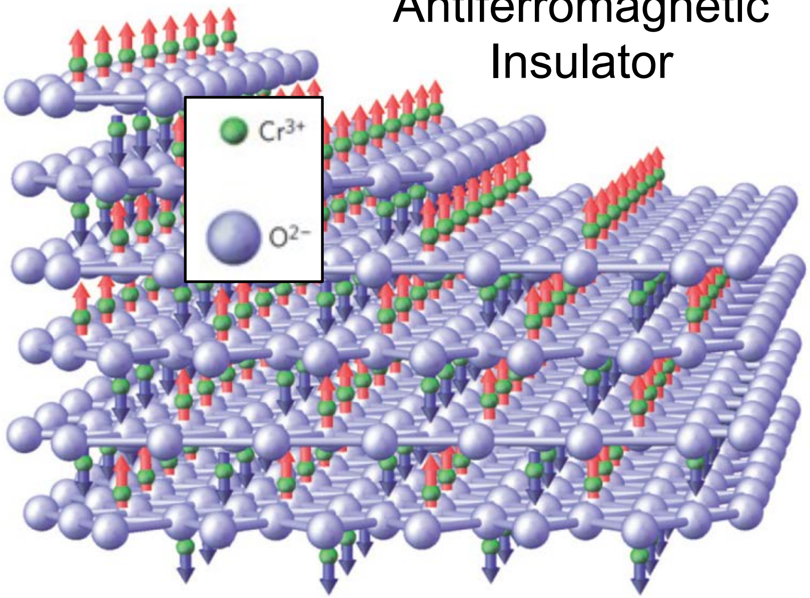
$\boldsymbol{\alpha}_{\mathbf{ij}}$

Magnetoelectric tensor

Cr_2O_3

Magnetoelectric Antiferromagnetic Insulator



X. He et al., *Nature Mat.* **9**, 579 (2010)

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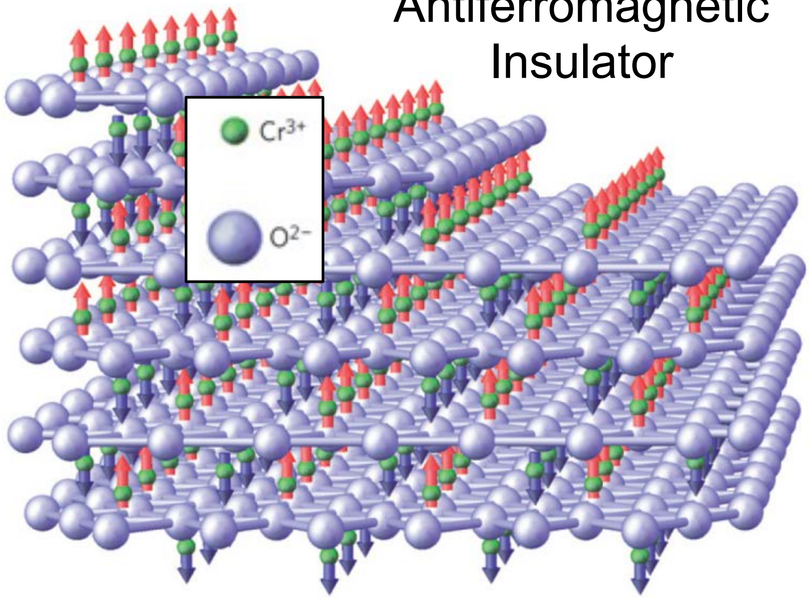
Cr_2O_3

Magnetoelectric Antiferromagnetic Insulator



X. He et al., *Nature Mat.* **9**, 579 (2010)

www.etsy.com

Multifunctional

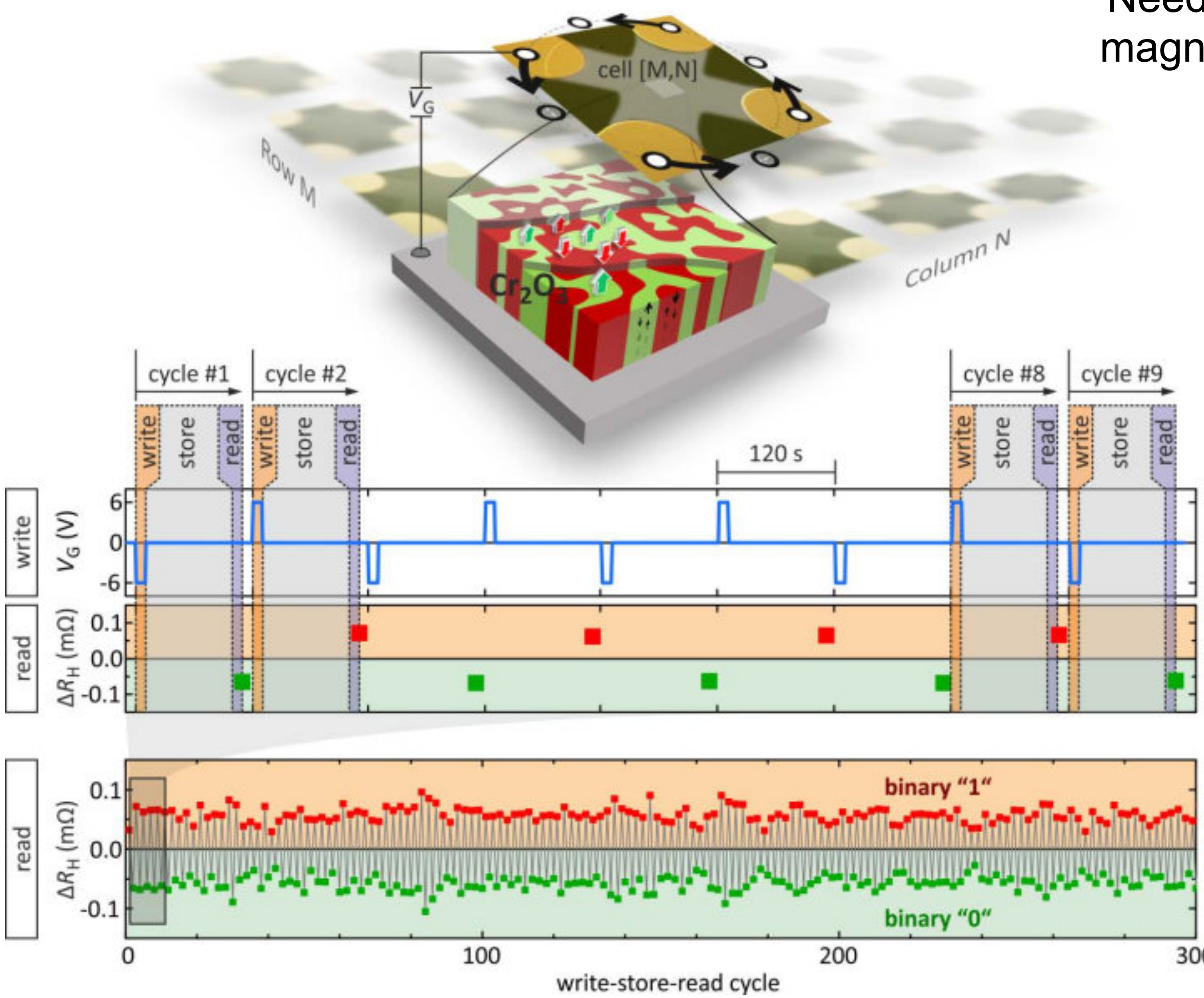
Optoelectronics

Solar cells

Pigment

Magnetoelectric RAM based on Pt/Cr_2O_3

Needs permanent magnetic field bias



T. Kosub et al., *Nature Commun.* **8**, 13985 (2017)

Magnetostrictive materials

Dr. Denys Makarov I E-Mail: d.makarov@hzdr.de I Intelligent Materials and Systems

Magnetism and mechanical deformation

Magnetostriction: change of the shape or dimensions of a magnetic material upon magnetisation (in an applied magnetic field)

Magnetism and mechanical deformation

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Anisotropic magnetostriction (Joule magnetostriction): elongation/contraction (for positive/negative magnetostrsiction coefficient) of the material in an applied field

https://www.tf.uni-kiel.de/servicezentrum/neutral/praktika/anleitungen/m205

Magnetism and mechanical deformation

Magnetostriction: change of the shape or dimensions of a magnetic material upon magnetisation (in an applied magnetic field)

Anisotropic magnetostriction (Joule magnetostriction): elongation/contraction (for positive/negative magnetostrsiction coefficient) of the material in an applied field

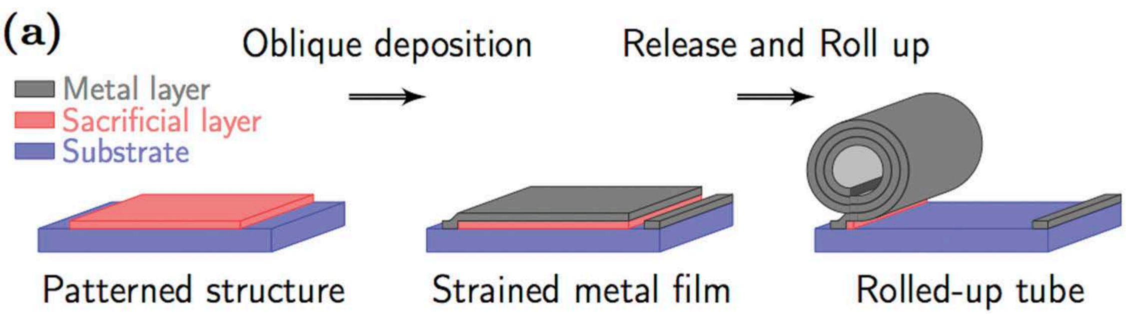
Typically small: relative elongation is in the order of 10×10^{-6}

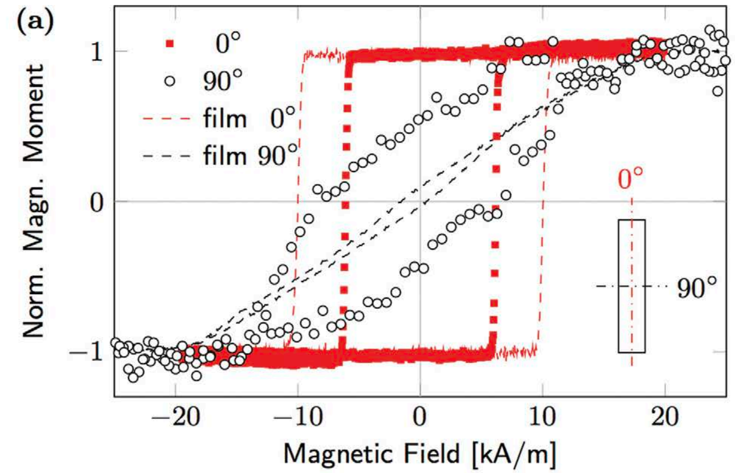
Terfenol-D ($TbDyFe_2$ alloy): about 2000×10^{-6} at 2 kOe and room temperature

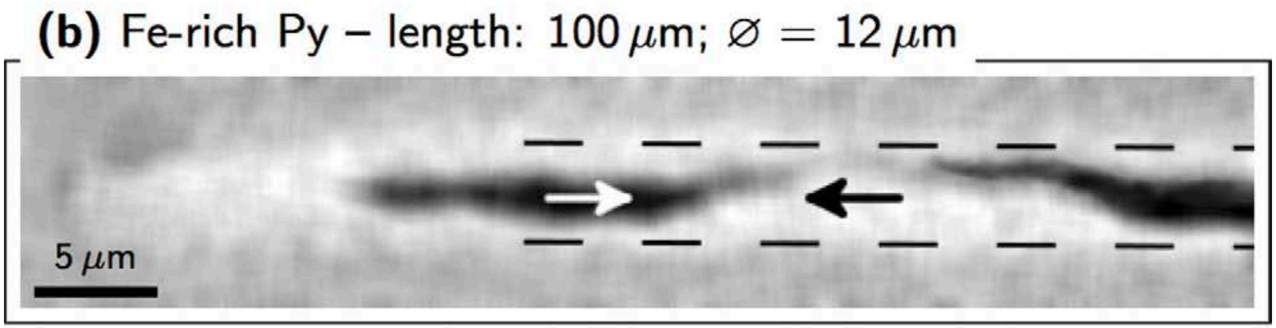
FeAl alloy: about 300×10^{-6} at 0.2 kOe

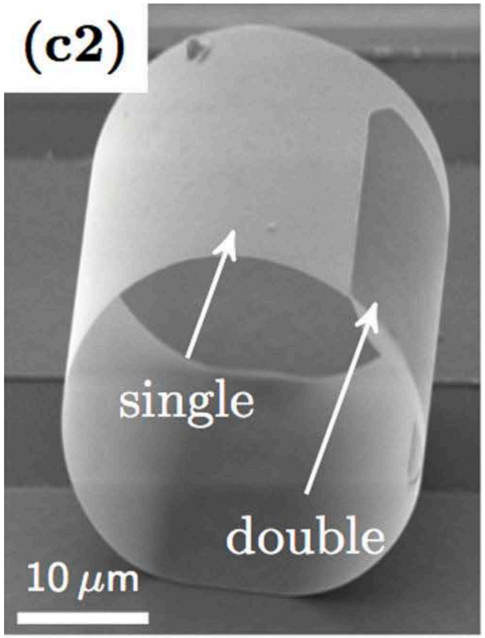
https://www.tf.uni-kiel.de/servicezentrum/neutral/praktika/anleitungen/m205

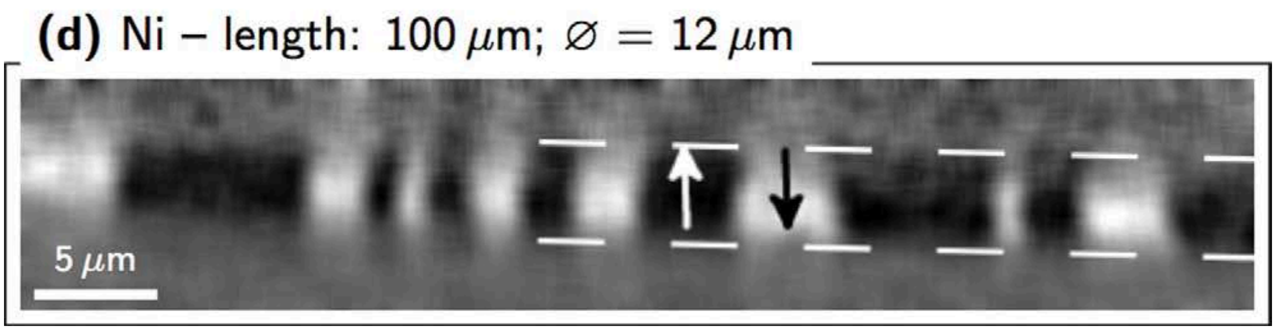
Magnetostiction effects on magnetic textures





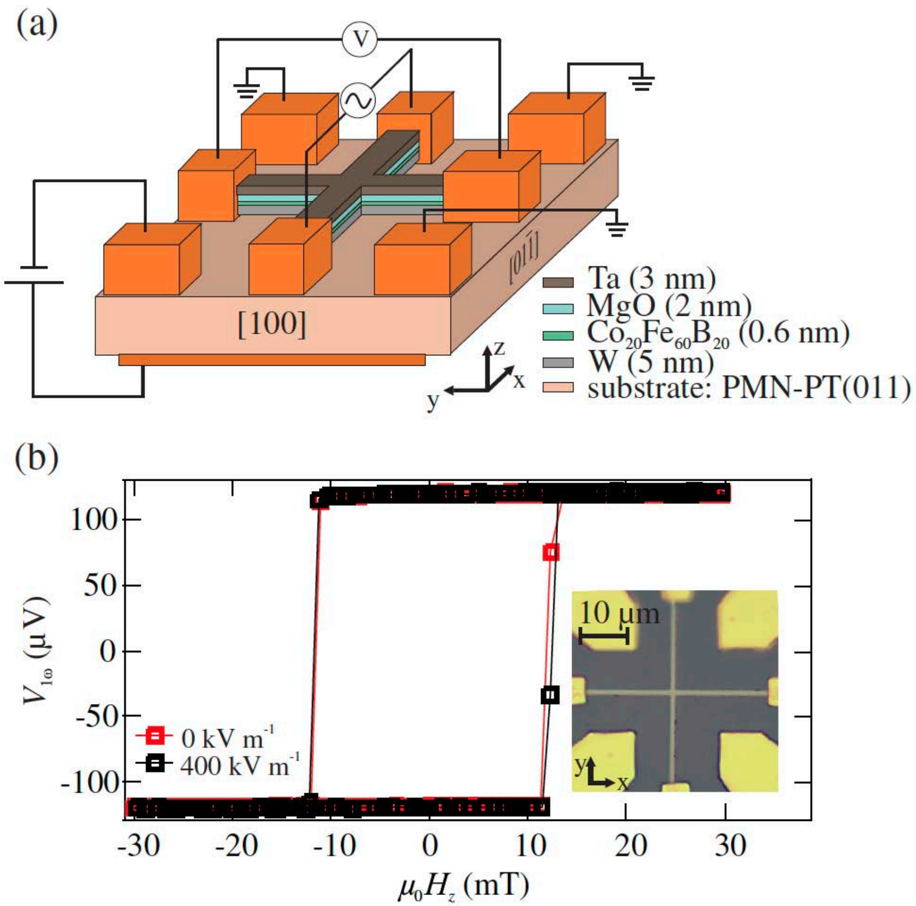


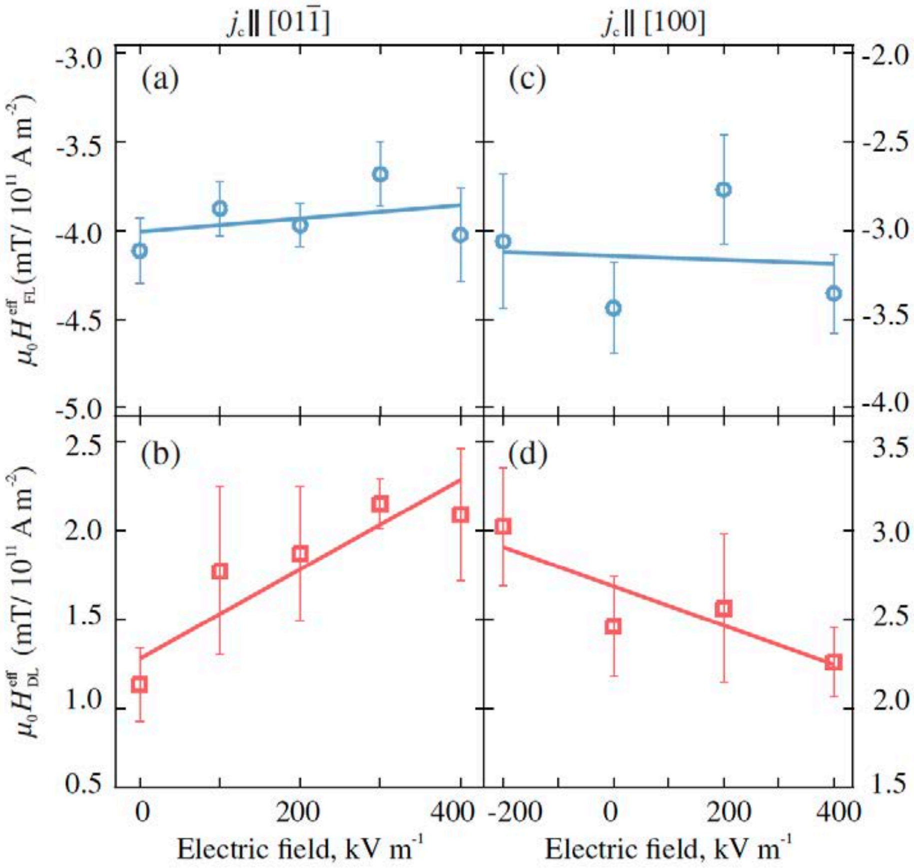




Streubel, DM et al., *Adv. Mater.* **26**, 316 (2014)

Impact of strain effects on spin-orbit torques

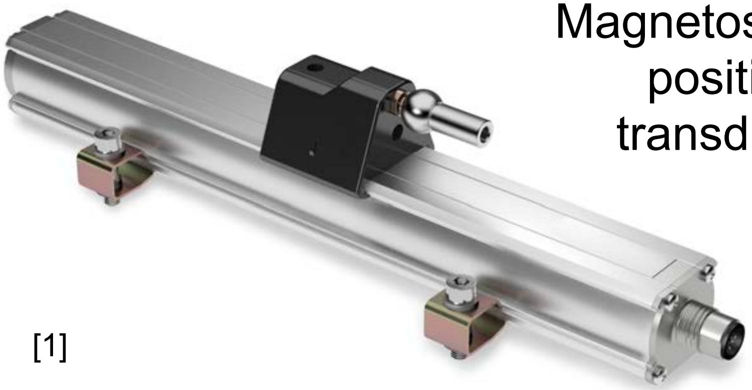




Filianina et al., *Phys. Rev. Lett.* **124**, 217701 (2020) & *APL* **118**, 032401 (2021)

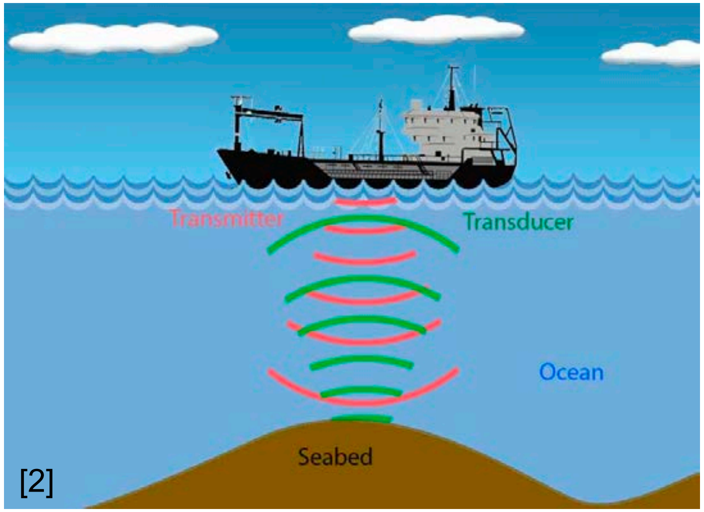
Magnetostriction: applications

Magnetostrictive position transducer

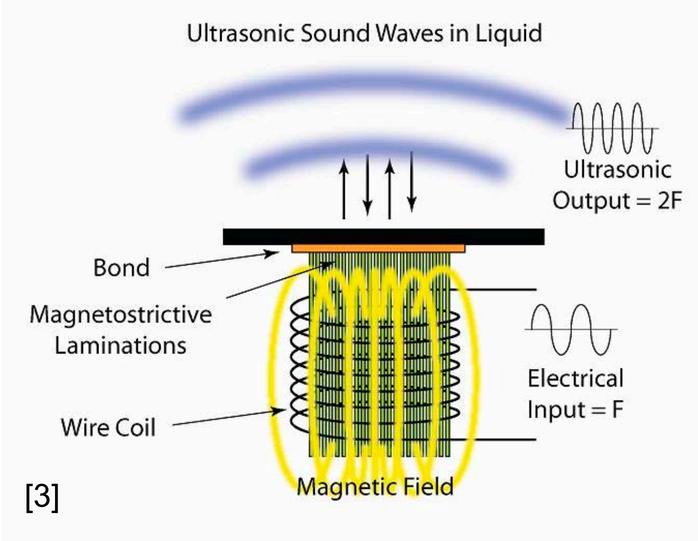


[1]

Magnetostrictive sonar

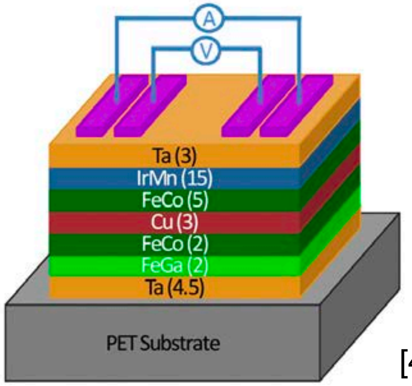


[2]

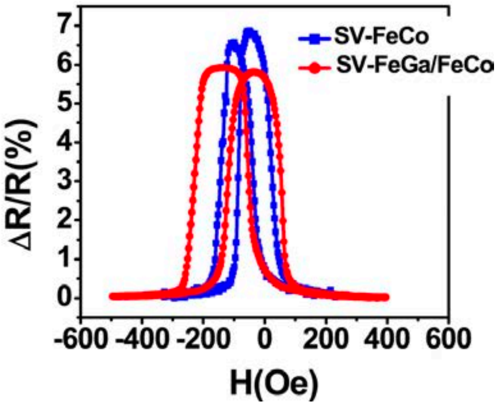


[3]

Magnetostrictive spin valves



[4]



[1] https://www.powertransmissionworld.com/a-new-contacless-magnetostrictive-position-transducer/

[2] https://news.vidyaacademy.ac.in/wp-content/uploads/2019/02/Active-sonar.jpg

[3] https://techblog.ctgclean.com/2012/01/ultrasonics-transducers-magnetostrictive-hardware/

[4] https://aip.scitation.org/doi/10.1063/1.4943770

Dr. Denys Makarov I E-Mail: d.makarov@hzdr.de I Intelligent Materials and Systems

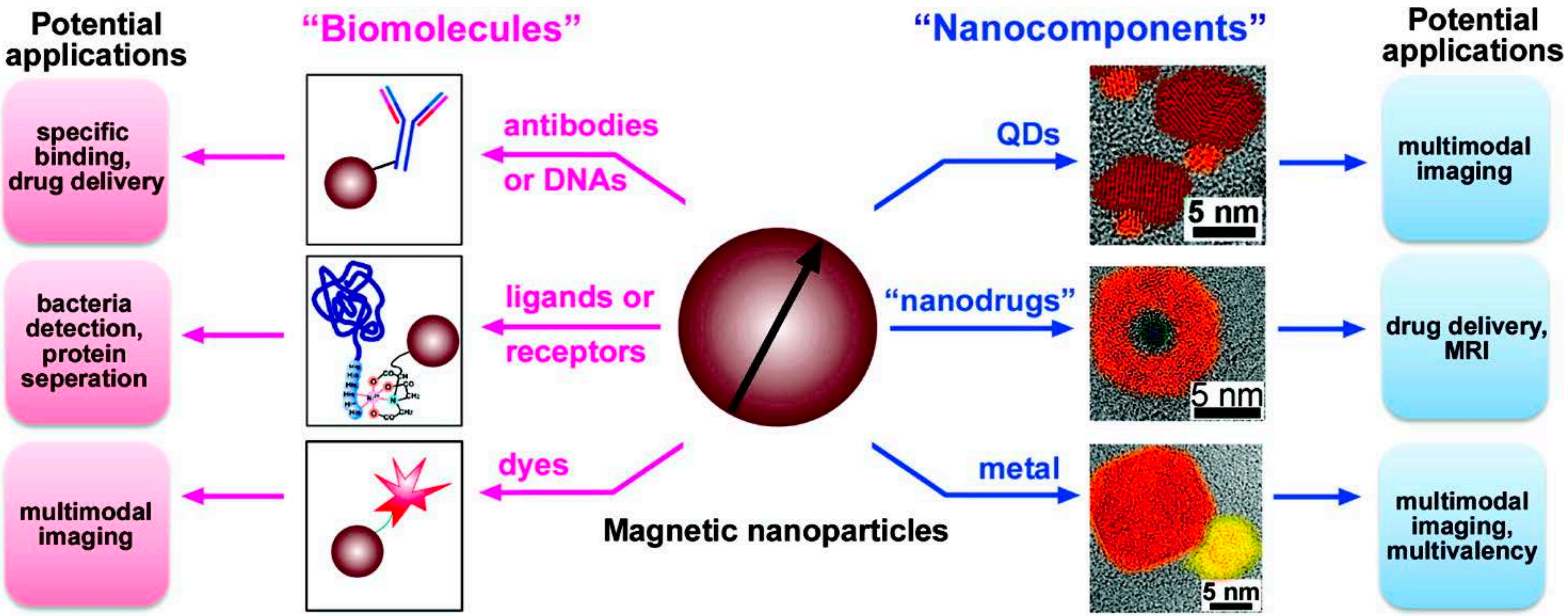
Magnetic composites for sensors and actuators

Magnetic particles and polymers

Dr. Denys Makarov I E-Mail: d.makarov@hzdr.de I Intelligent Materials and Systems

Multifunctional magnetic nanoparticles

Lecture by Annelies Coene



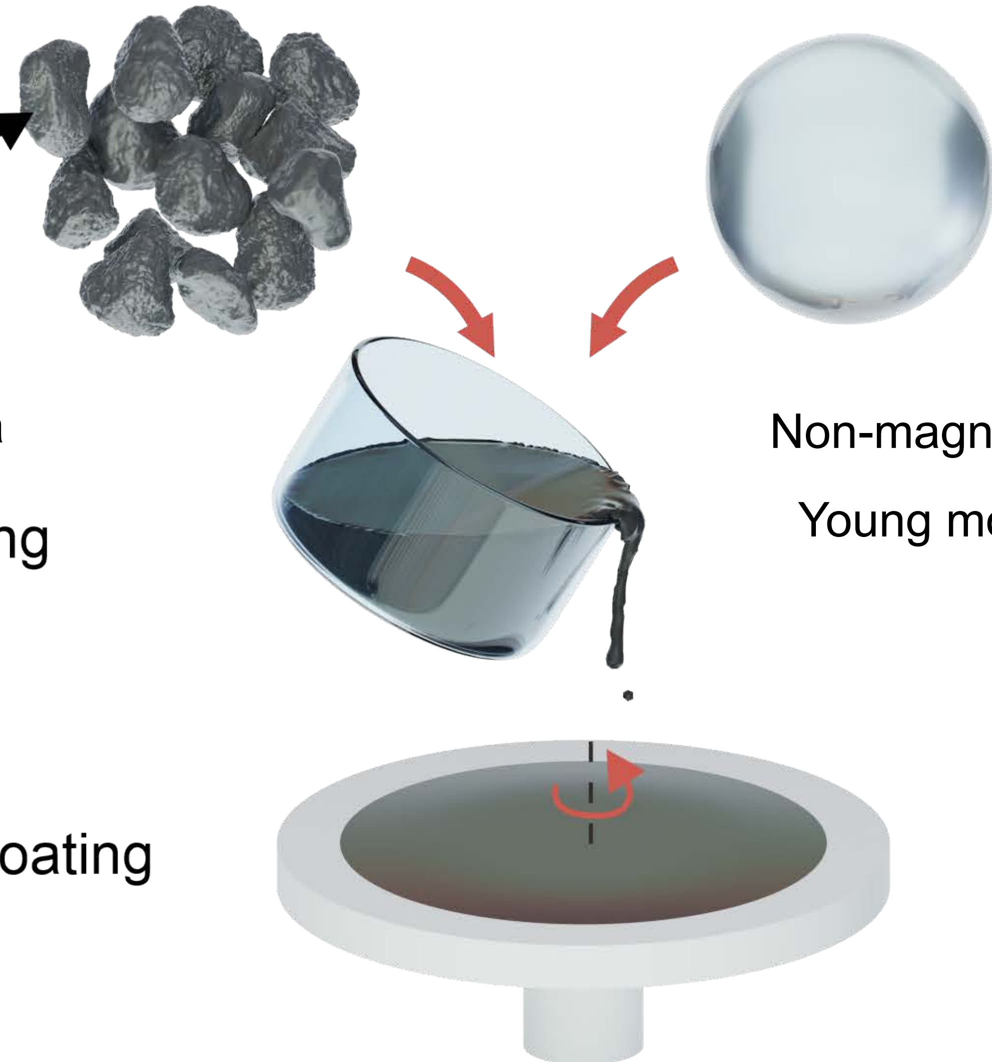
J. Gao et al., *Acc. Chem. Res.* **42**, 1097 (2009)

Magnetic particles and polymers

NdFeB microparticles

PDMS

~5 µm



Magnetic / brittle

Young modulus: 100 GPa

Non-magnetic elastomer

Young modulus: 1 MPa

Mixing

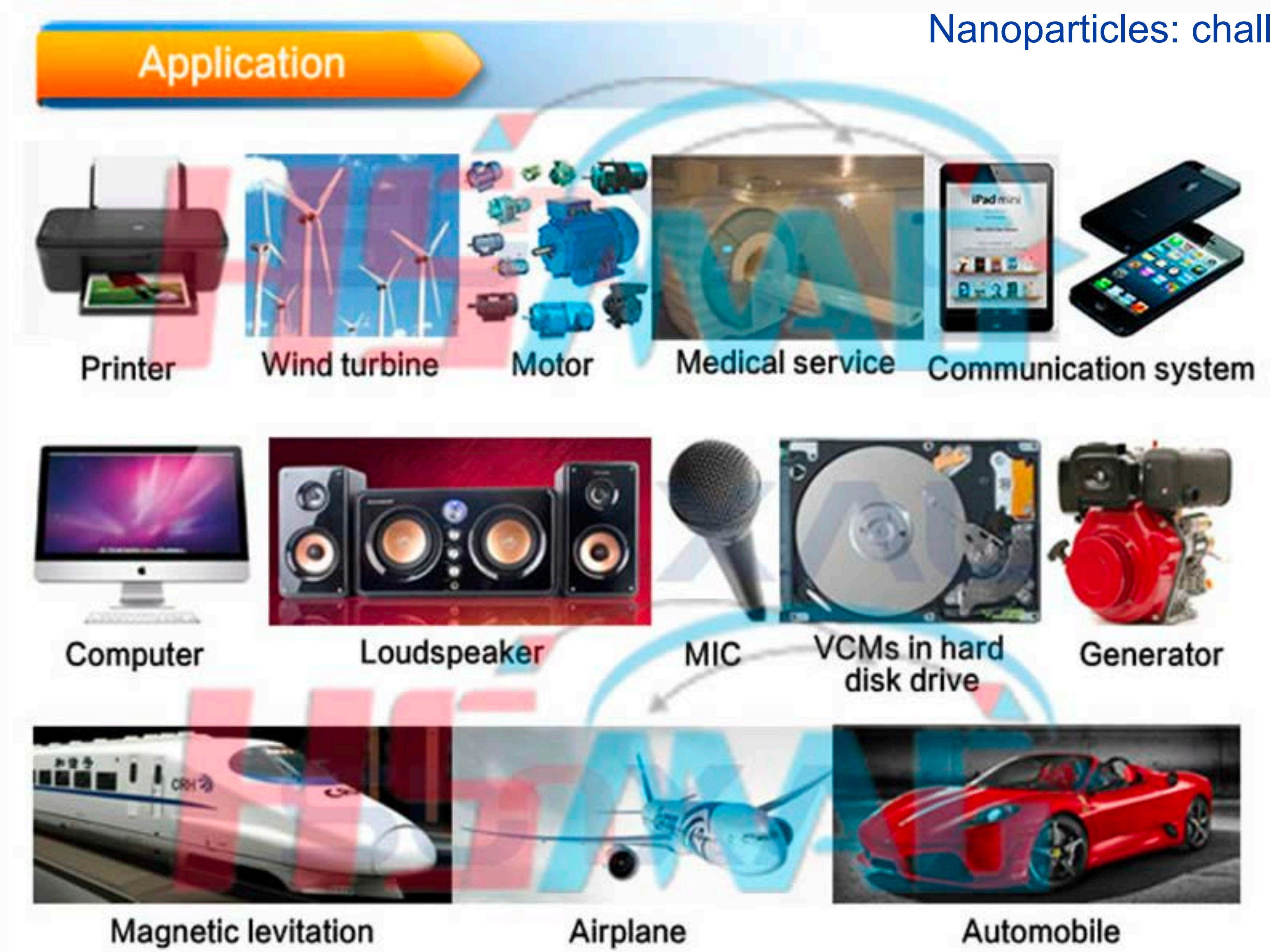
Spincoating

X. Wang et al., *Communications Materials* **1**, 67 (2020)

NdFeB - hard permanent magnet

Primarily microparticles

Nanoparticles: challenging

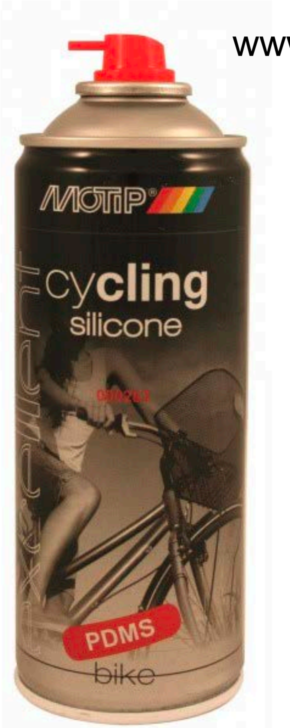


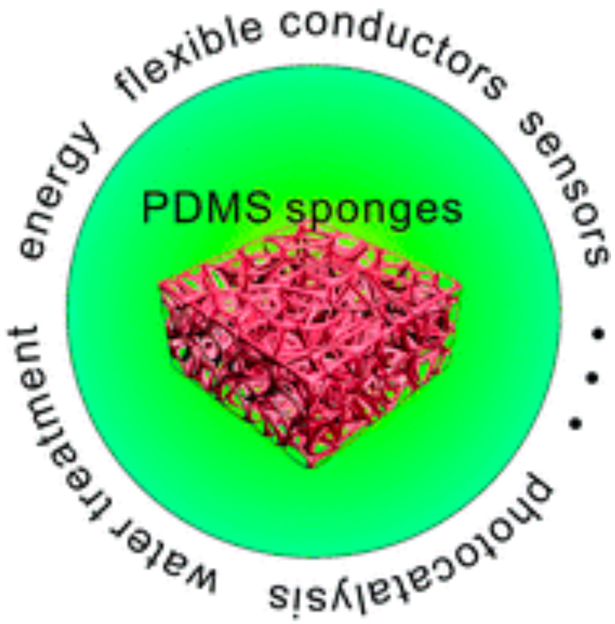
https://www.hsmagnets.com/blog/ndfeb-magnets-application/

PDMS: polydimethylsiloxane

Elongation: 50%; Young's modulus: 1 MPa

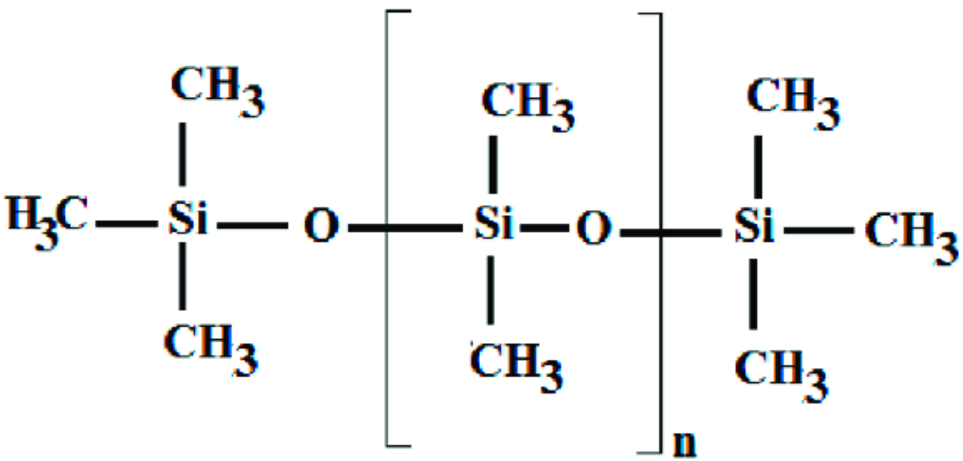
www.nonpaints.com





https://pubs.rsc.org/en/content/articlelanding/2017/ta/c7ta04577h

www.siliconeall.com/product/html/?637.html

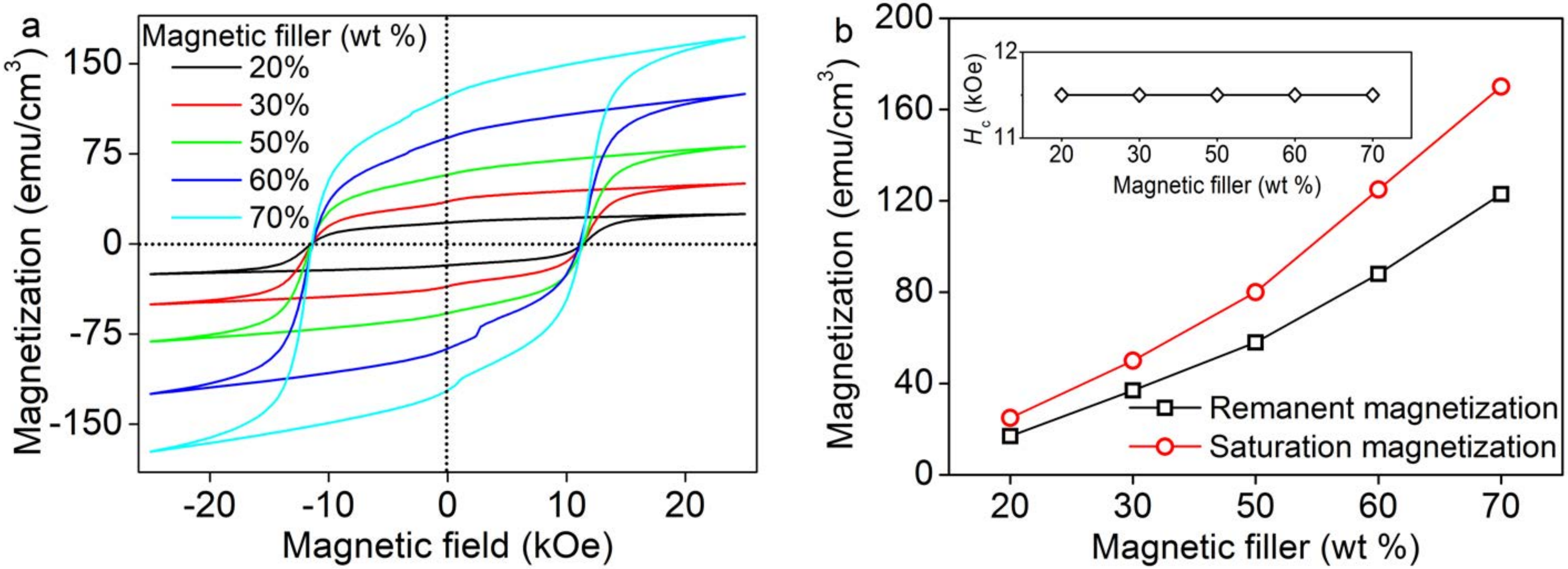


Biocompatible rubber

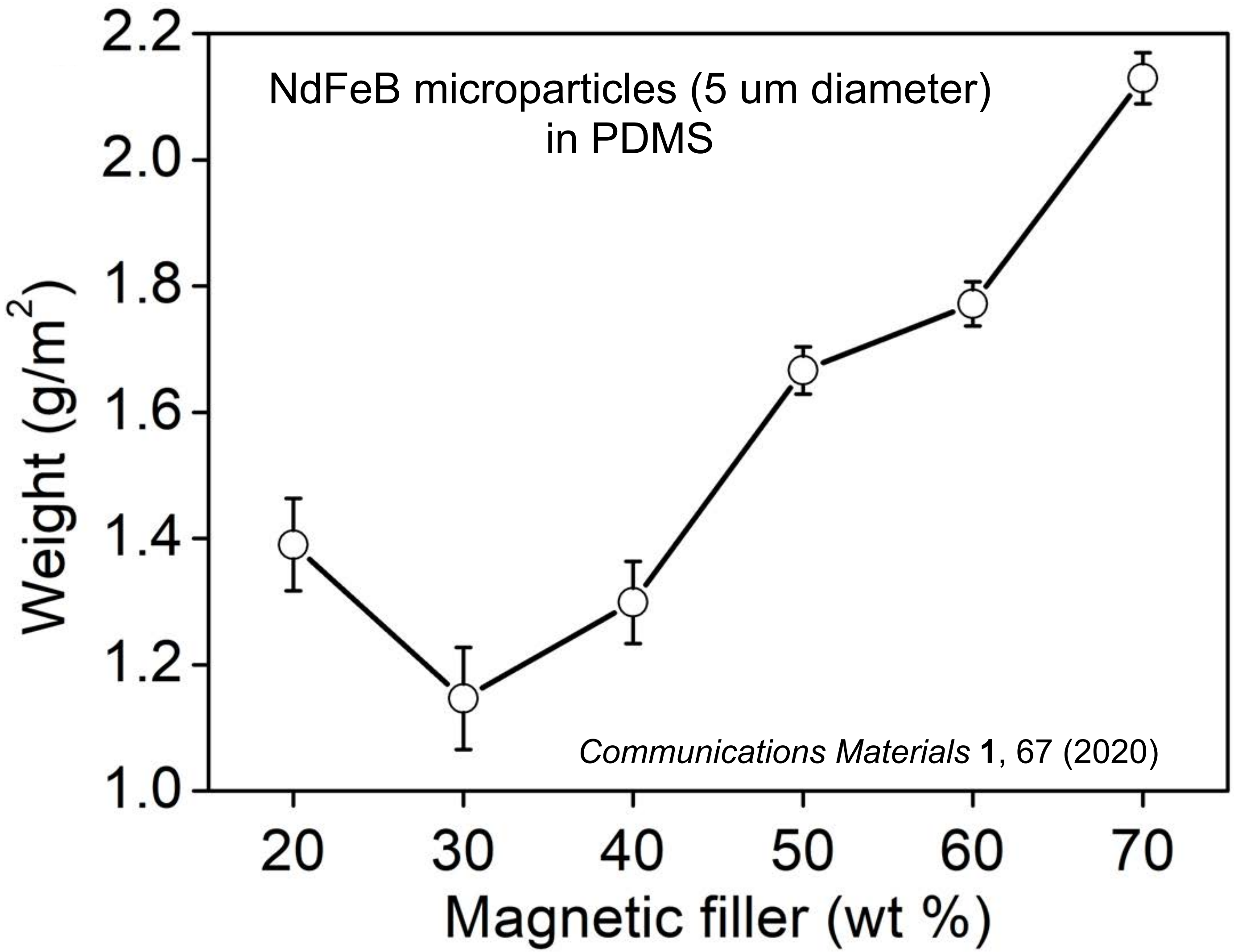
Cosmetics, fluidics, smart skins, smart textiles…

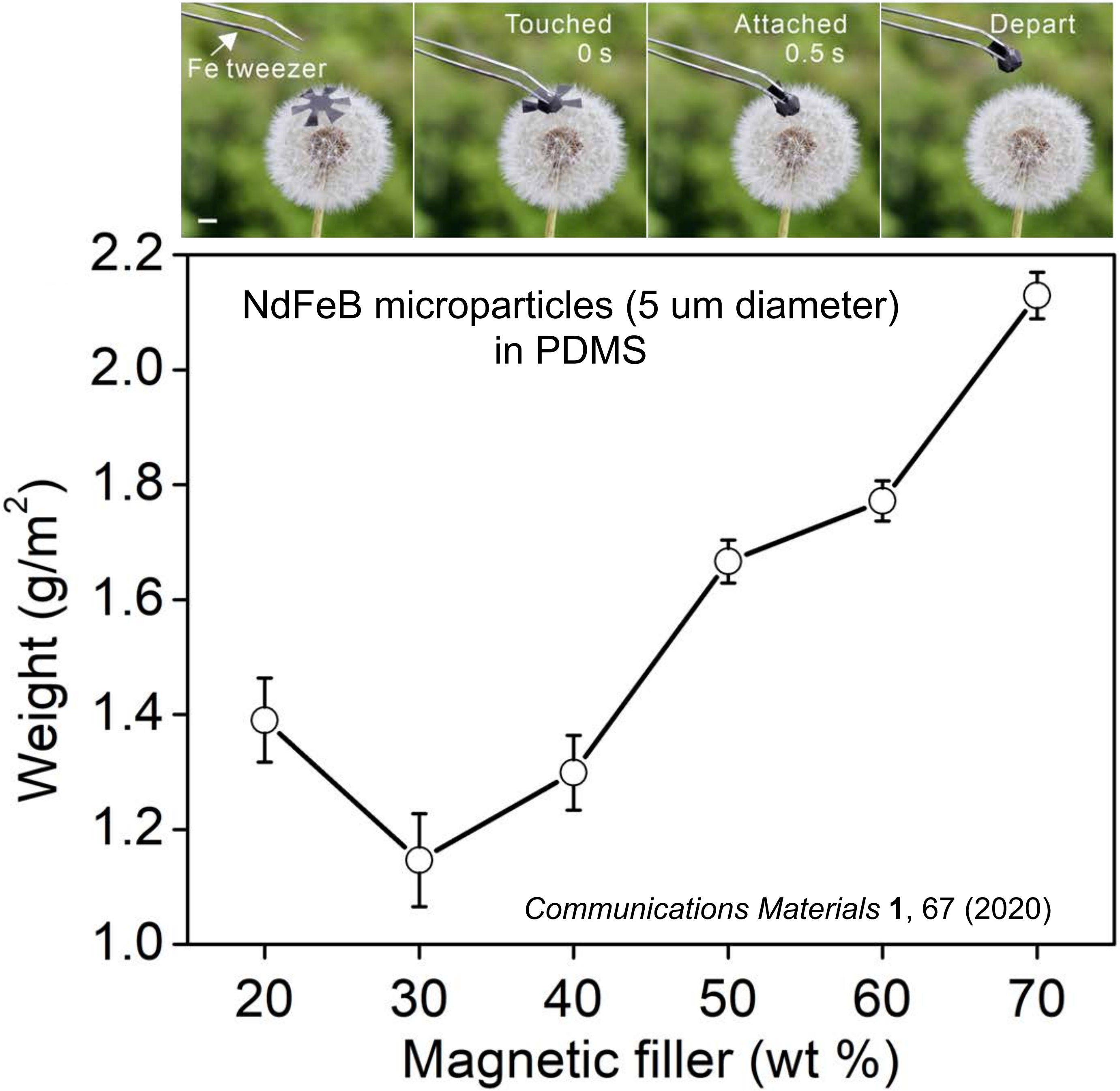
Hard magnetic composite: NdFeB in PDMS

NdFeB microparticles (5 um diameter) in PDMS

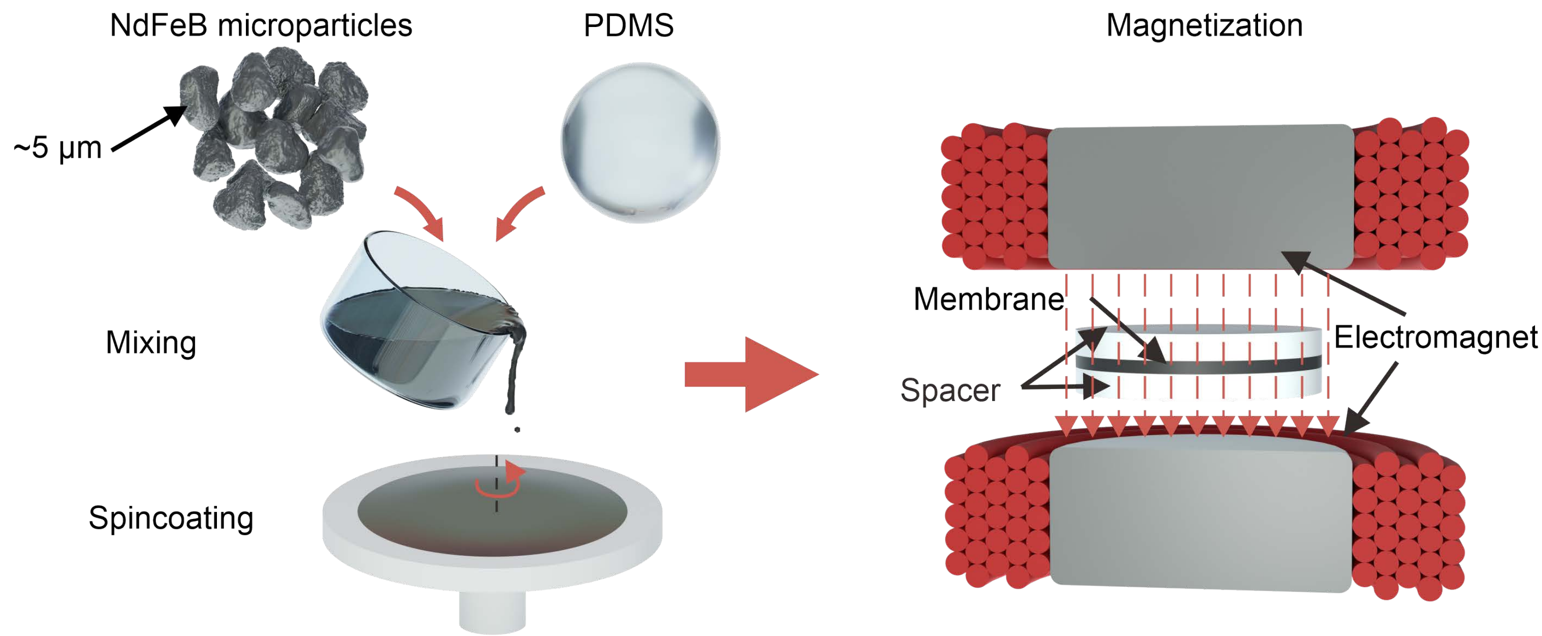


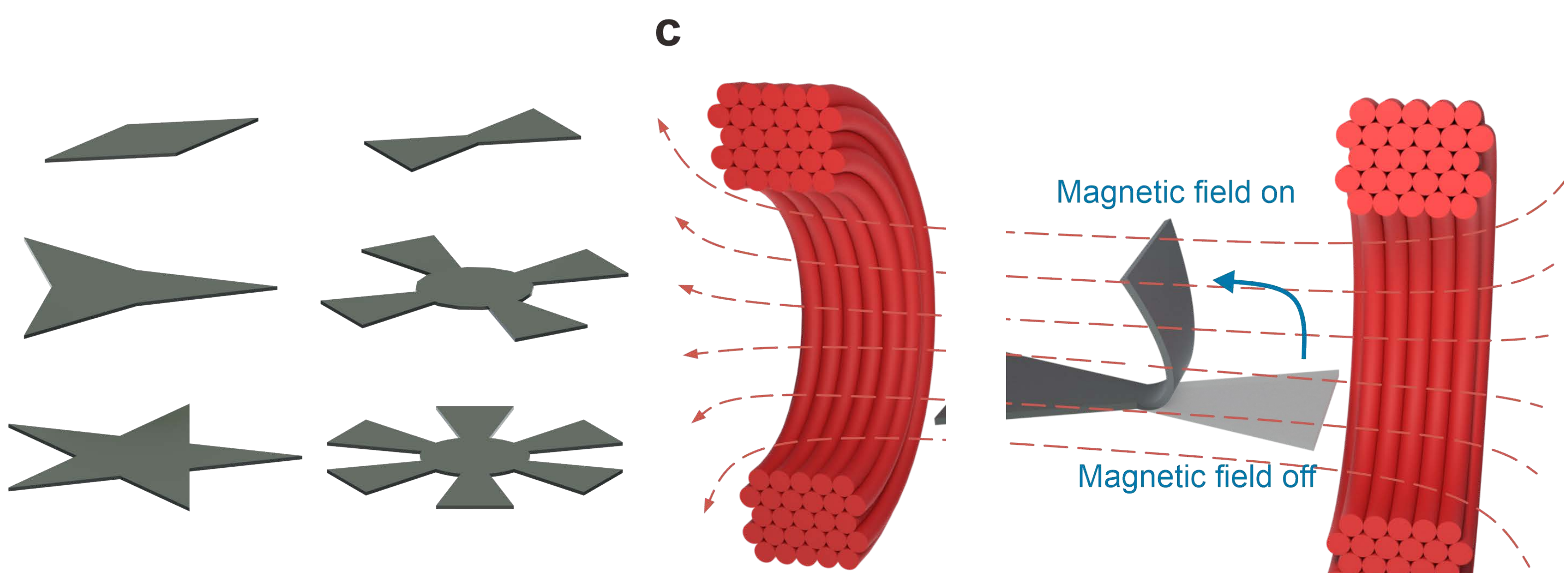
X. Wang et al., *Communications Materials* **1**, 67 (2020)


NdFeB microparticles (5 um diameter)
in PDMS
Communications Materials **1**, 67 (2020)
Weight (g/m2)
2.2
2.0
1.8
1.6
1.4
1.2
1.0
20
30
40
50
60
70
Magnetic filler (wt %)


Fe tweezer
Touched
0 s
Attached
0.5 s
Depart
NdFeB microparticles (5 um diameter)
in PDMS
Weight (g/m^2)
2.2
2.0
1.8
1.6
1.4
1.2
1.0
20
30
40
50
60
70
Magnetic filler (wt %)
Communications Materials **1**, 67 (2020)

Mechanically soft magnetically hard actuators

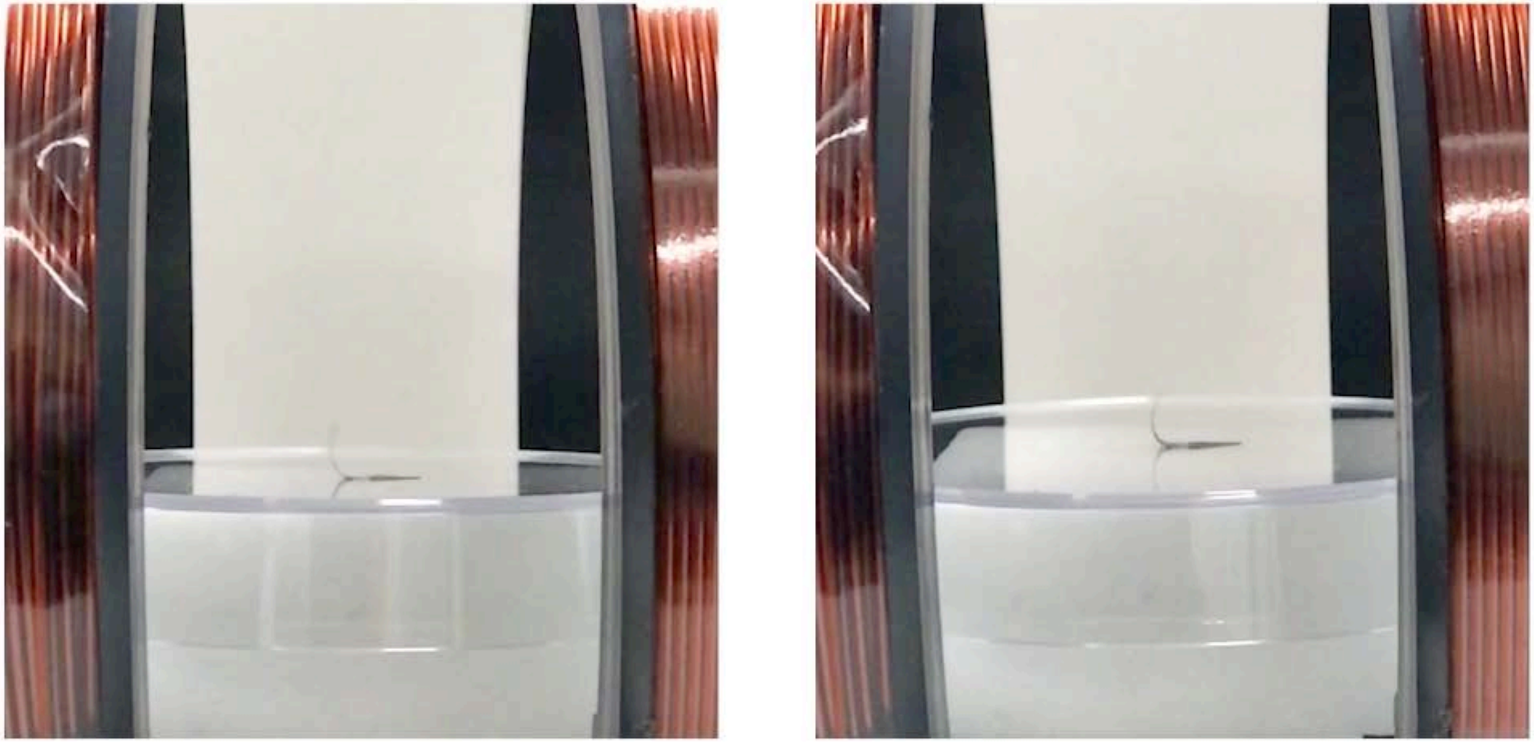




X. Wang et al., *Communications Materials* **1**, 67 (2020)

Durability of magnetic soft actuators

X20 slower

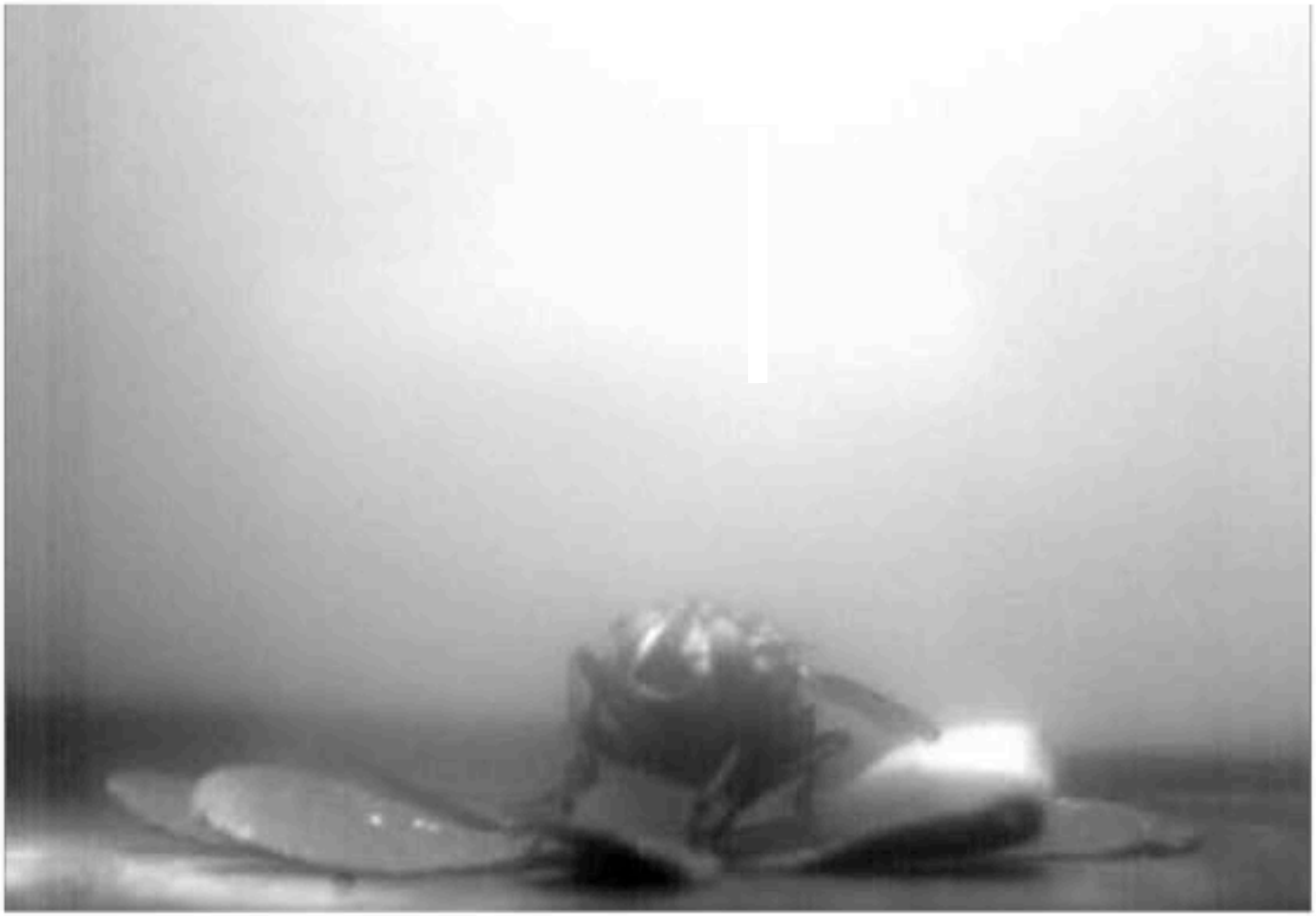


Test start | After 2.1 million cycles

X. Wang et al., *Communications Materials* **1**, 67 (2020)

Interaction with delicate objects

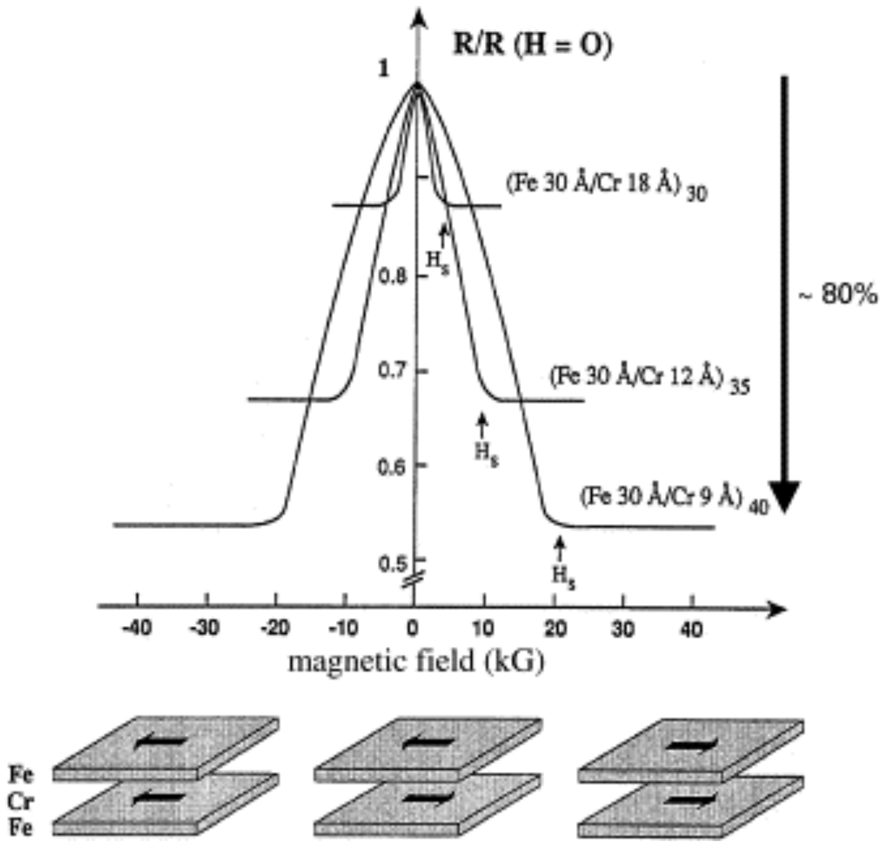
80 times slower



X. Wang et al., *Communications Materials* **1**, 67 (2020)

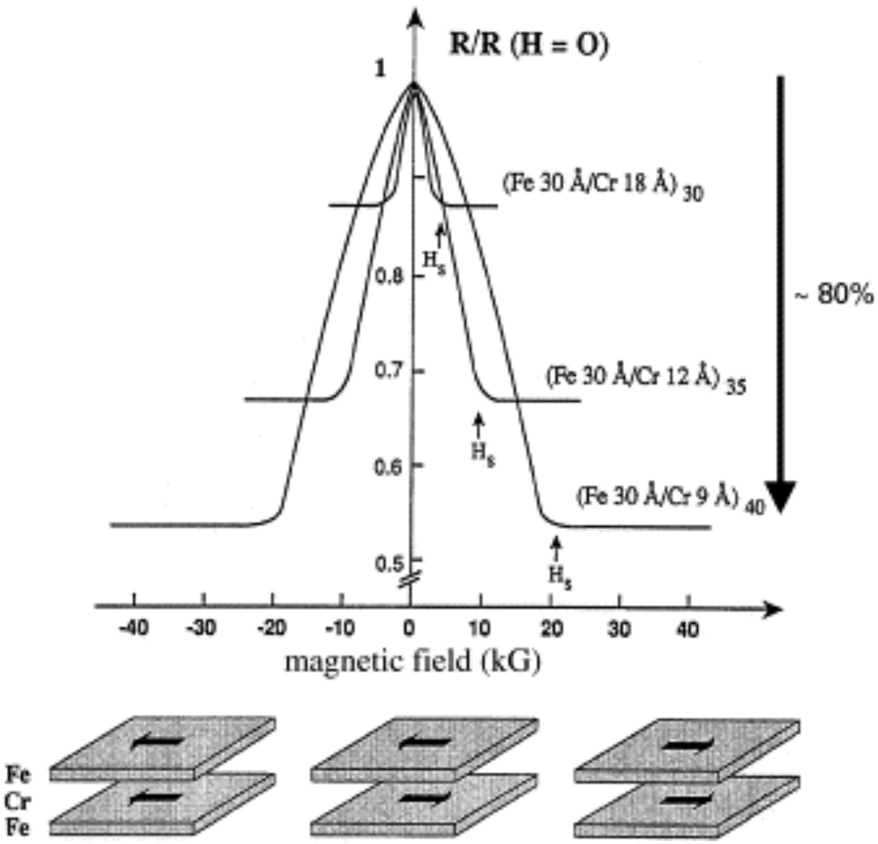
Magnetic composites for sensor applications

Spintronics



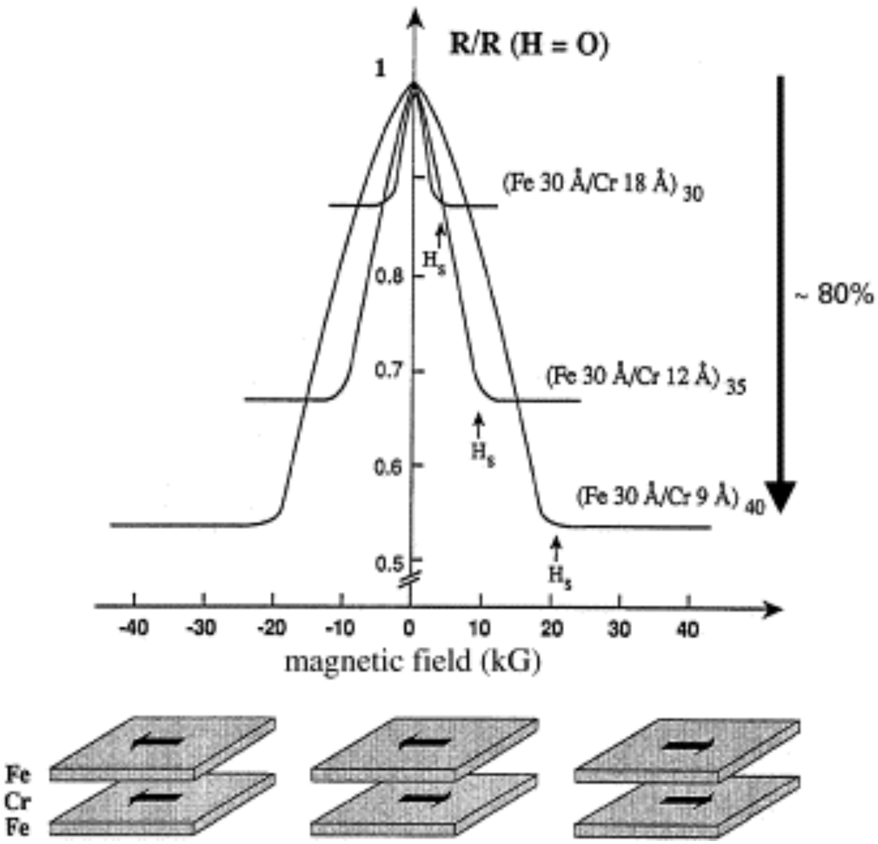
A.Barthélémy et al., JMMM 242-245, 68 (2002)

Spintronics

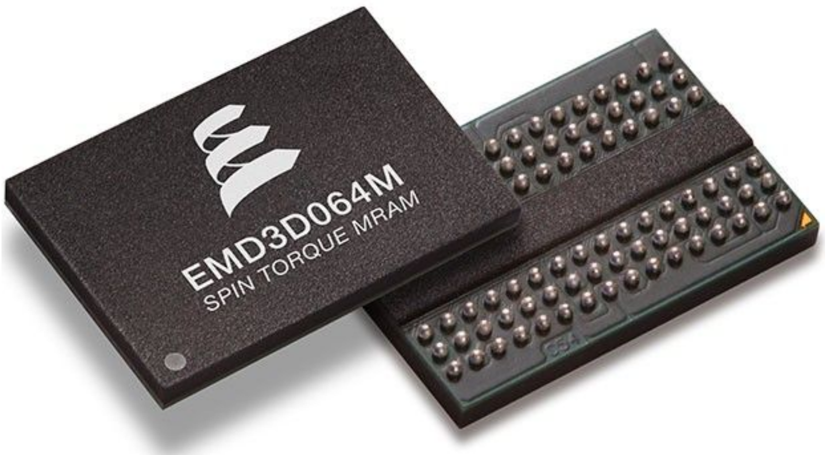


A.Barthélémy et al., JMMM 242-245, 68 (2002)

Spintronics



A.Barthélémy et al., JMMM 242-245, 68 (2002)

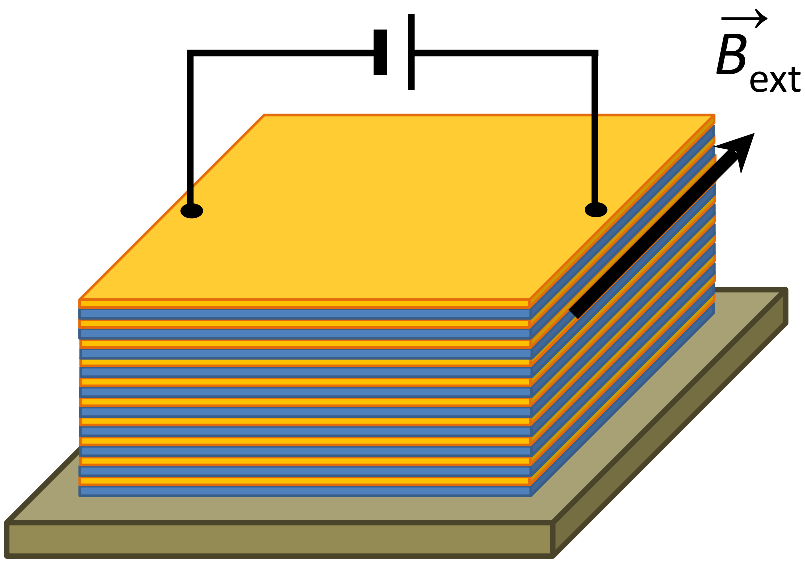


Giant magnetoresistive (GMR) sensors

20 to 50 doublelayers of ferro- and nonmagnetic conductors

Current-in-plane measurement

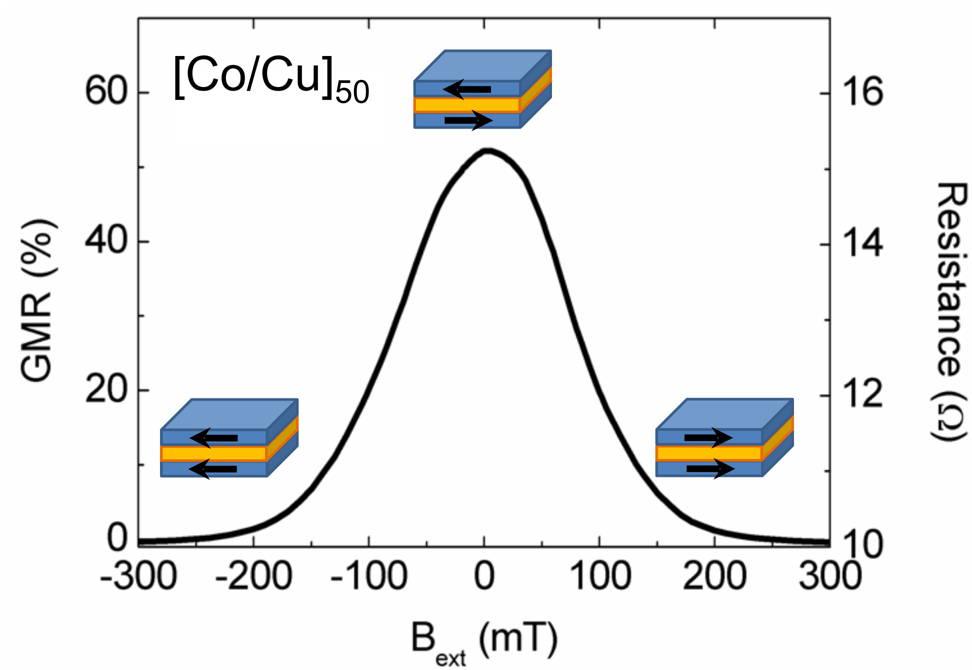
Sensitive to in-plane fields



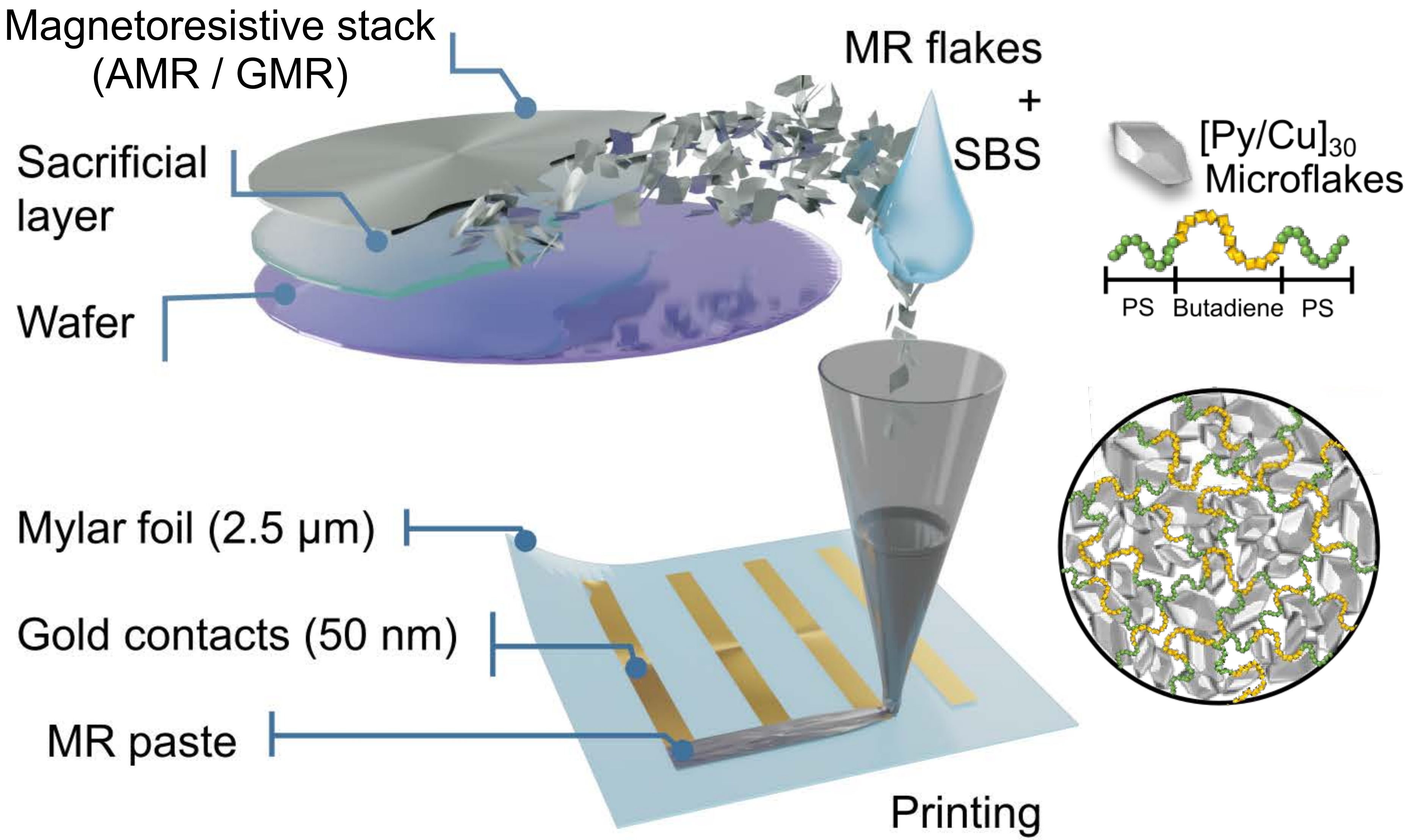
Phys. Rev. Lett. **57**, 2442 (1986)

Giant **M**agneto-**R**esistance

$$\mathrm{GMR}(B_{ext}) = [R(B_{ext}) - R_{sat}] \,/\, R_{sat}$$

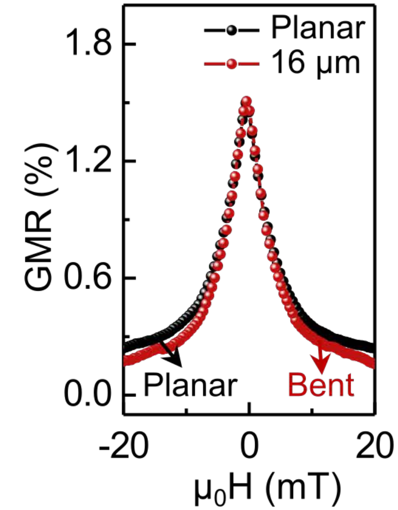


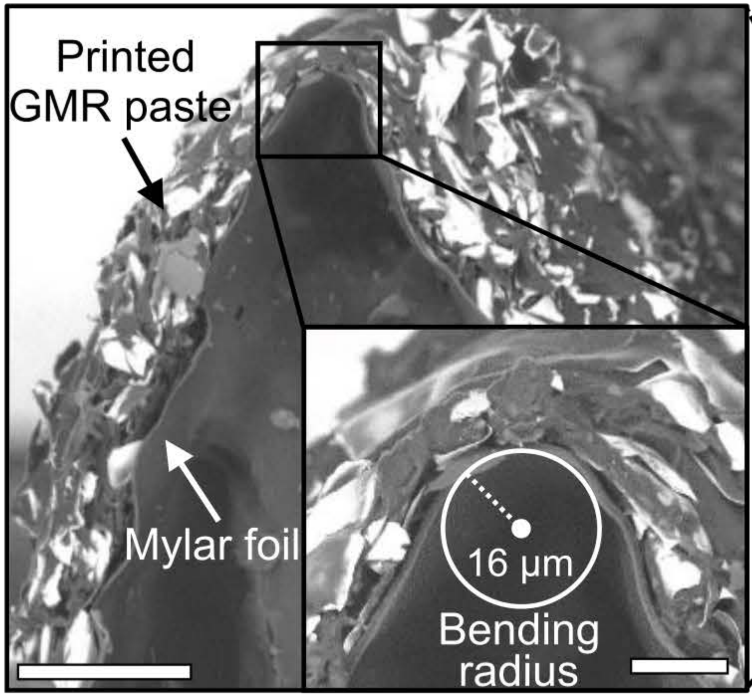
Printed skin-conformal magnetoelectronics

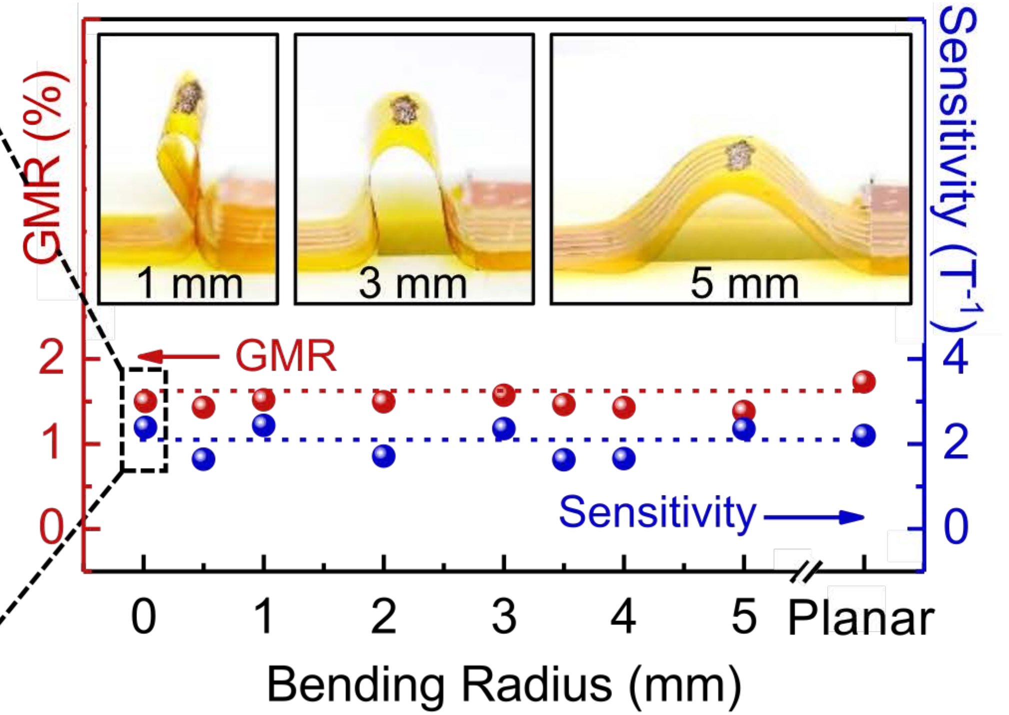


M. Ha et al., *Adv. Mater.* **33**, 2005521 (2021) & E. S. Oliveros Mata et al., *Appl. Phys. A* **127**, 280 (2021)

Printed skin-conformal magnetoelectronics

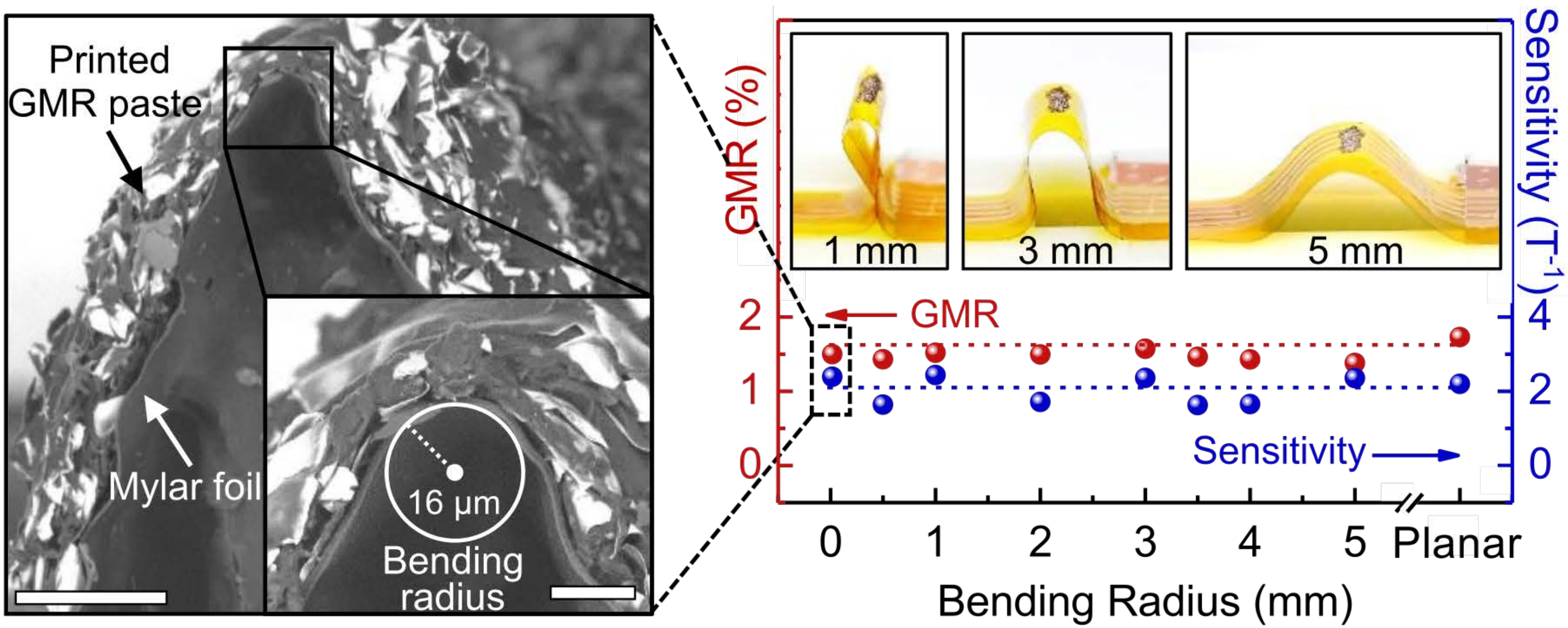






M. Ha et al., *Adv. Mater.* **33**, 2005521 (2021) & E. S. Oliveros Mata et al., *Appl. Phys. A* **127**, 280 (2021)

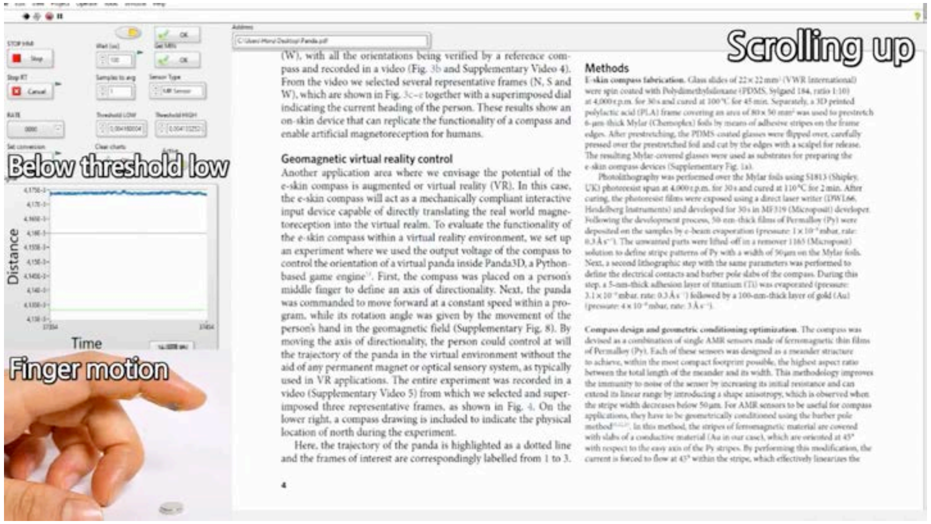
Printed skin-conformal magnetoelectronics



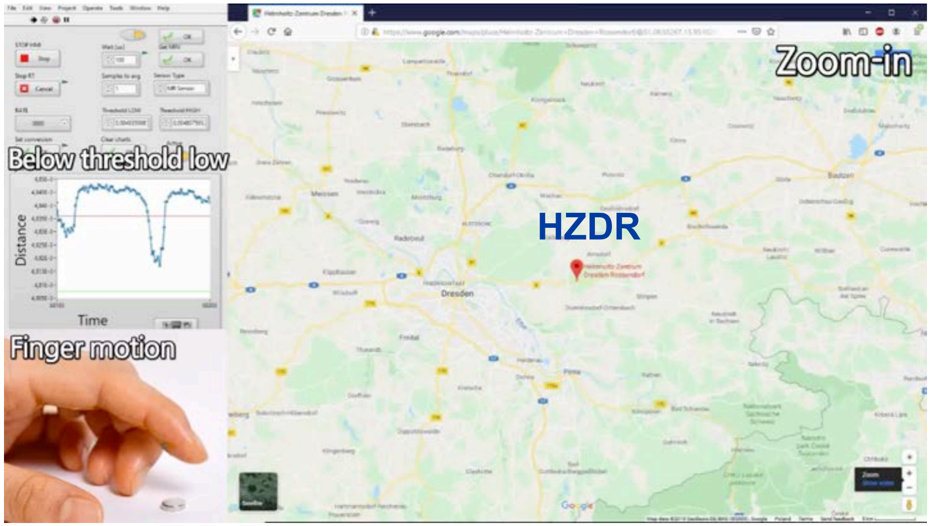
M. Ha et al., *Adv. Mater.* **33**, 2005521 (2021) & E. S. Oliveros Mata et al., *Appl. Phys. A* **127**, 280 (2021)

Printed skin-conformal magnetoelectronics

Scrolling documents



Interacting with a map



M. Ha et al., *Adv. Mater.* **33**, 2005521 (2021) & E. S. Oliveros Mata et al., *Appl. Phys. A* **127**, 280 (2021)

Magnetic heterostructures

Definition

Heterostructures

Heterostructures show different synergistic relations between two or more building blocks that improve functional characteristics

Each component plays a complementary role in producing multifunctionality

Definition

Heterostructures

Heterostructures show different synergistic relations between two or more building blocks that improve functional characteristics

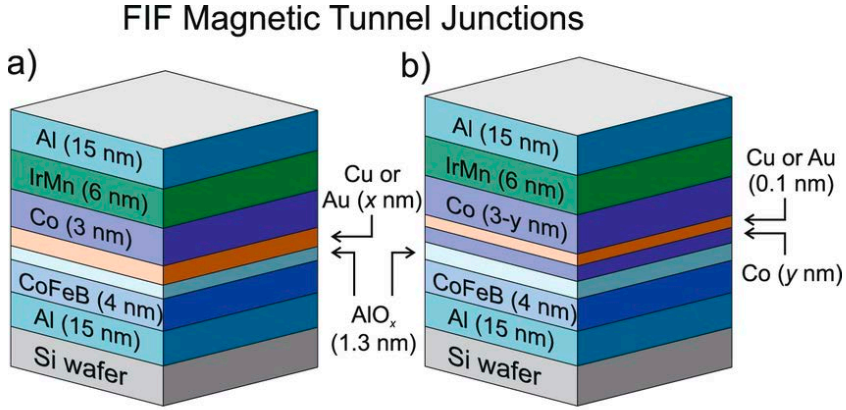
Each component plays a complementary role in producing multifunctionality

Heterostructures consist of combinations of different materials, which are in contact through at least one interface

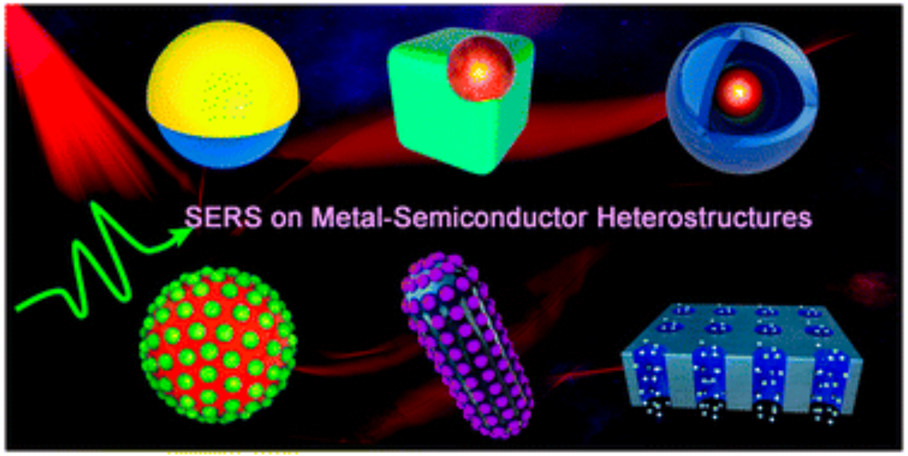
Magnetic heterostructures combine different physical properties which do not exist in nature

Editors: Hartmut Zabel and Samuel D. Bader
Magnetic Heterostructures: Advances and Perspectives in Spinstructures and Spintransport
Springer Trends in Modern Physics (2008)

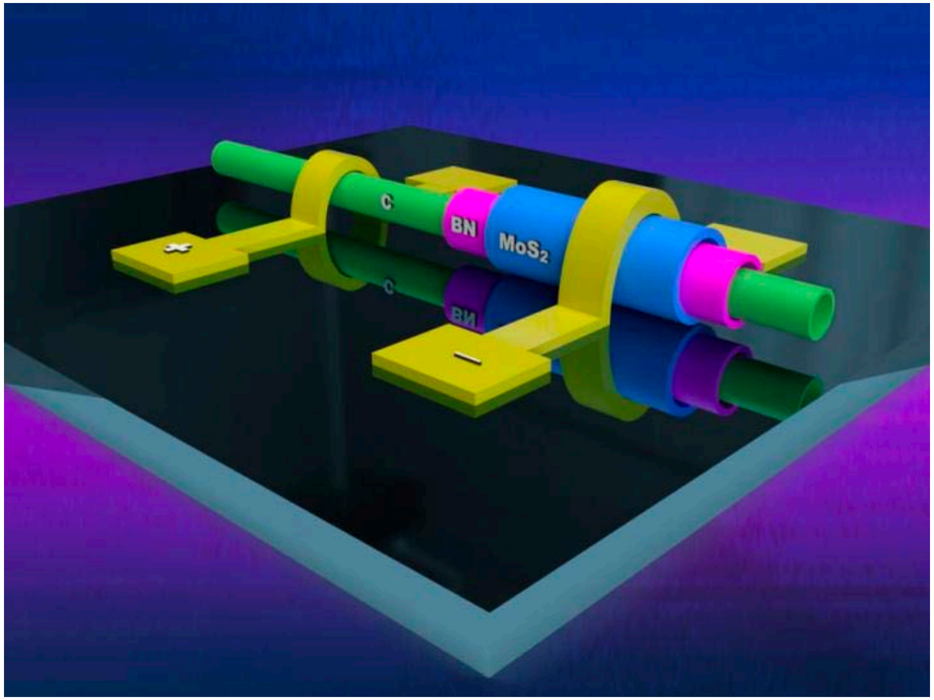
Heterostructures



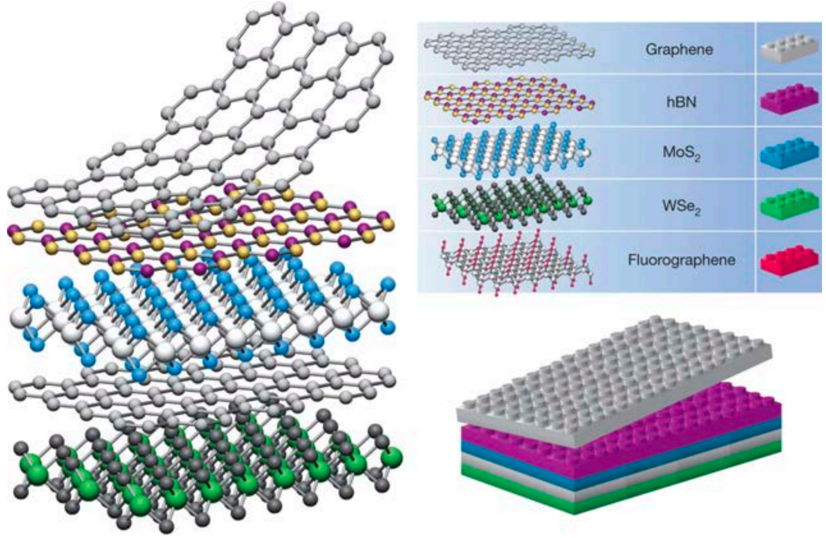
New J. Phys. 16, 043008 (2014)



https://pubs.rsc.org/en/content/articlelanding/2021/mh/d0mh01356k



https://www.eurekalert.org/news-releases/776488

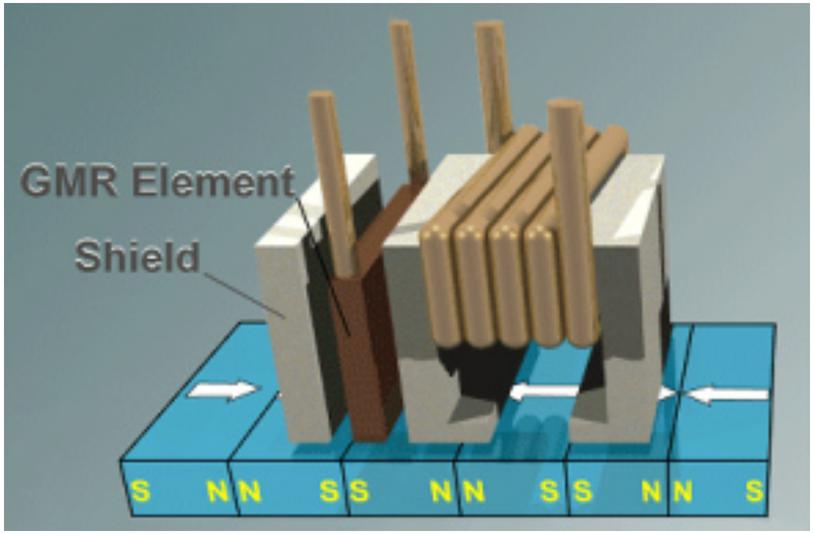


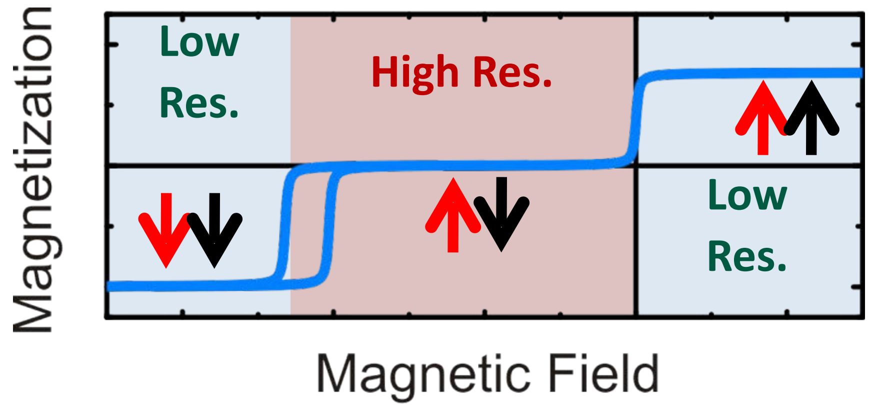
https://www.nature.com/articles/nature12385

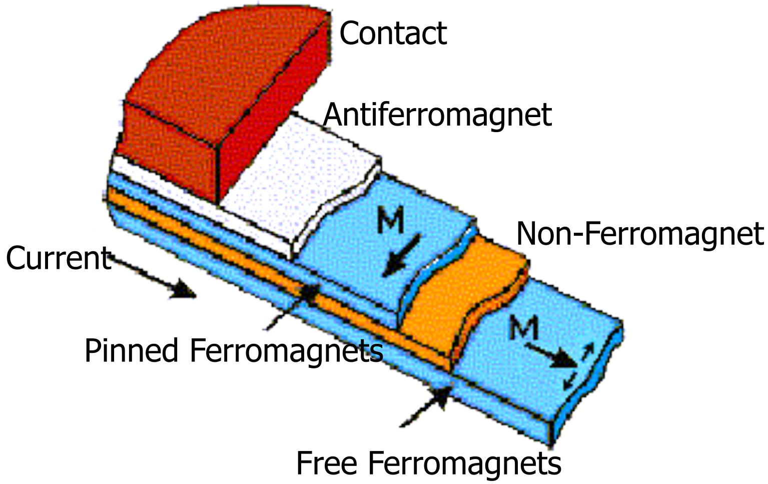
Heterostructures of ferro- and antiferromagnets
Exchange bias effect

Magnetic sensors based on magnetoresistive effect

Read heads in magnetic data storage





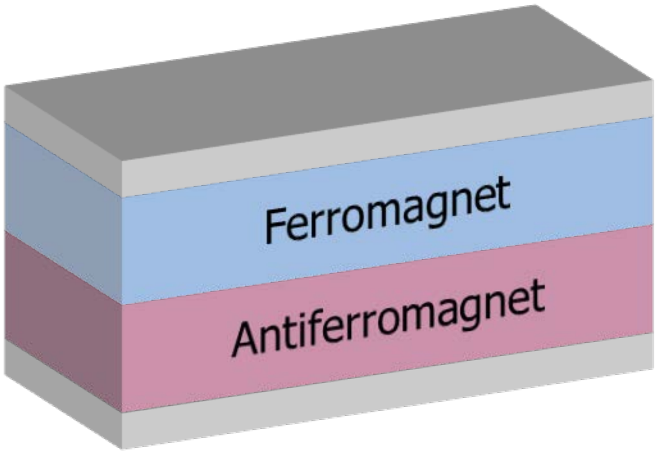


GMR sensor elements:

- Resistance change in small external fields
- Antiparallel orientation of the magnetic moment increases resistance
- Sensing layer is a soft F layer
- Reference layer pinned by exchange bias

S. S. P. Parkin, Annu. Rev. Mater. Sci. **25** (1995) 357

Exchange bias effect: coupling between F and AF layers



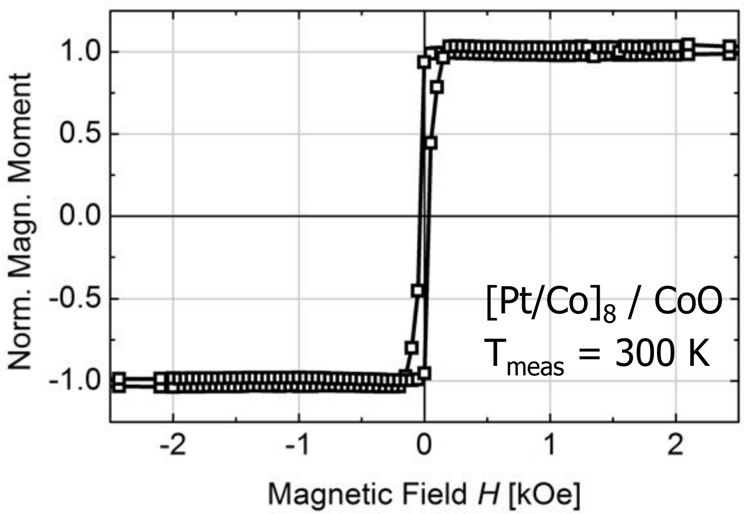
Characteristic features:

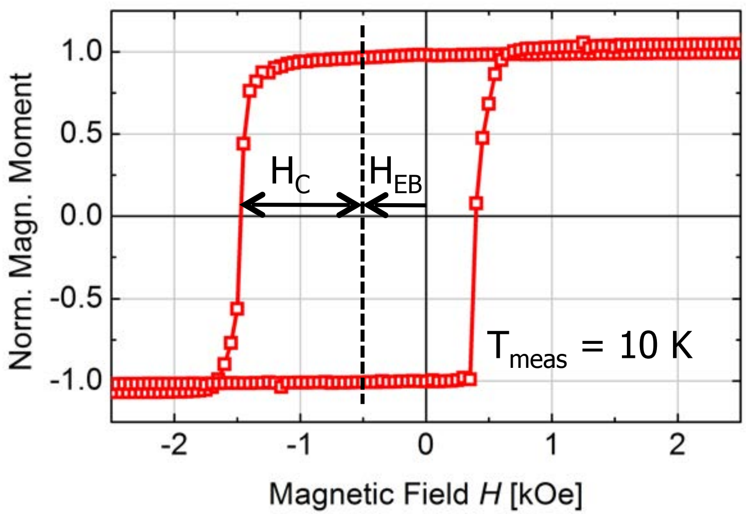
A. AF layer has to be cooled in a magnetic field

B. Hysteresis loop is shifted and broadened

C. Asymmetric magnetization reversal processes

D. Effect is strongly temperature dependent

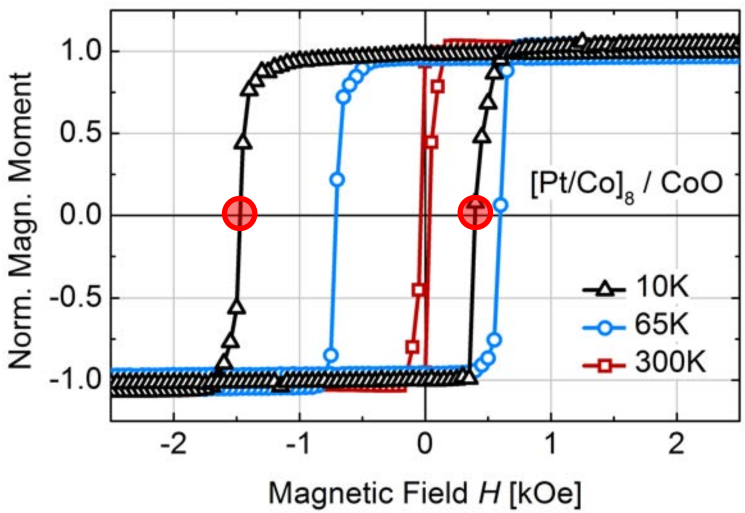


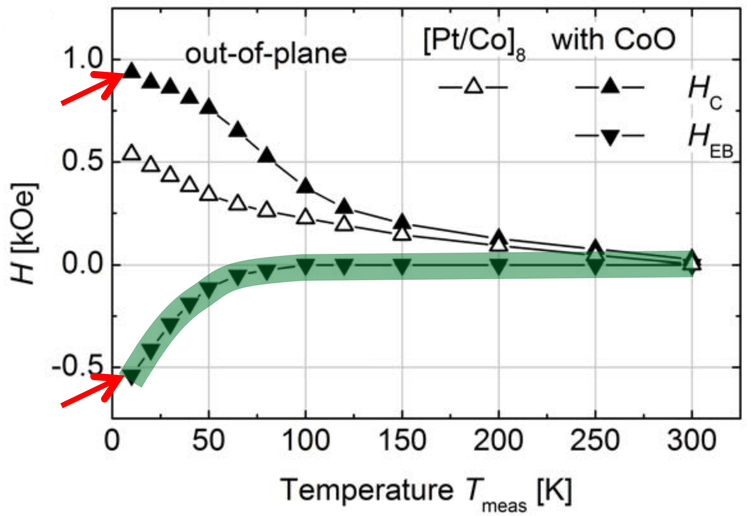


A. E. Berkowitz and K. Takano, J. Magn. Magn. Mater. **200** (1999) 552
B. K. O'Grady et al., J. Magn. Magn. Mater. **322** (2010) 883

Dr. Denys Makarov I E-Mail: d.makarov@hzdr.de I Intelligent Materials and Systems

Integral magnetic investigations of EB effect





Exchange bias measurements:

(1) Warm sample to 320 K and apply H_{cool} = 70 kOe

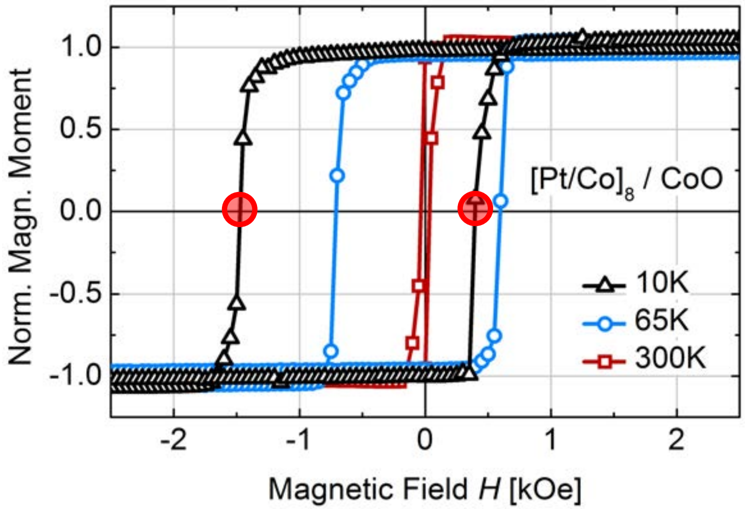
(2) Cool sample to the measurement temperature

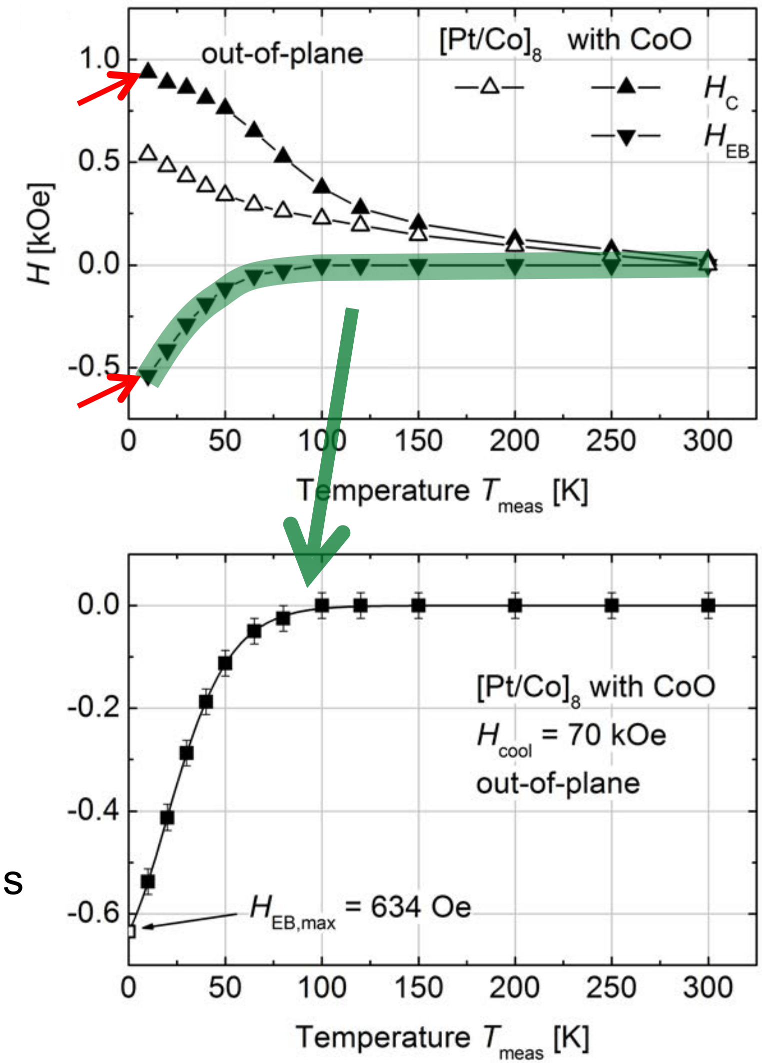
(3) Measure hysteresis loop and acquire coercive fields

$$H_C = (H_C^R - H_C^L) / 2 \qquad H_{EB} = (H_C^R + H_C^L) / 2$$

K. O'Grady et al., J. Magn. Magn. Mater. **322** (2010) 883
M. D. Stiles and R. D. McMichael, Phys. Rev. B **63** (2001) 064405

Integral magnetic investigations of EB effect





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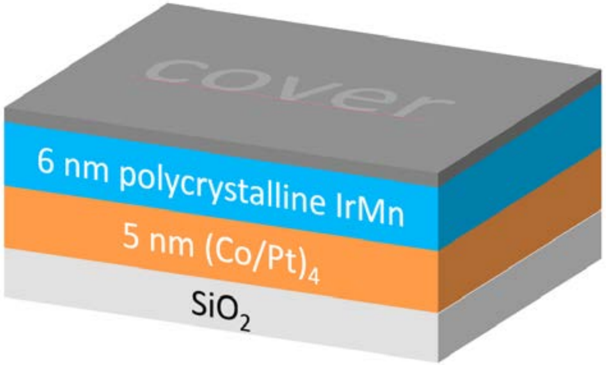
K. O'Grady et al., J. Magn. Magn. Mater. **322** (2010) 883
M. D. Stiles and R. D. McMichael, Phys. Rev. B **63** (2001) 064405

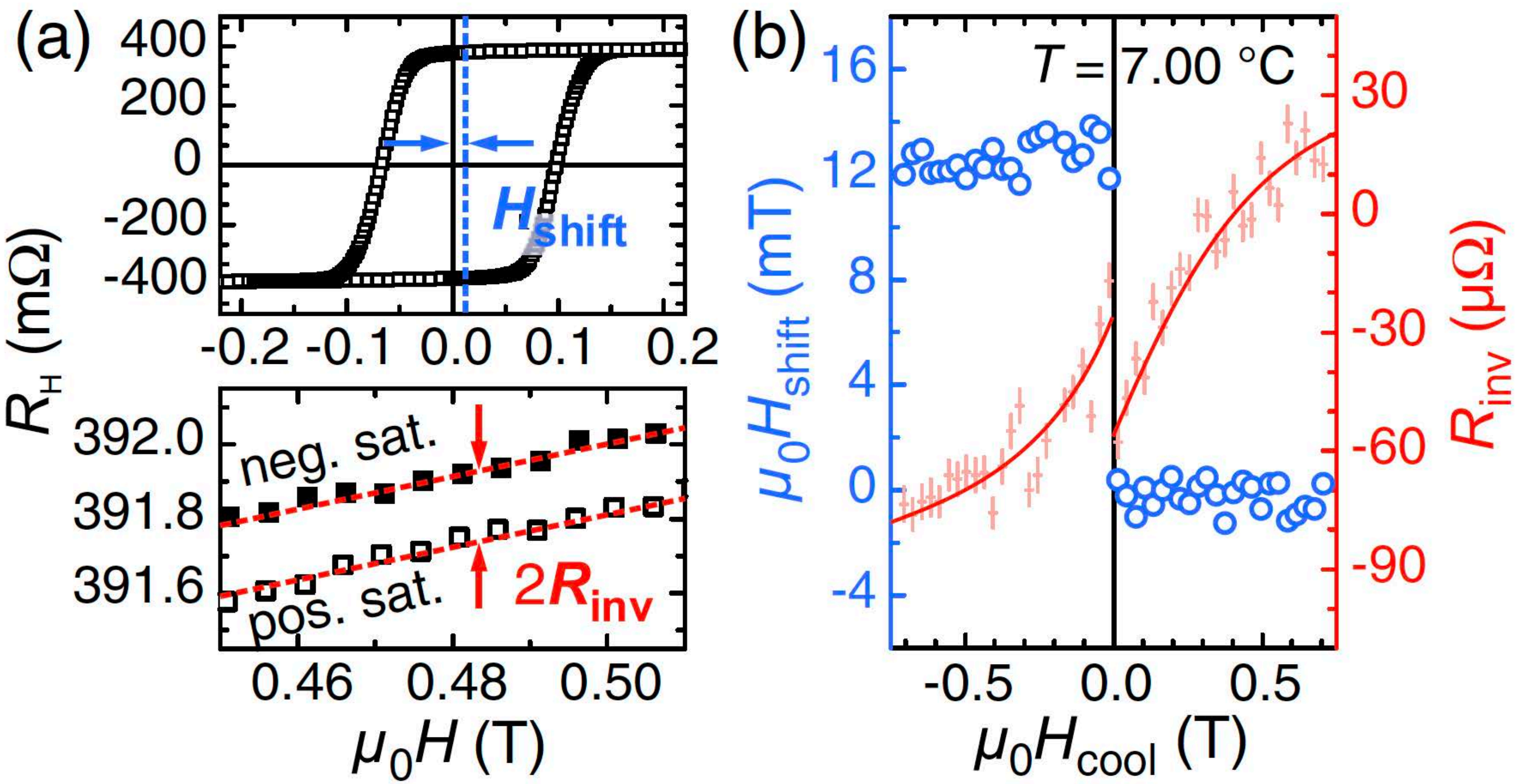
IrMn/$(Co/Pt)_4$ exchange bias system



Probe coupling at nm scales

Distinct behaviour of bulk and interface in 6 nm IrMn

Field-cooled from 45°C to 7°C



T. Kosub et al., *Phys. Rev. Lett.* **115**, 097201 (2015)

Heterostructures of ferro- and non-magnetic materials
Giant magnetoresistive effect

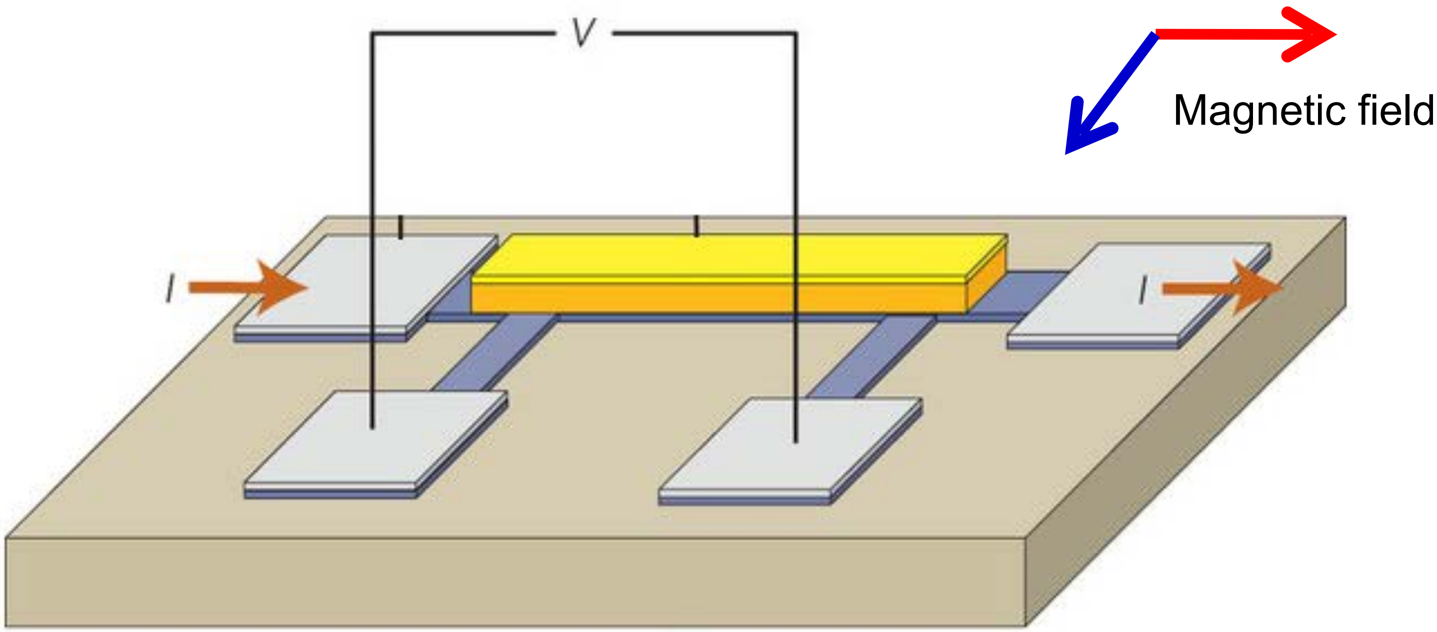
Dr. Denys Makarov I E-Mail: d.makarov@hzdr.de I Intelligent Materials and Systems

Anisotropic magnetoresistance (AMR): about 2% effect

AMR: electrical conductivity of ferromagnetic materials depends on the orientation of the magnetization with respect to the direction of the flowing current

Observed in 1856 by W. Thomson (Lord Kelvin)

W. Thomson, Proc. Roy. Soc. 8, 546 (1856/1857)



Explained by N.F. Mott in 1936: spin-orbit interaction needs to be accounted for

N.F. Mott, Proc. Roy. Soc. (London), Ser. A 153, 699 (1936)

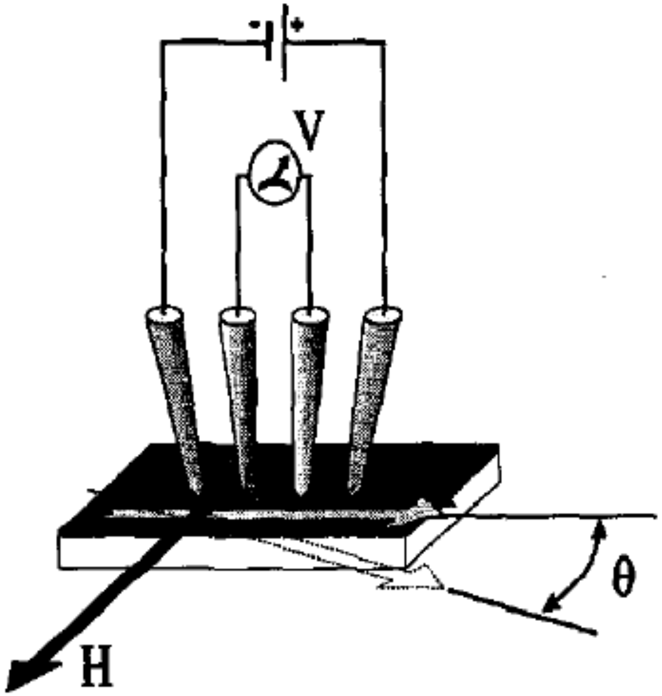
Giant magnetoresistance (GMR): about 100% effect

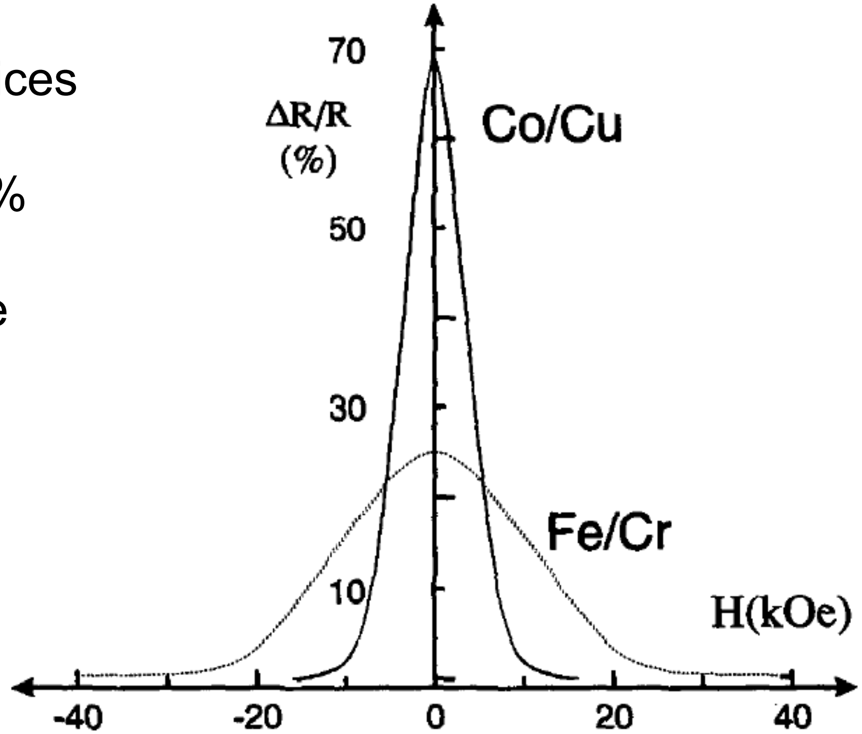
GMR: change of the resistance of the magnetic multilayer stack in magnetic field

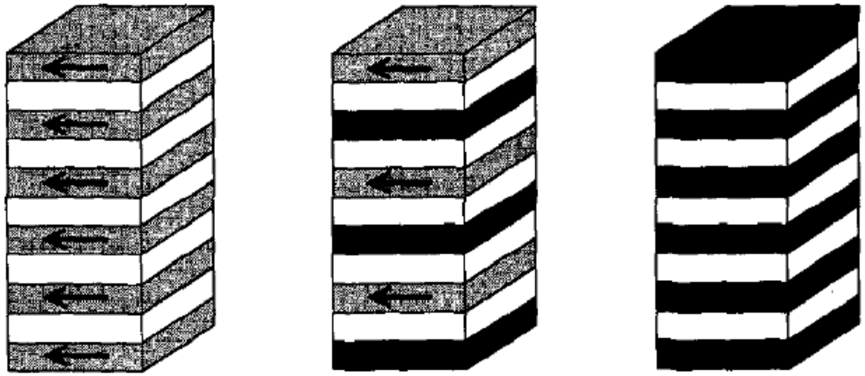
Application relevant for magnetic sensor devices

Typical GMR values: in the range of 20-100%

Current-in-plane (CIP) measurement scheme





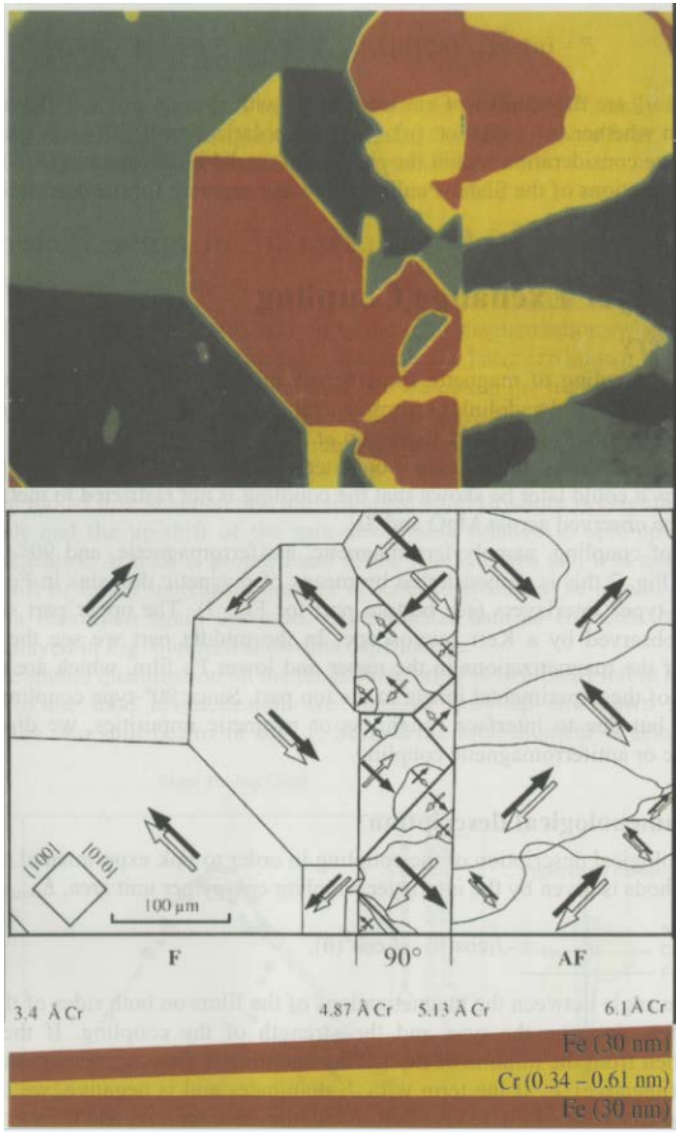


S.S.P. Parkin, *Annu. Rev. Mater. Sci.* **25**, 357 (1995)

Interlayer exchange coupling

Kerr microscopy image of the Fe/Cr bilayer with continuously varying Cr layer thickness

Lecture notes of the 40th IFF spring school: *Spintronics* (2009)



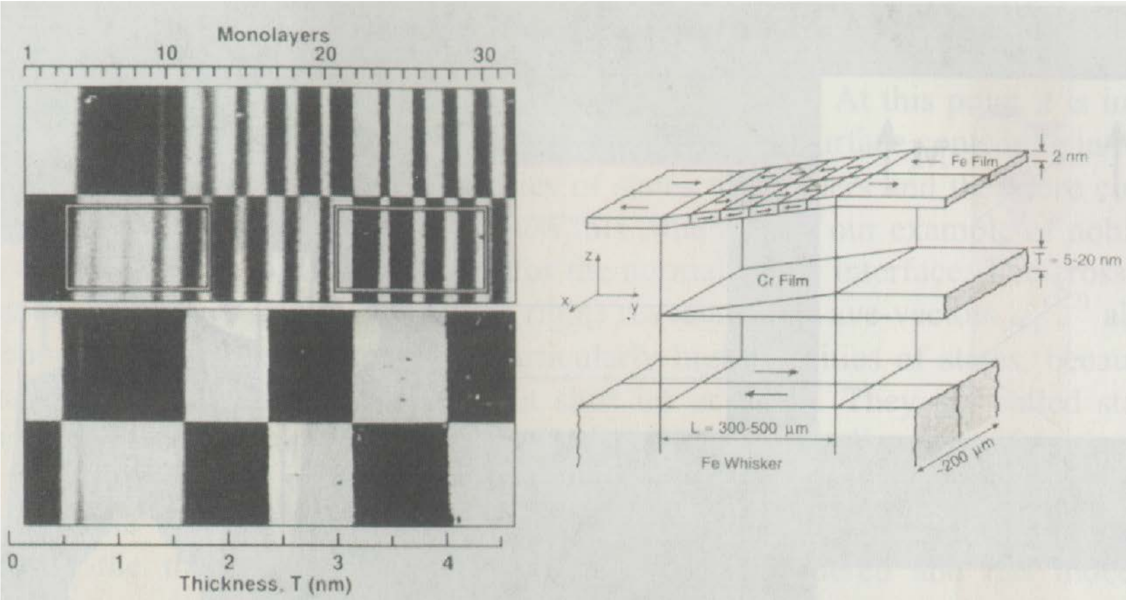
Dependent on the thickness of the spacer layer:

Ferromagnetic coupling

Antiferromagnetic coupling

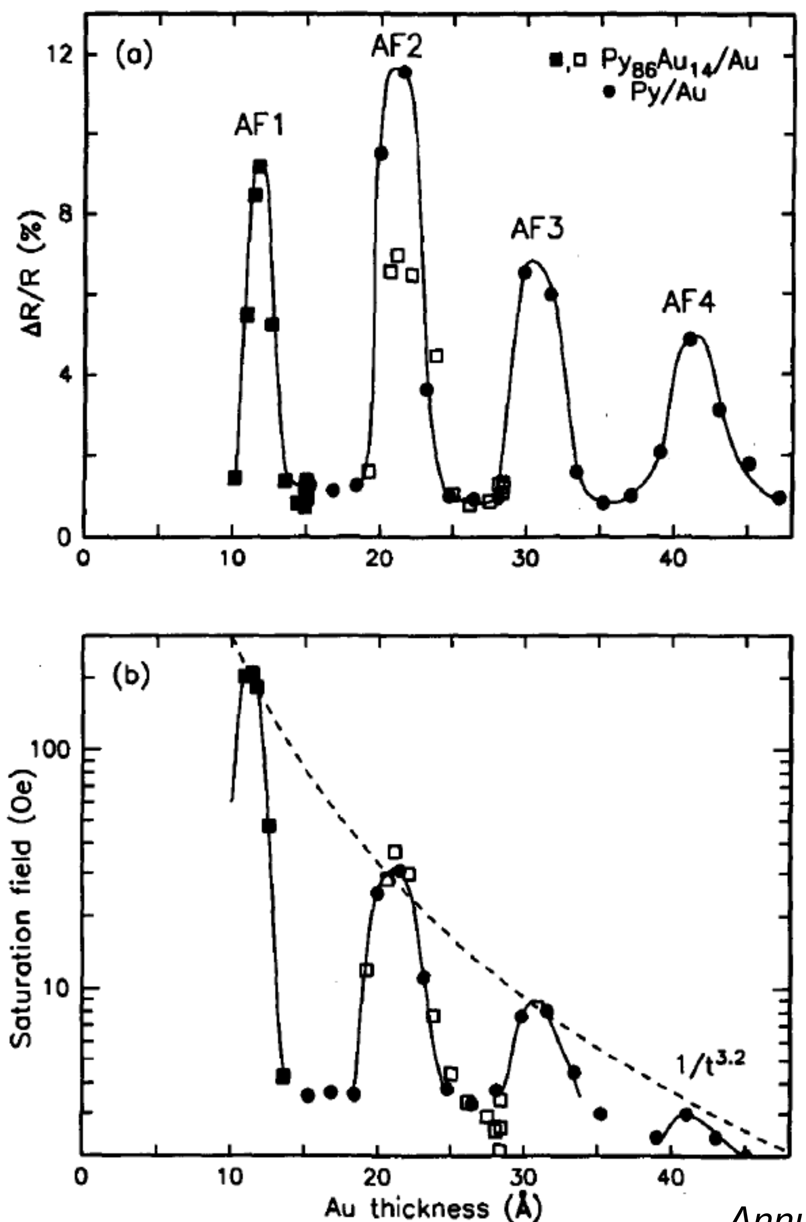
90° coupling

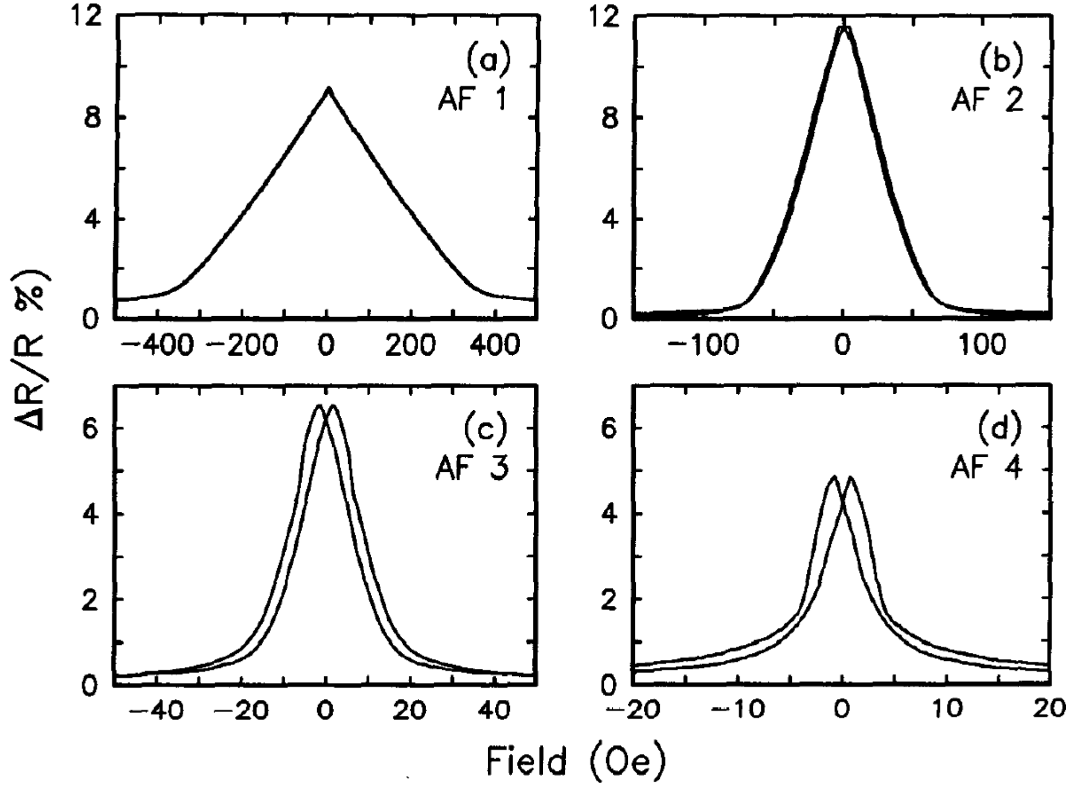
Oscillating F-AF coupling dependent on the thickness of the spacer



Dr. Denys Makarov I E-Mail: d.makarov@hzdr.de I Intelligent Materials and Systems

Tuning the sensitivity of the GMR sensor





Different thickness of the Au spacer layer:

AF1: 11.7 Å (43 x10^{-6} Ohm cm)

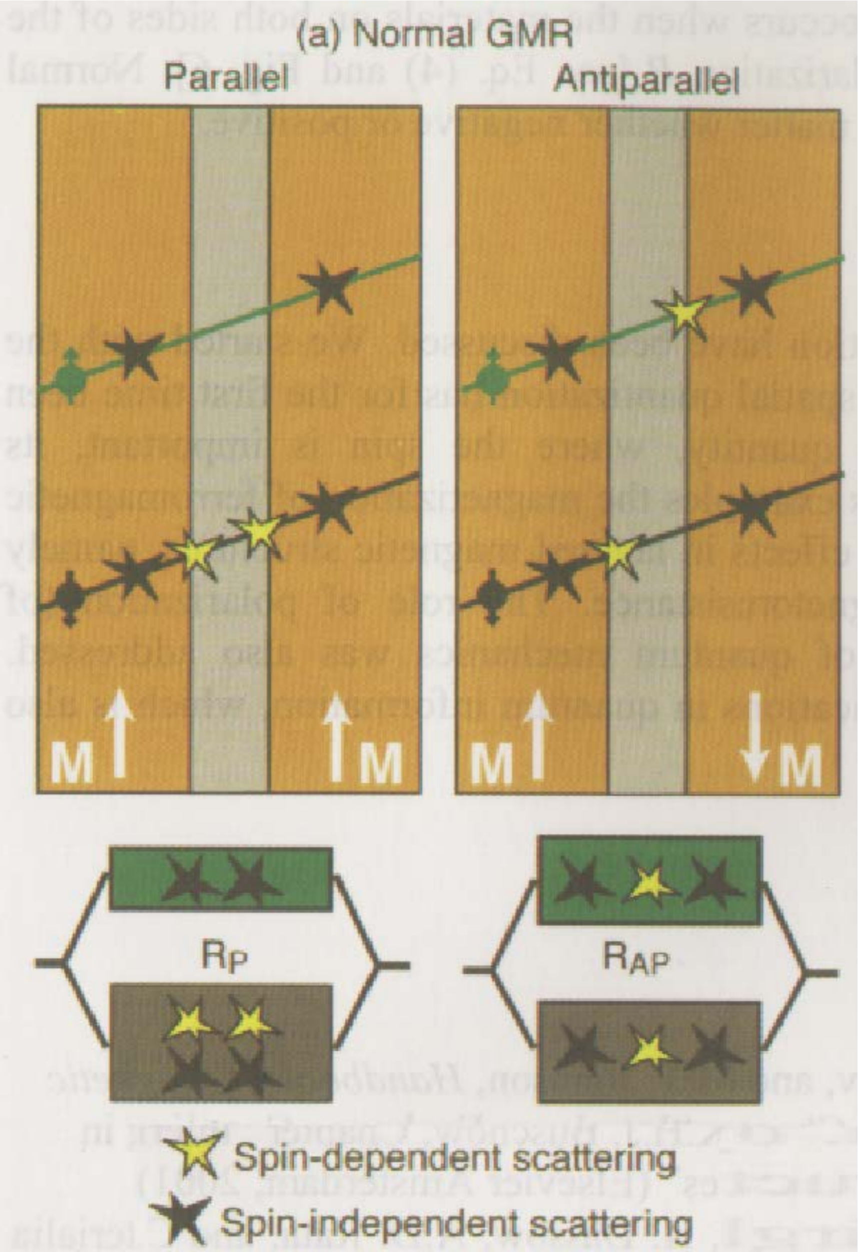
AF2: 21.5 Å (19 x10^{-6} Ohm cm)

AF3: 29.8 Å (13 x10^{-6} Ohm cm)

AF4: 41.0 Å (10 x10^{-6} Ohm cm)

Annu. Rev. Mater. Sci. **25**, 357 (1995)

Microscopic origin of GMR



Following the two-current model by Mott

N.F. Mott, Proc. Roy. Soc., Ser. A 153, 699 (1936)

Spin-dependent scattering at the interfaces

Scattering causes electrical resistance

Scattering inside the interlayer is neglected

Rates of spin-dependent and spin-independent scattering are the same

One scattering event contribute to the total resistance by an amount r

$$R_P = 2r \times 4r / (2r + 4r) = 8r/6$$

$$R_{AP} = 3r \times 3r / (3r + 3r) = 9r/6$$

$\Delta R/R_P$ = 12.5% (max in experiment = 17%)

Lecture notes of the 40th IFF spring school:

Spintronics (2009)

Interlayer exchange coupling

Phenomenological description

Lecture notes of the 40th IFF spring school: *Spintronics* (2009)

Interlayer exchange coupling energy: $E_{coupl} = -J_1 \cos(\theta) - J_2 \cos^2(\theta)$

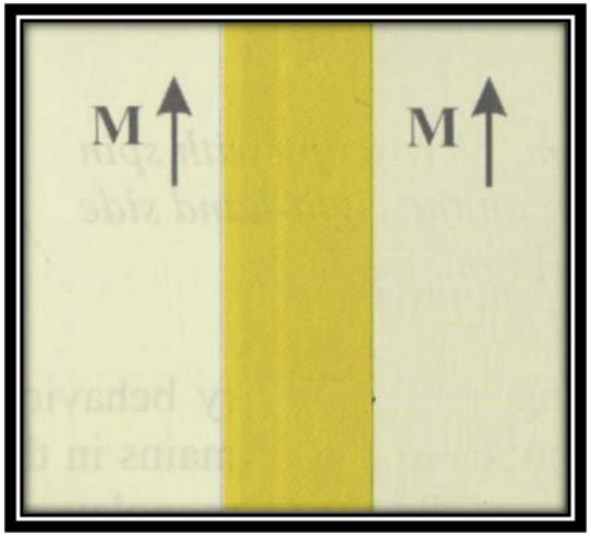
with θ – angle between the magnetizations of the films on both sides of the spacer layer

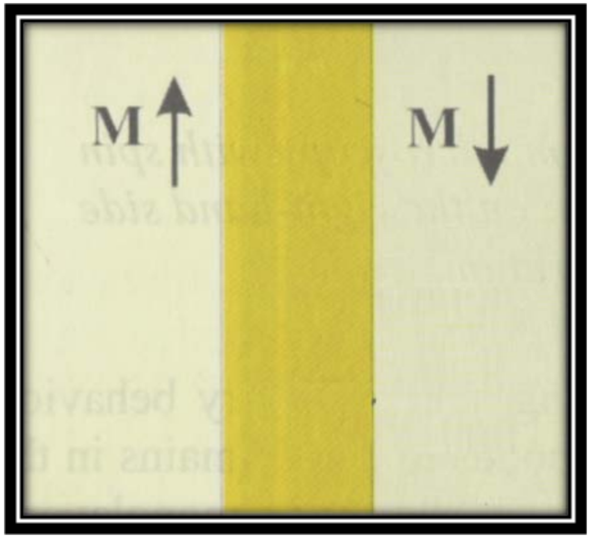
J_1 – bilinear coupling constant; J_2 – biquadratic coupling constant

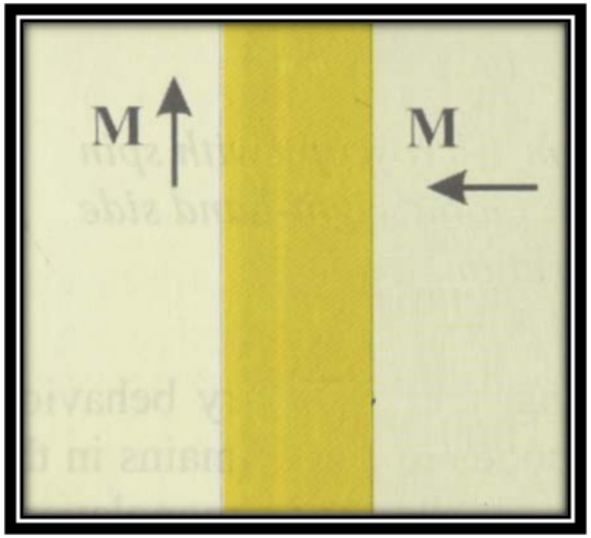
Parameters J_1 and J_2 determines the strength and type of the coupling

If $J_1 >> J_2$ and J_1 is positive (negative) then the coupling will be ferromagnetic (antiferromagnetic)

If $J_2 >> J_1$ and is negative, 90° coupling is favorable







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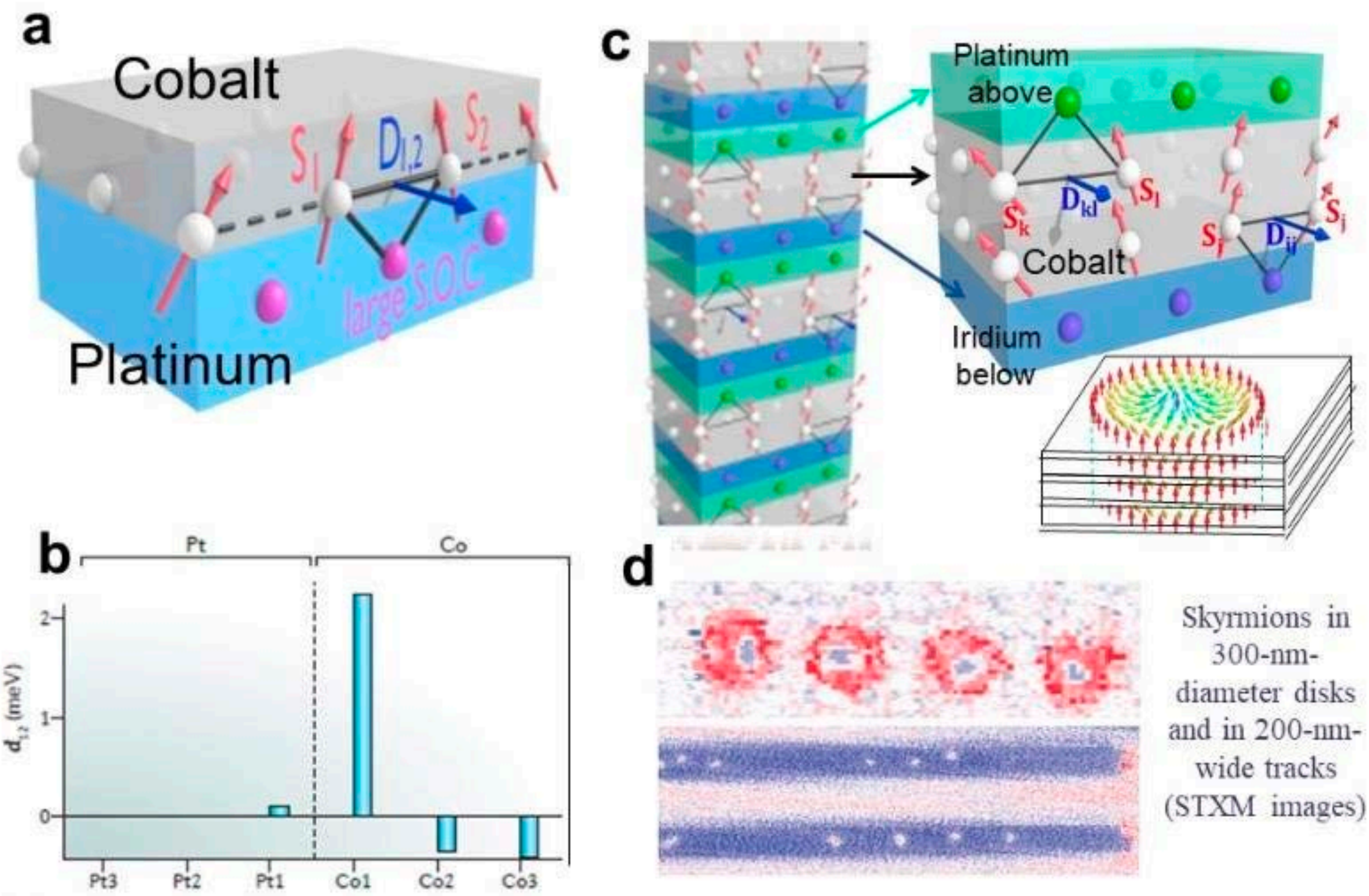
Heterostructures of ferro- and non-magnetic materials

Dzyaloshinskii–Moriya interaction

Physique **20**, 817 (2019)

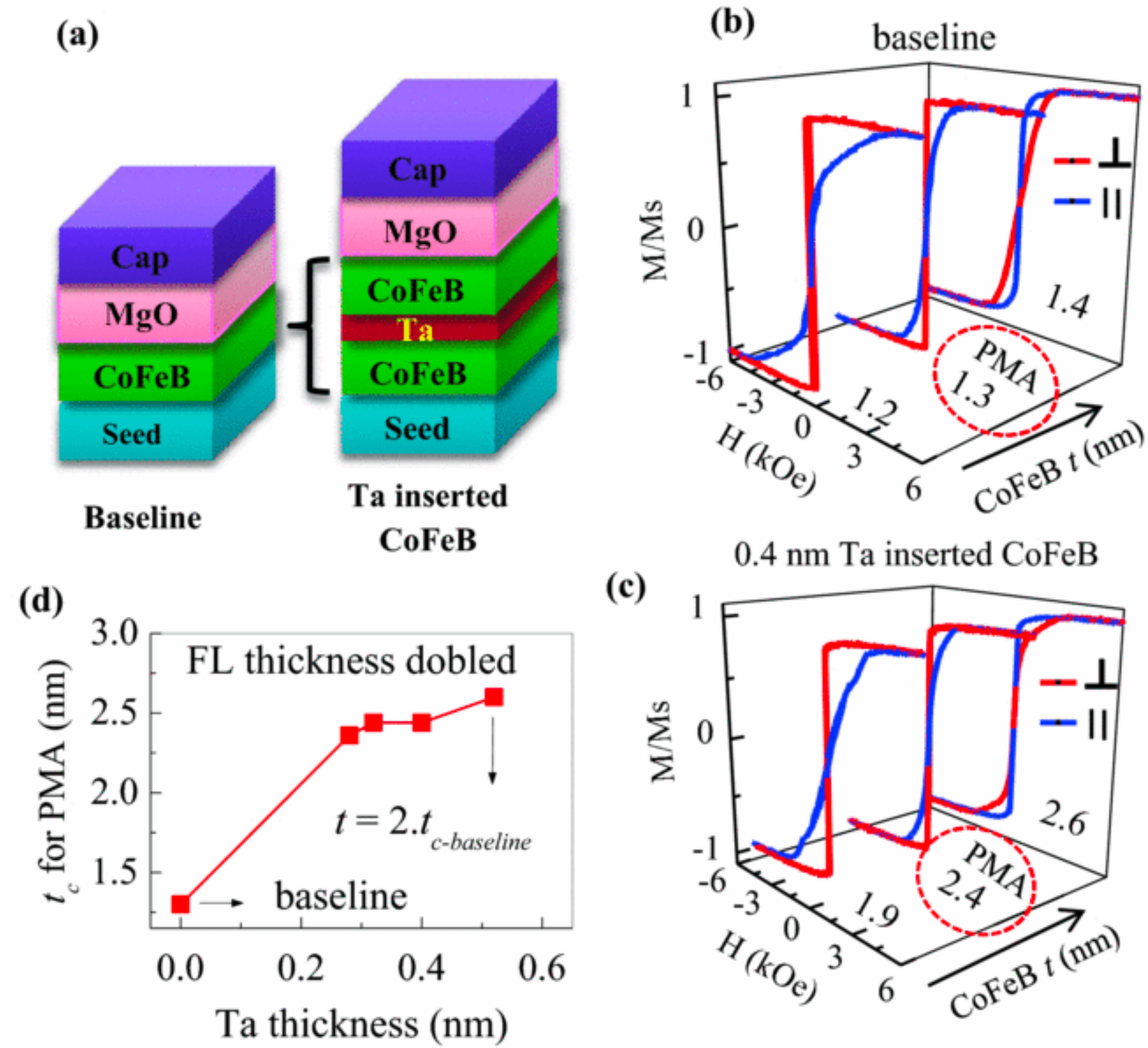


Skyrmions in 300-nm-diameter disks and in 200-nm-wide tracks (STXM images)

Heterostructures of ferro- and non-magnetic materials

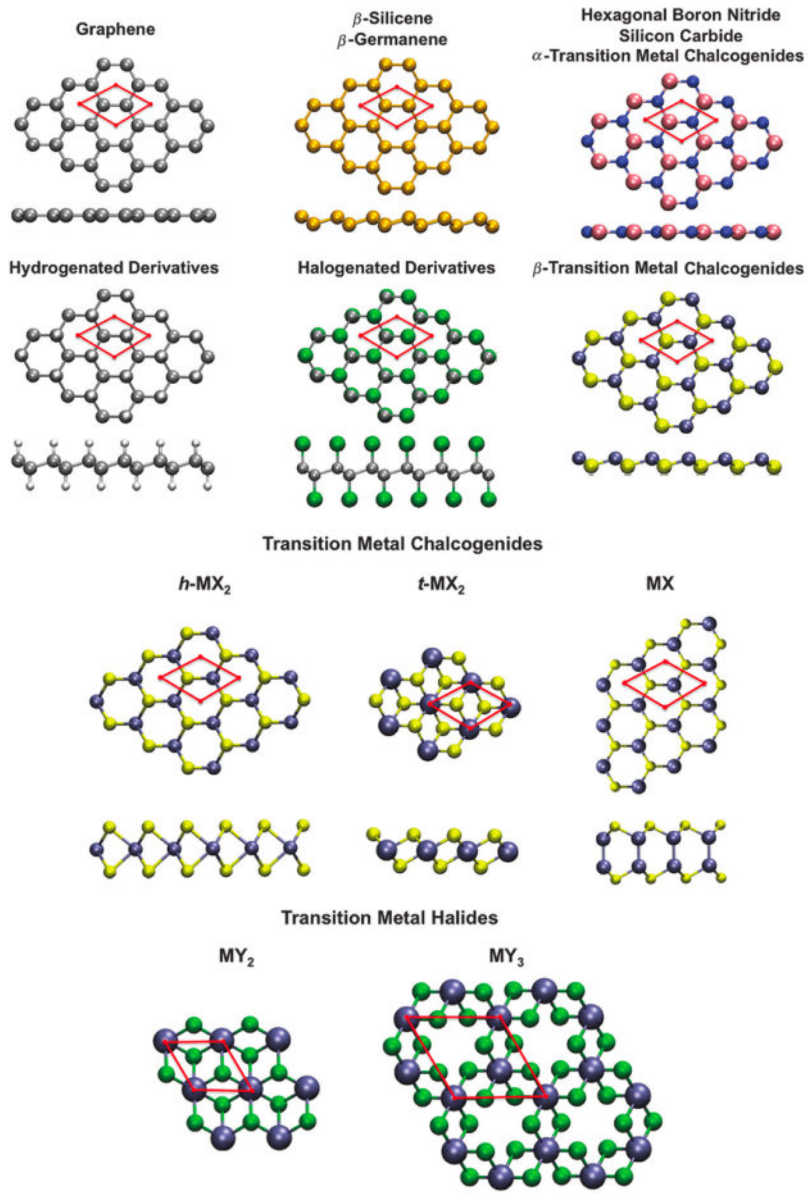
Perpendicular magnetic anisotropy

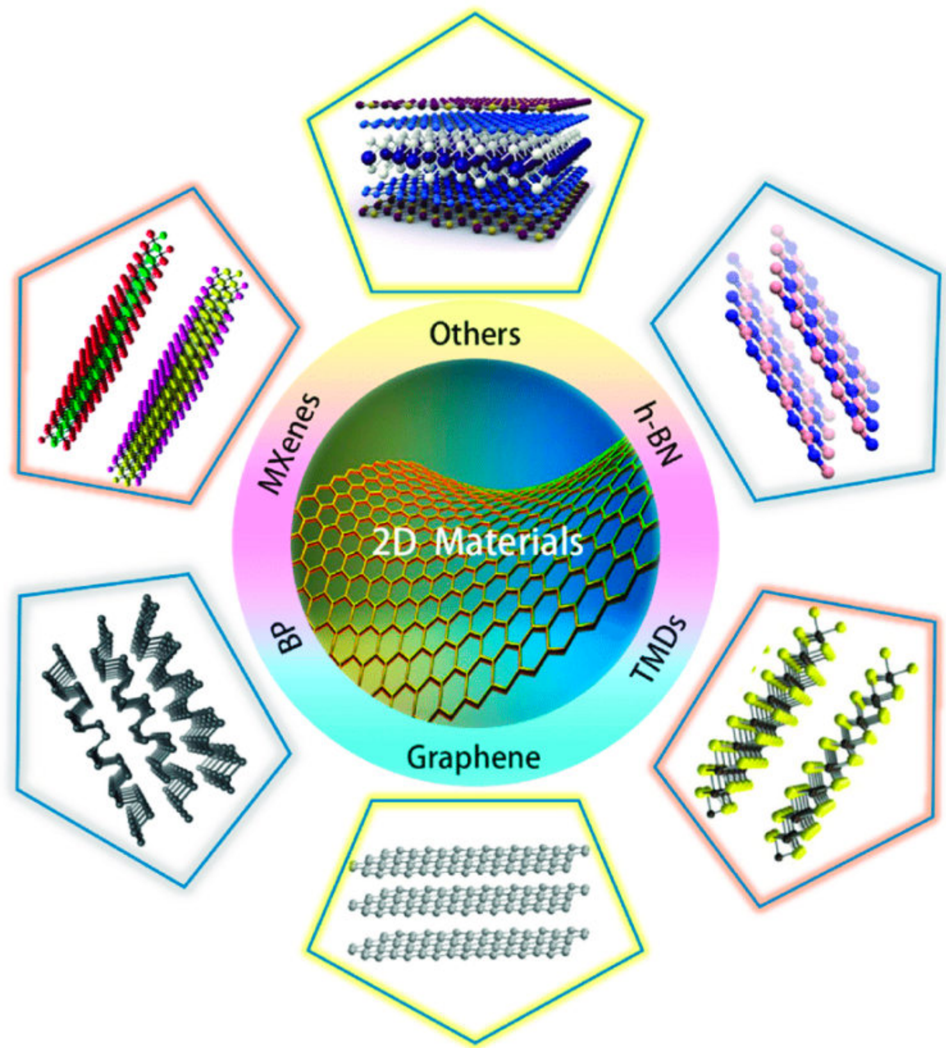
AIP Advances **2**, 042182 (2012)



2D magnetic materials and heterostructures

2D magnetic materials and heterostructures



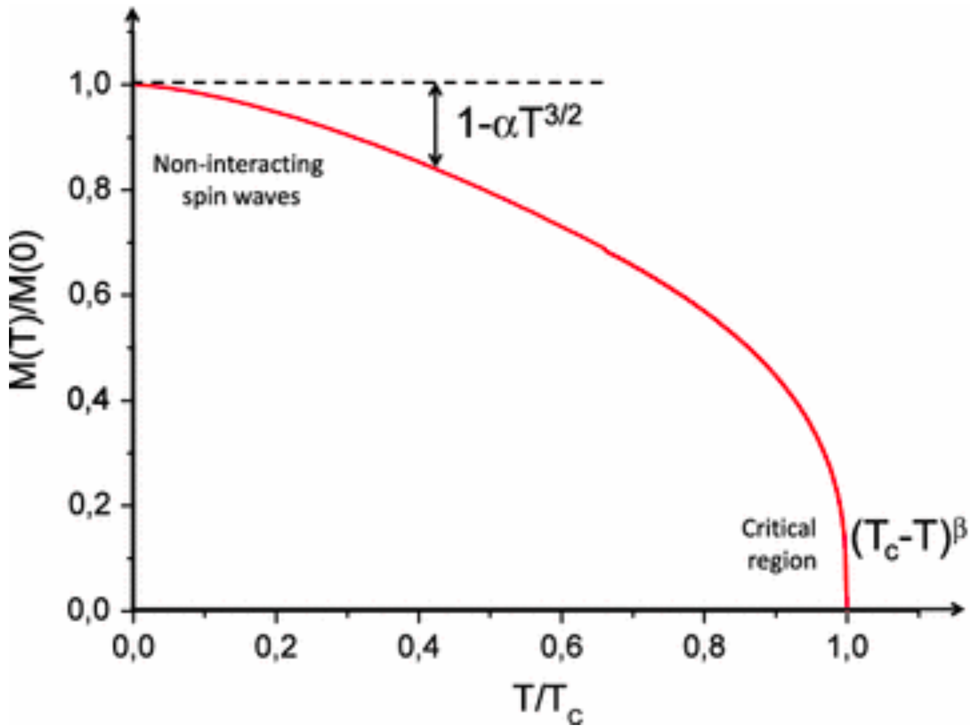


Molecules **24**, 88 (2019)

Chem. Soc. Rev. **43**, 6537 (2014)

Magnetic 2D materials and heterostructures

3D system: a magnetic phase transition occurs at a finite temperature



https://doi.org/10.1007/978-3-319-17897-4_17

Magnetic 2D materials and heterostructures

3D system: a magnetic phase transition occurs at a finite temperature

1D system: long-range order is possible only at $T = 0$ *Proc. Camb. Philos. Soc.* **32**, 477 (1936)

https://www.nature.com/articles/s41565-019-0438-6

Magnetic 2D materials and heterostructures

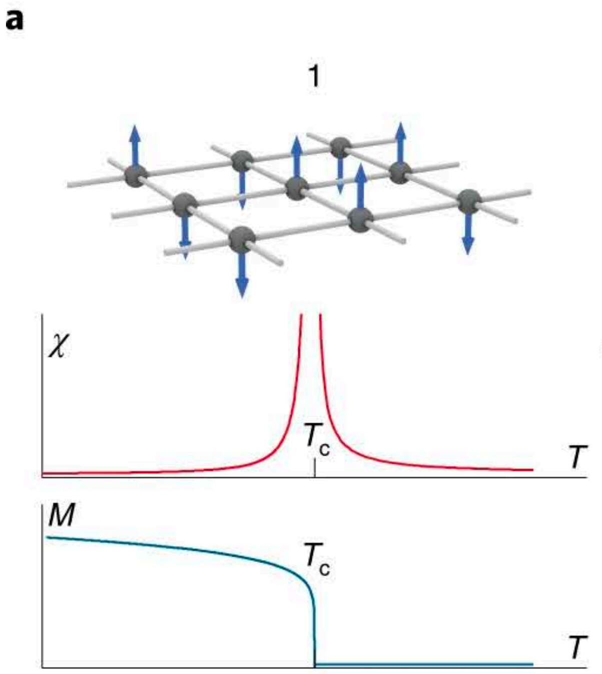
3D system: a magnetic phase transition occurs at a finite temperature

1D system: long-range order is possible only at $T = 0$ *Proc. Camb. Philos. Soc.* **32**, 477 (1936)

2D system: the existence of magnetic long-range order at any finite temperature crucially depends on the number n of relevant spin components, usually called spin dimensionality, and determined by the physical parameters of the system (for example, the presence and strength of magnetic anisotropy)

https://www.nature.com/articles/s41565-019-0438-6

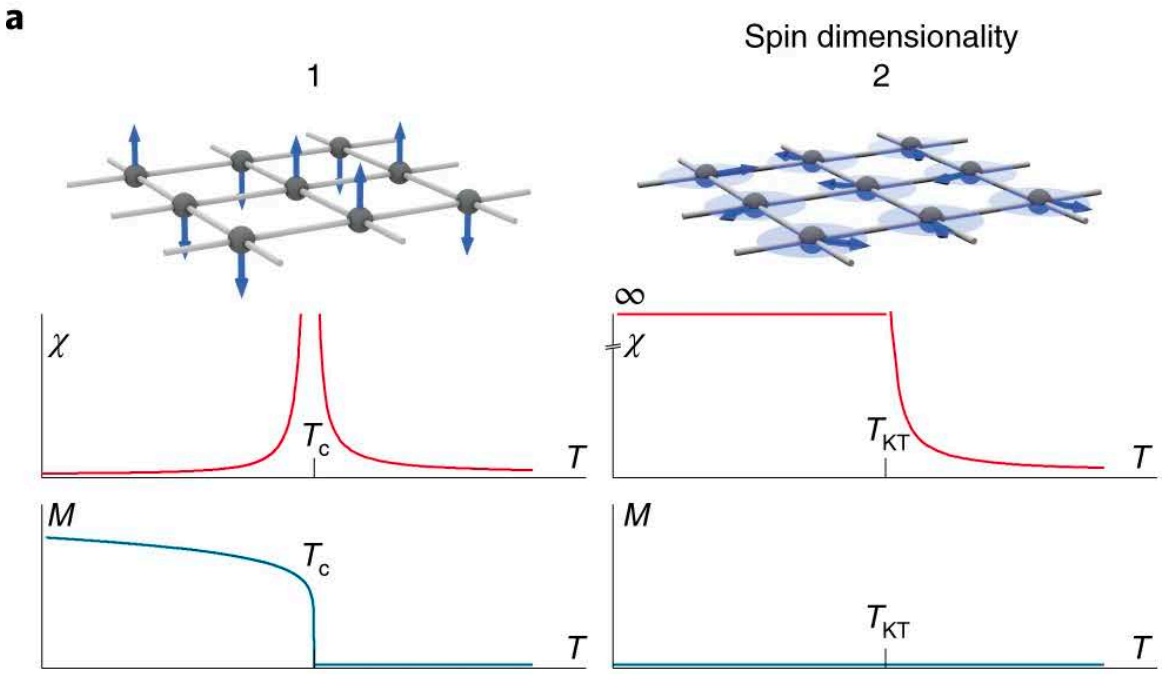
Magnetic 2D materials and heterostructures



Spin dimensionality n = 1: the system has a strong uniaxial anisotropy and the spins point in either of the two possible orientations (‘up’ or ‘down’) along a given direction

https://www.nature.com/articles/s41565-019-0438-6

Magnetic 2D materials and heterostructures

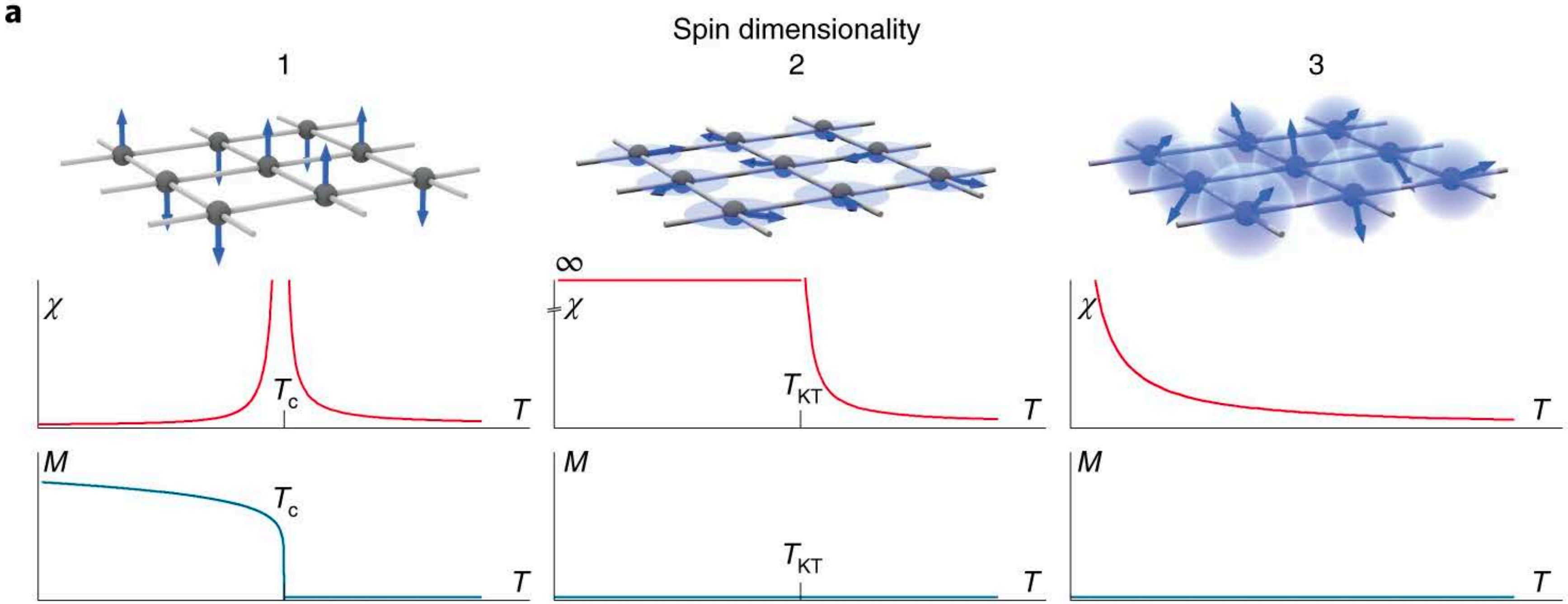


Spin dimensionality n = 1: the system has a strong uniaxial anisotropy and the spins point in either of the two possible orientations (‘up’ or ‘down’) along a given direction

Spin dimensionality n = 2 corresponds to an easy-plane anisotropy that favours the spins to lie in a given plane, although the orientation within the plane is completely unconstrained.

https://www.nature.com/articles/s41565-019-0438-6

Magnetic 2D materials and heterostructures



Spin dimensionality n = 1: the system has a strong uniaxial anisotropy and the spins point in either of the two possible orientations ('up' or 'down') along a given direction

Spin dimensionality n = 2 corresponds to an easy-plane anisotropy that favours the spins to lie in a given plane, although the orientation within the plane is completely unconstrained.

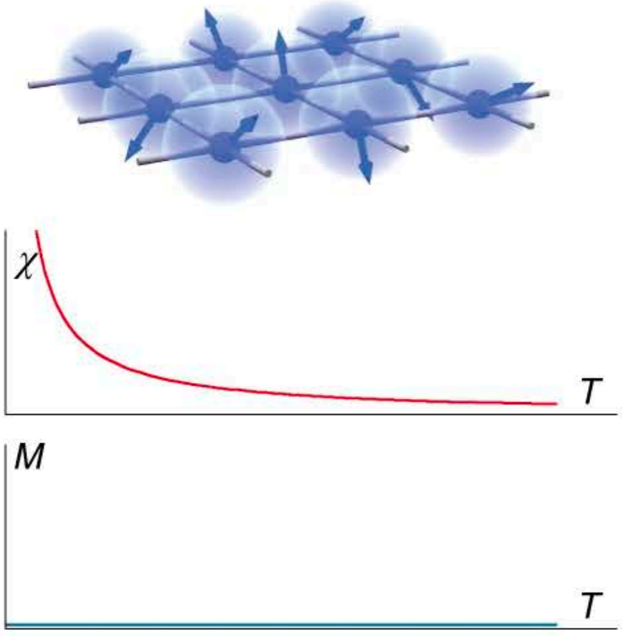
Isotropic systems are characterised with n = 3: there is no constraint on the direction of spins

https://www.nature.com/articles/s41565-019-0438-6

Mermin-Wagner(-Hohenberg) theorem

Phys. Rev. Lett. **17**, 1133 (1966)
Phys. Rev. **158**, 383 (1967)

Thermal fluctuations destroy long-range magnetic order in 2D systems at any finite temperature when the spin dimensionality is 3 (isotropic Heisenberg model)



There is no isotropic 2D ferromagnet: long-wavelength excitations (spin waves) can be excited at any finite temperature as there is no gap in the spin wave spectrum (no anisotropy)

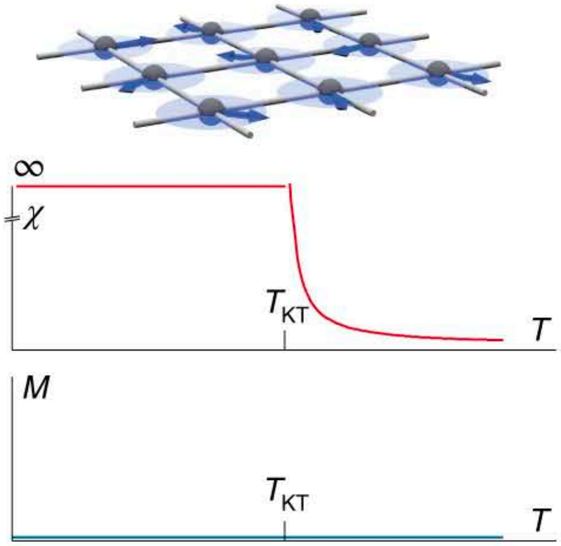
https://www.nature.com/articles/s41565-019-0438-6

2D magnet with n = 2

These systems are described by the so-called XY model

They do not possess a conventional transition to long-range order

The susceptibility diverges below a finite temperature



Berezinskii, Kosterlitz and Thouless pointed out that this divergence is associated with the onset of topological order, characterized by an algebraic decay of spin correlations and by the presence of bound pairs of vortex and antivortex arrangements of spins

Sov. Phys. JETP-USSR **32**, 493 (1971)
J. Phys. C. **6**, 1181 (1973)

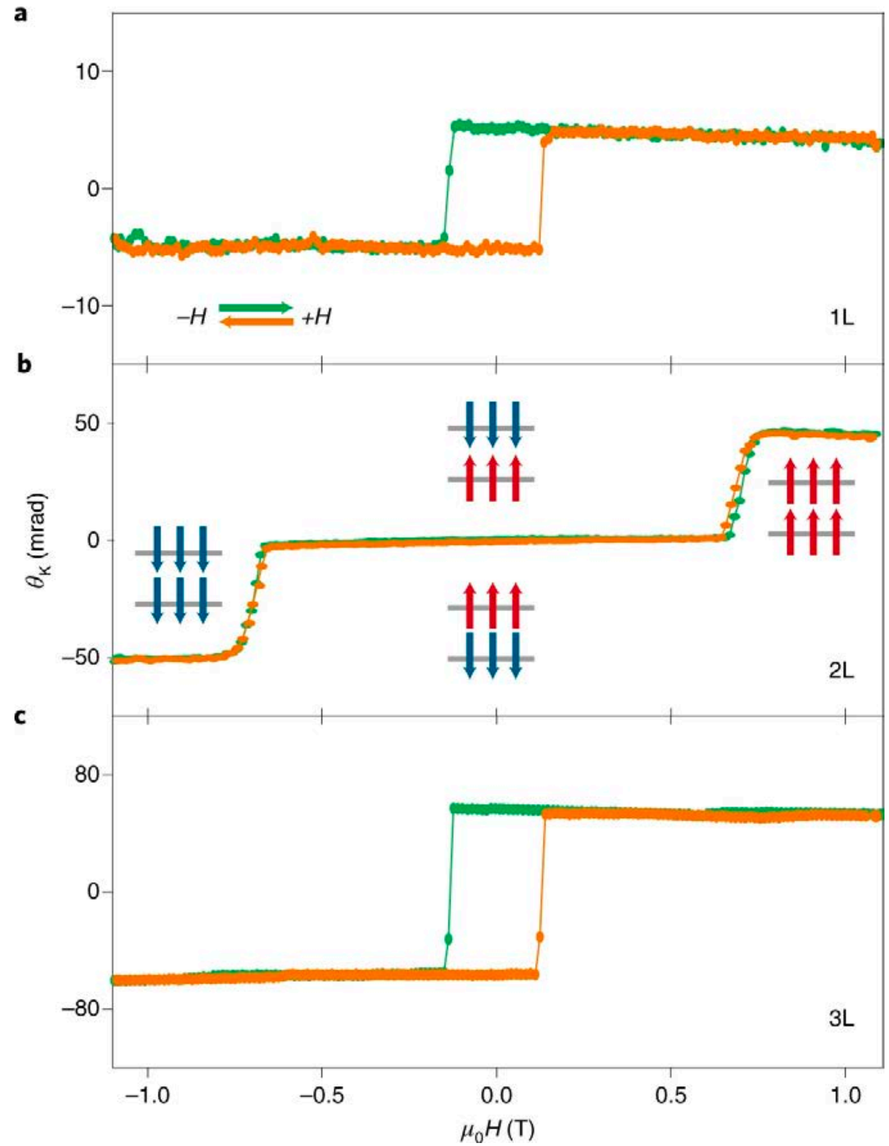
Below the Kosterlitz–Thouless temperature T_{KT}, quasi-long-range magnetic order is established, and the existence of a finite order parameter is suppressed only marginally with the system size

https://www.nature.com/articles/s41565-019-0438-6

CrI3

- Semiconducting layered vdW material
- Undergoes low-temperature magnetic transitions
- Exhibits different forms of magnetic order

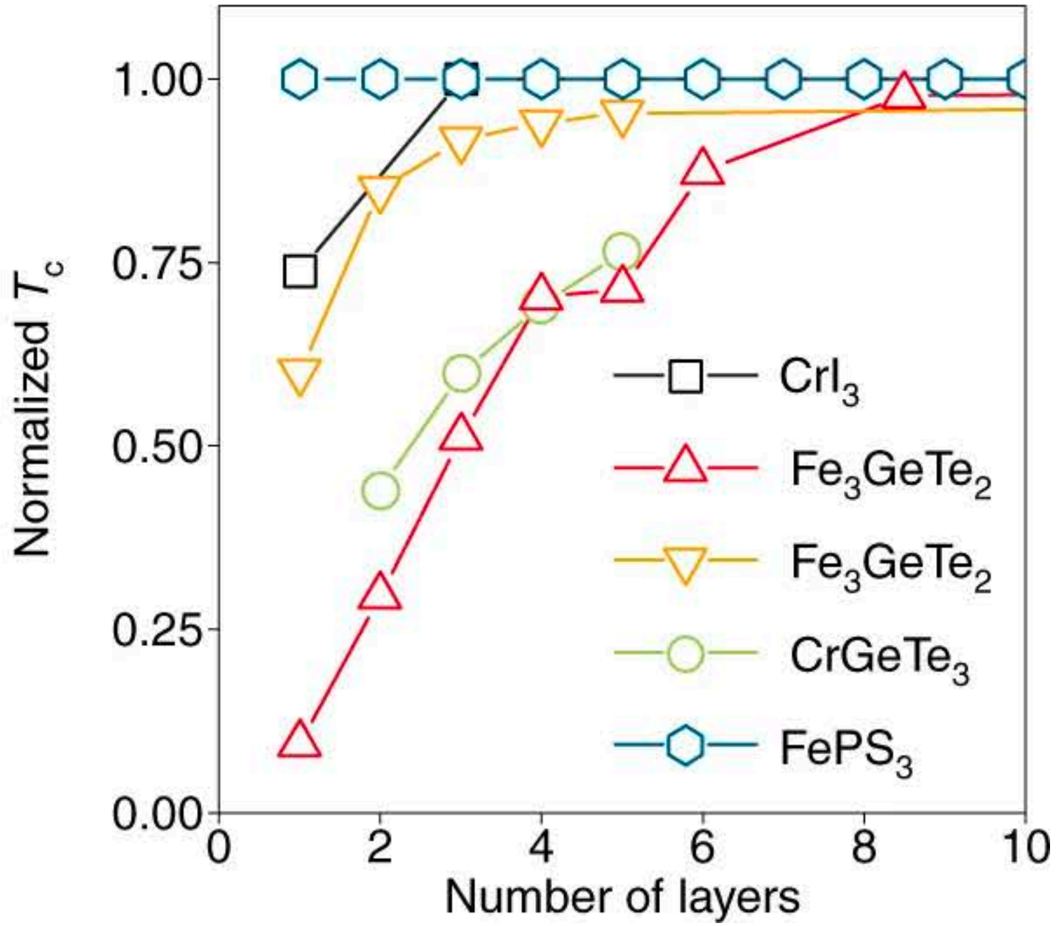
Magnetization and magnetic susceptibility measurements show that bulk CrI_3 is a strongly anisotropic ferromagnet below the Curie temperature (T_C = 61 K), with its easy axis pointing perpendicular to the layers, and a saturation magnetization consistent with a spin S = 3/2 state of the Cr atoms



Nature **546**, 270–273 (2017)

https://www.nature.com/articles/s41565-019-0438-6

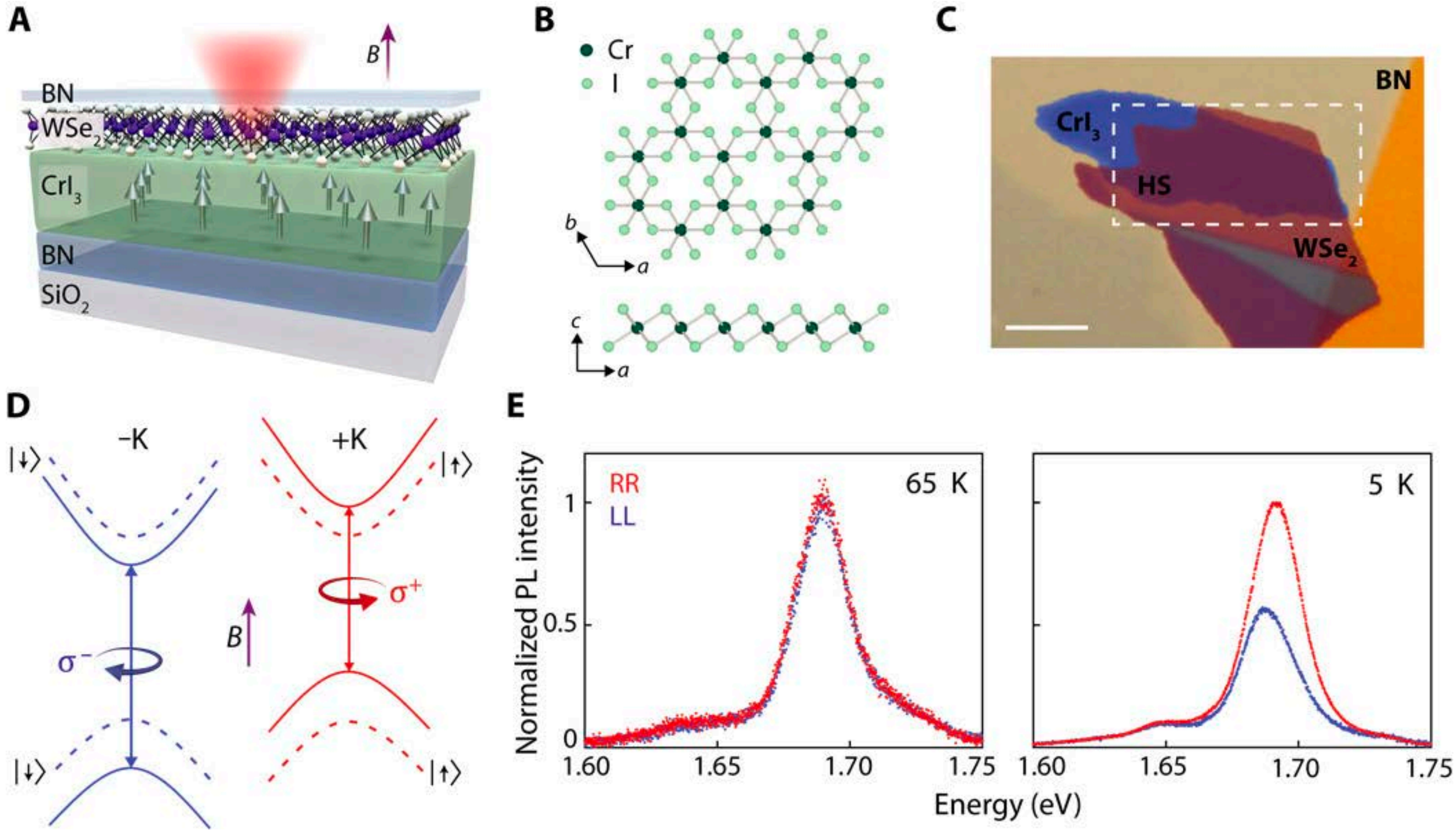
Magnetic 2D materials and heterostructures



https://www.nature.com/articles/s41565-019-0438-6

Heterostructures with semiconducting TMDCs

Heterostructure of a ferromagnetic semiconductor CrI_3 and a monolayer of WSe_2

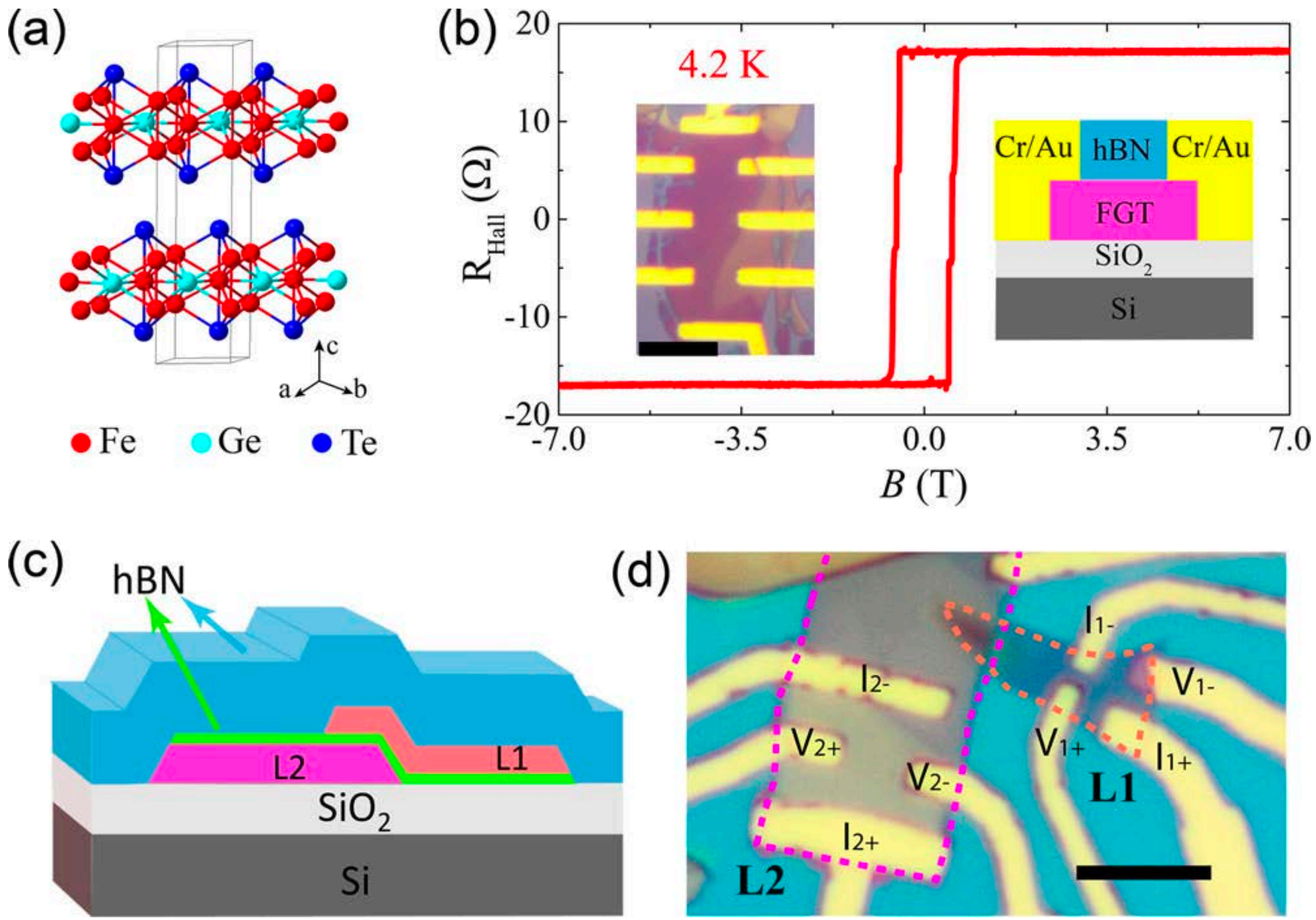


Sci. Adv. **3**, e1603113 (2017)

2D materials based magnetic tunnel junctions

Fe_3GeTe_2 / hBN / Fe_3GeTe_2 stack

Metallic 2D ferromagnet: Fe_3GeTe_2



Nano Lett. **18**, 4303 (2018)

2D materials based magnetic tunnel junctions

Fe_3GeTe_2 / hBN / Fe_3GeTe_2 stack

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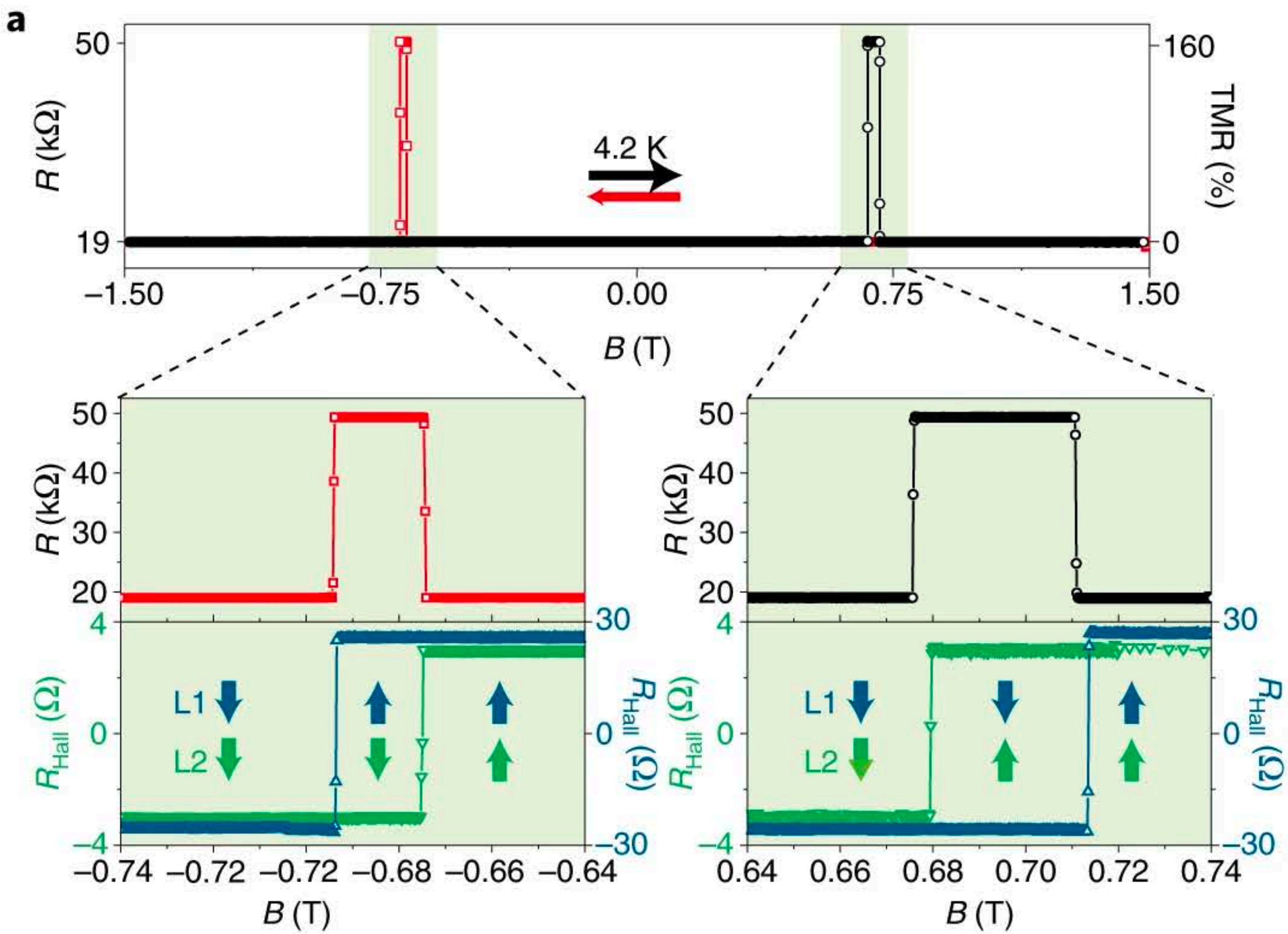

Nano Lett. **18**, 4303 (2018)

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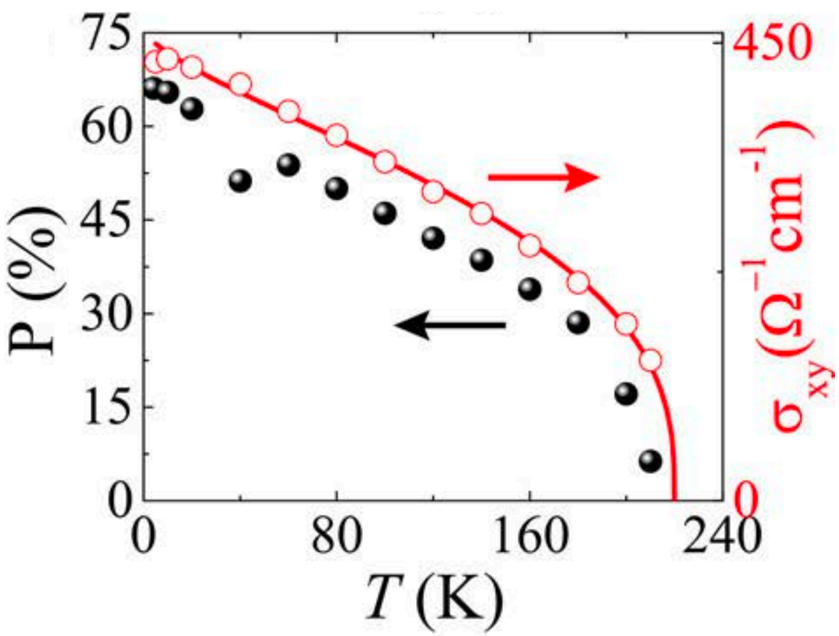
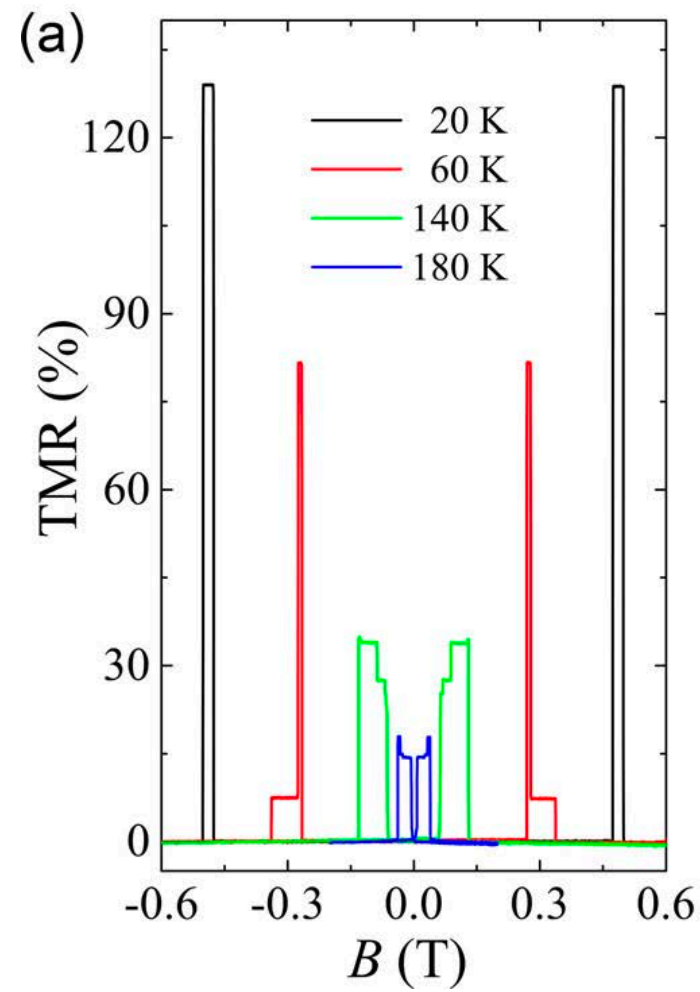
Fe_3GeTe_2 / hBN / Fe_3GeTe_2 stack



Metallic 2D ferromagnet: Fe_3GeTe_2

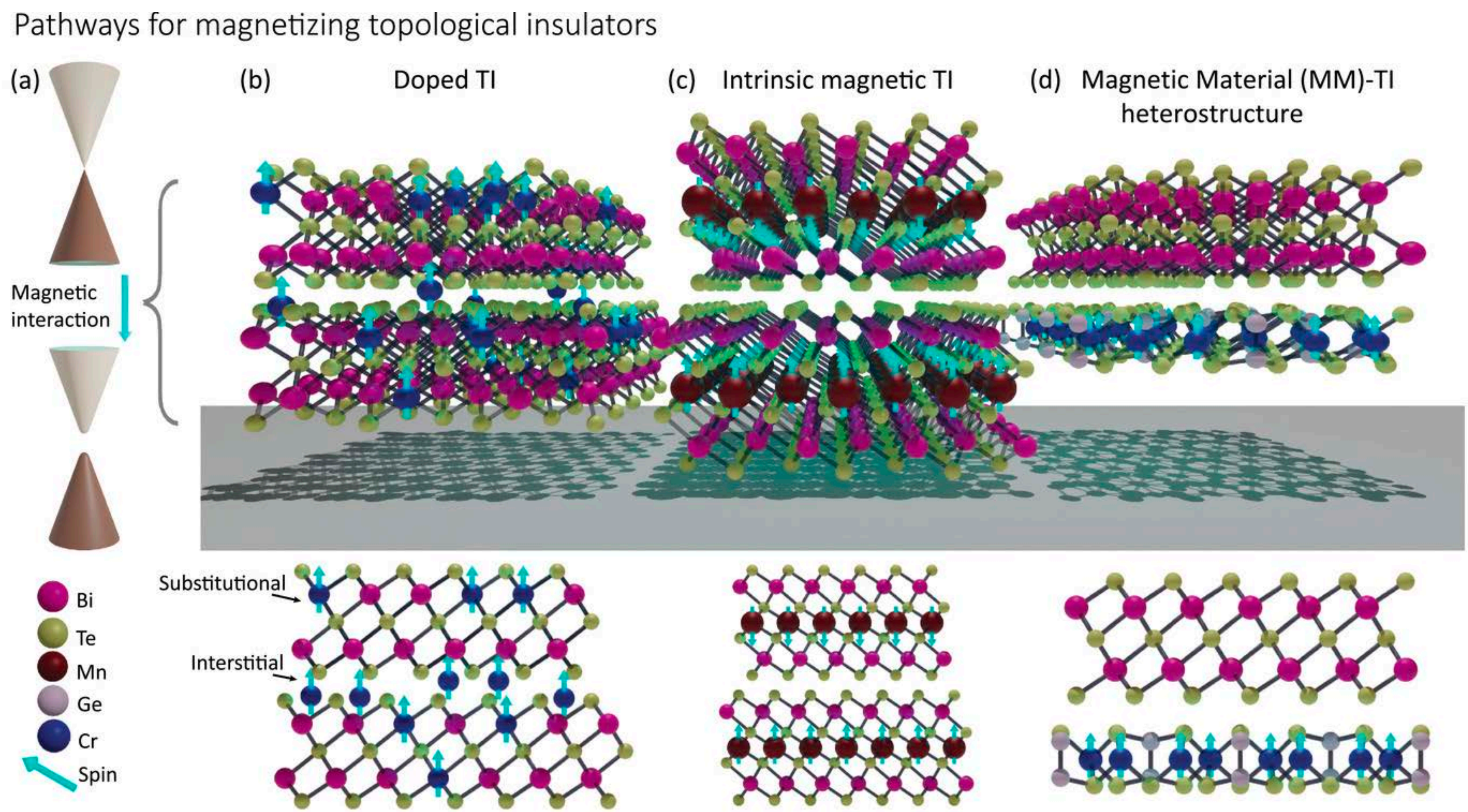


Nano Lett. **18**, 4303 (2018)

Magnetic Material – Topological Insulator Heterostructures

Dr. Denys Makarov I E-Mail: d.makarov@hzdr.de I Intelligent Materials and Systems

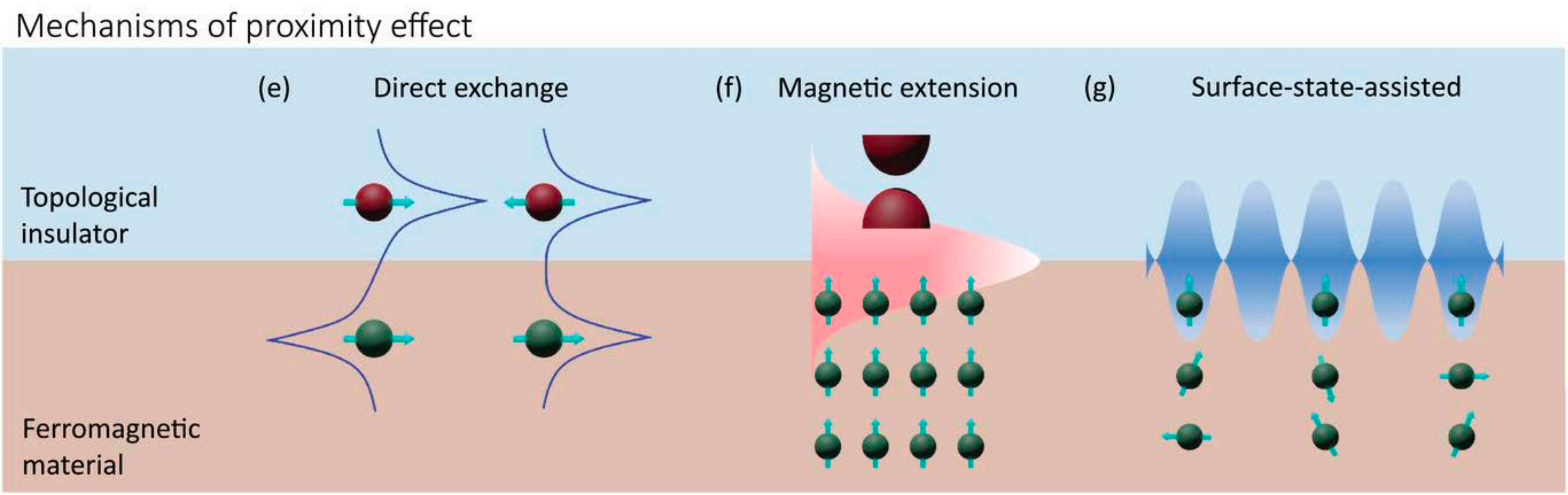
Magnetic topological insulators



$(Cr_x,Bi_{1-x})_2Te_3$ $MnBi_2Te_4$ Bi_2Te_3–$Cr_2Ge_2Te_6$

https://onlinelibrary.wiley.com/doi/full/10.1002/adma.202007795

Heterostructure: ferromagnet and topological insulator



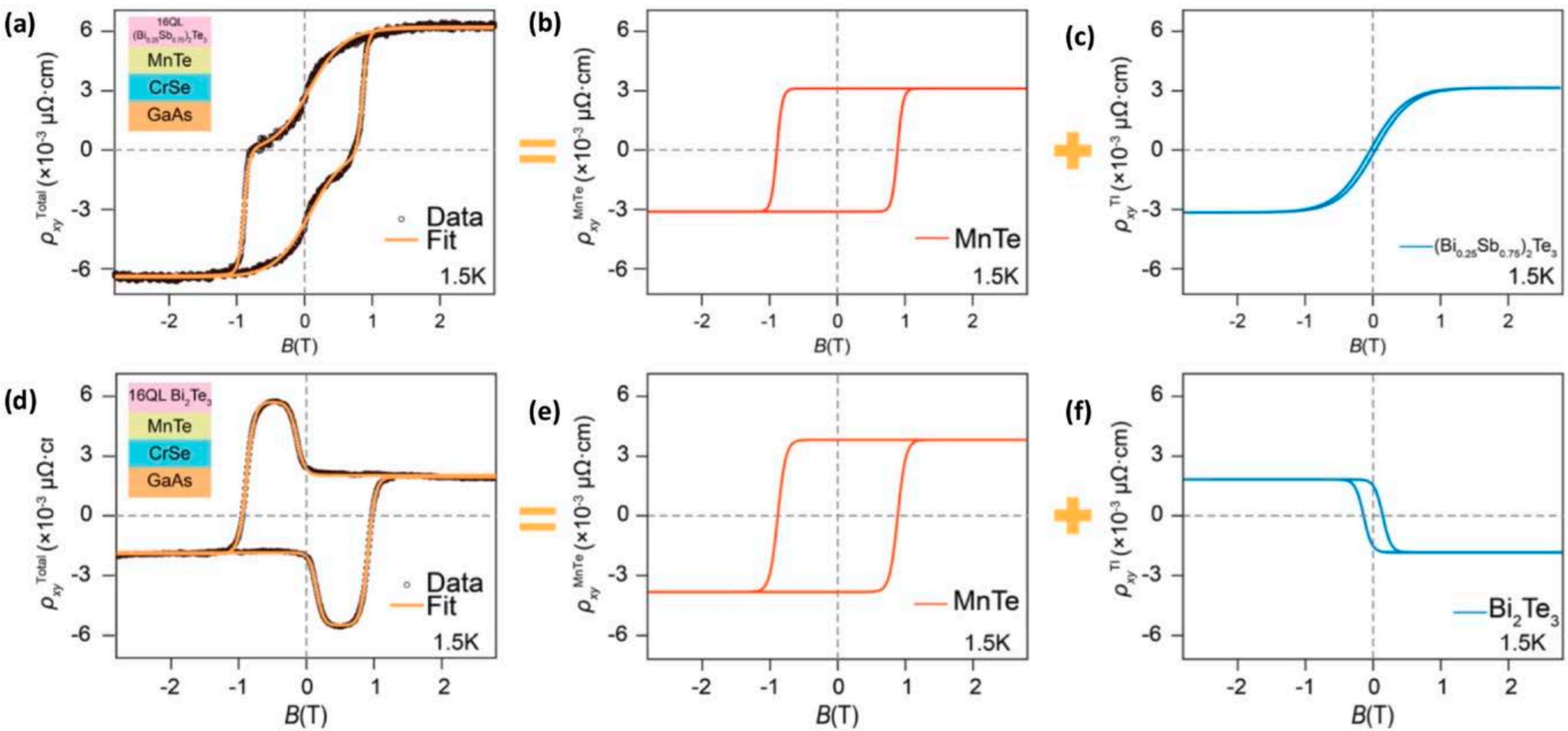
Magnetic proximity effect has a relatively short length scale (few Å). Hence, time-reversal symmetry is broken only at the interface of the TI and MM, and not in the bulk of the TI.

Therefore, typically TI must be sandwiched in between two layers of magnetic insulator (MI) with perpendicular magnetic anisotropy

Sci. Adv. **5**, eaaw1874 (2019)

https://onlinelibrary.wiley.com/doi/full/10.1002/adma.202007795

Anomalous Hall effect in FM/TI heterostructures



a) p-type 16 quintuple layer (QL) $(Bi_{0.25}Sb_{0.75})_2Te_3$–MnTe heterostructure and d) n-type 16 QL Bi_2Te_3–MnTe heterostructure

Nano Lett. **20**, 1731 (2020)

[magnetic material] / TI heterostructures

Magnetic metal - TI heterostructure						
[118]	AFMM	CrSb	$Cr_x(Bi_{1-y}Sb_y)_{2-x}Te_3$	–	35 K	Neutron reflectometry, magnetometry, magneto-transport
[121]	AFMM	CrSb	$(Bi_{1-y}Sb_y)_2Te_3$	–	90 K	Magneto-transport
[206]	AFMM	CrSe	$(Bi_{1-y}Sb_y)_2Te_3$	–	120 K	Magneto-transport, Magnetometry, Neutron reflectometry

…and many more…

Magnetic metal - TI heterostructure						
[118]	AFMM	CrSb	$Cr_x(Bi_{1-y}Sb_y)_{2-x}Te_3$	–	35 K	Neutron reflectometry, magnetometry, magneto-transport
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[121]	AFMM	CrSb	$(Bi_{1-y}Sb_y)_2Te_3$	–	90 K	Magneto-transport
[206]	AFMM	CrSe	$(Bi_{1-y}Sb_y)_2Te_3$	–	120 K	Magneto-transport, Magnetometry, Neutron reflectometry

…and many more…

https://onlinelibrary.wiley.com/doi/full/10.1002/adma.202007795

Thank you for your attention