Surface and interfaces in magnetism: phenomena and functions

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Slides: https://fruchart.eu/slides

AI from Chat GPT

ESM and the Vikings

(Part of the) steering committee

Thanks to Heike and Biplab for chairing and all the onsite practical work

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SPIN IN ELECTRONICS

What is a surface?

What is an interface?

FOREWORD – Defining the scope

Surface

Merriam-Webster

- *The exterior or upper boundary of an object or body*
- *A plane or curved two-dimensional locus of points (such as the boundary of a three-dimensional region)*

Interface

- *A surface forming a common boundary of two bodies, spaces, or phases*

What a surface is, in the context of magnetic materials?

MISTRAL AI_

- *A surface refers to the boundary layer where the material interfaces with another medium (e.g., air, vacuum, a substrate, or another material). This region exhibits distinct magnetic properties compared to the bulk of the material*

What is an interface, in the context of magnetic materials, and how it is different from a surface?

- *An interface is the atomic-scale boundary where two different materials or phases meet, creating a region where their structural, electronic, and magnetic properties interact and hybridize.*
- *Unlike a surface (which is a boundary with vacuum, air, or a non-magnetic medium), an interface involves two distinct condensed phases (e.g., metal/metal, metal/oxide, ferromagnet/antiferromagnet)*

FOREWORD – Defining the scope

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My own choice:

- Surface: the 2nd material does not contribute
- Interface: the 2nd material plays an active role in the specific properties
- Can be: 2D, but also 1D or 0D and have finite thickness

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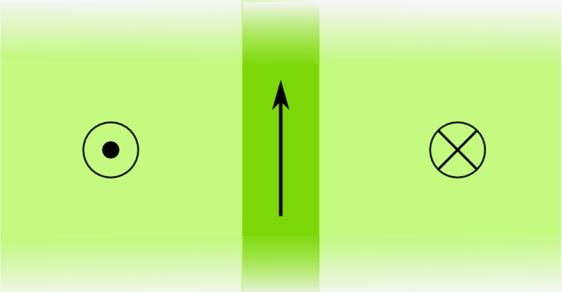
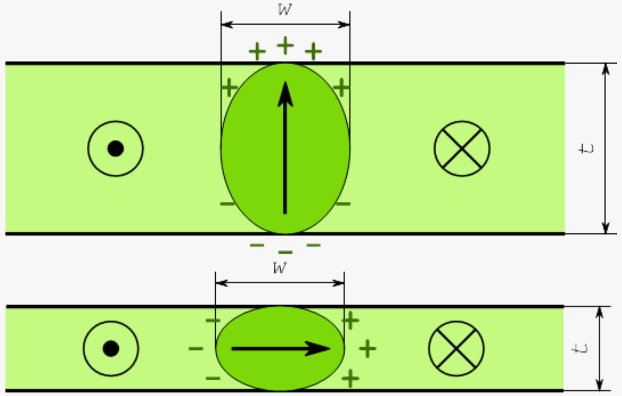
Bloch wall in the bulk (2D)



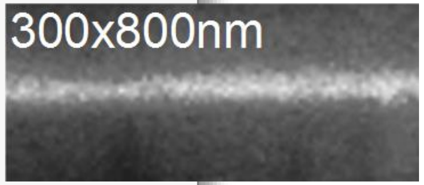
- No magnetostatic energy
- Width $\Delta_u = \sqrt{A/K}$
- Energy $\gamma_W = 4\sqrt{AK}$

F. Bloch, Z. Phys. 74, 295 (1932)

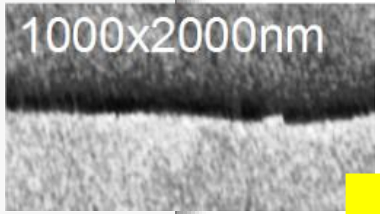
Domain walls in thin films (towards 1D)



Bloch wall
$t \gtrsim w$



Néel wall
$t \lesssim w$



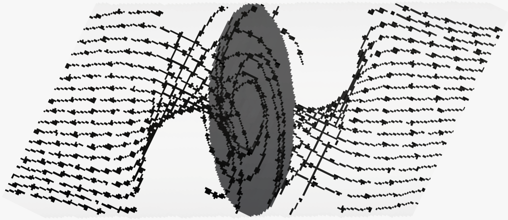
- Implies magnetostatic energy
- No exact analytic solution

L. Néel, C. R. Acad. Sciences 241, 533 (1956)

Lecture
Lukas Körber

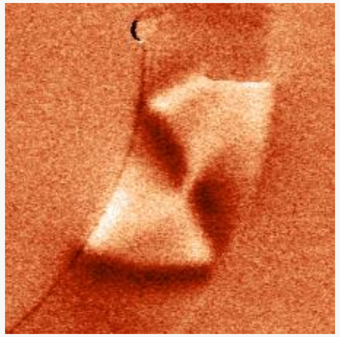
Bloch point (0D)

- Point with vanishing magnetization



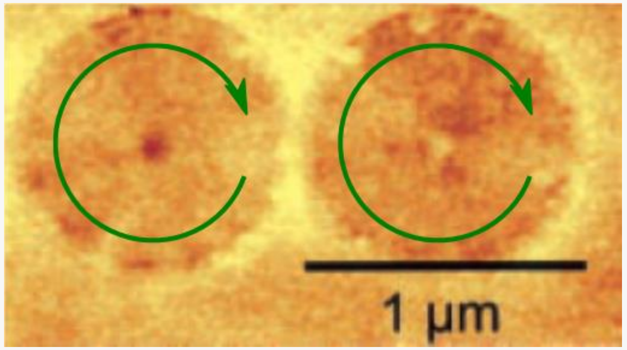
W. Döring,
JAP 39, 1006 (1968)

Constrained walls (eg in strips)



Permalloy (15nm)
Strip width 500nm

Vortex (1D → 0D)



T. Shinjo et al., Science 289, 930 (2000)

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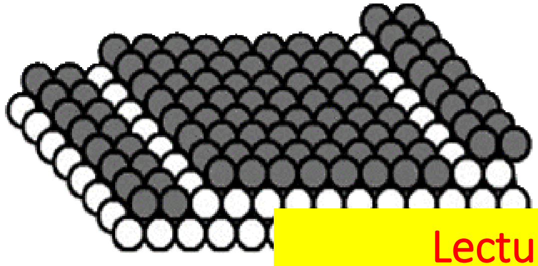
- Moments and orbitals

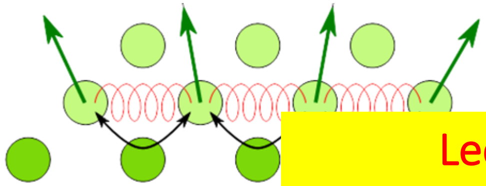


Lecture
Heiker Herper

- Magnetic anisotropy

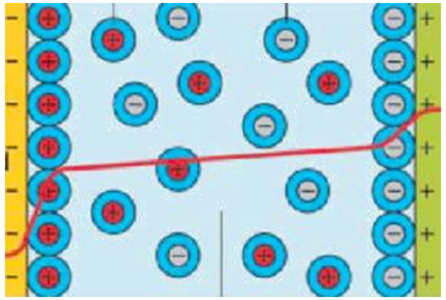
Lecture
Franziska Scheibel

- Dzyaloshinskii-Moriya

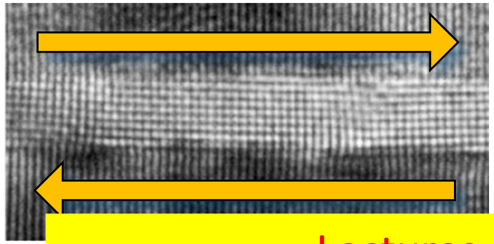


Lecture
Olle Errikson

- Electric field effects

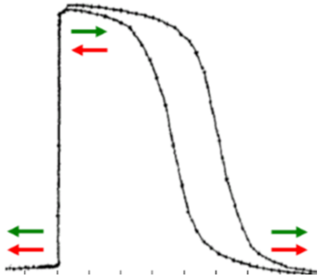


- Magneto-Transport



Lectures
Peter Oppeneer, Mads Brandbyge

- Heterostructures



Covered in other lectures

- Ordering and critical phenomena
  Bertrand Dupe
- Domains and domain walls
  Lukas Körber

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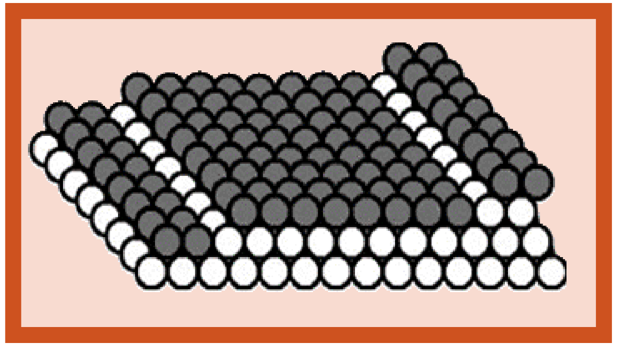
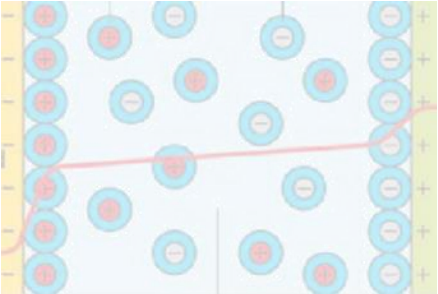
- Moments and orbitals

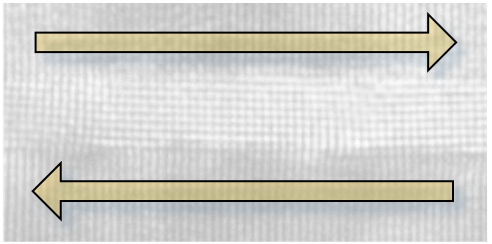


- Electric field effects

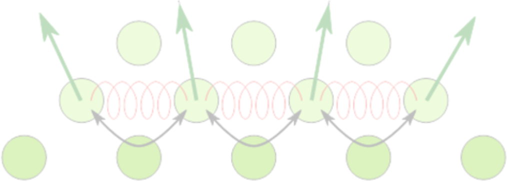


- Magnetic anisotropy

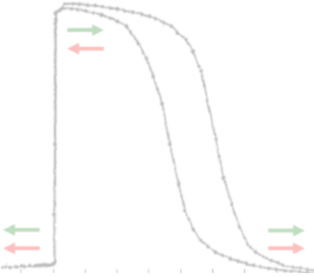
- Magneto-Transport



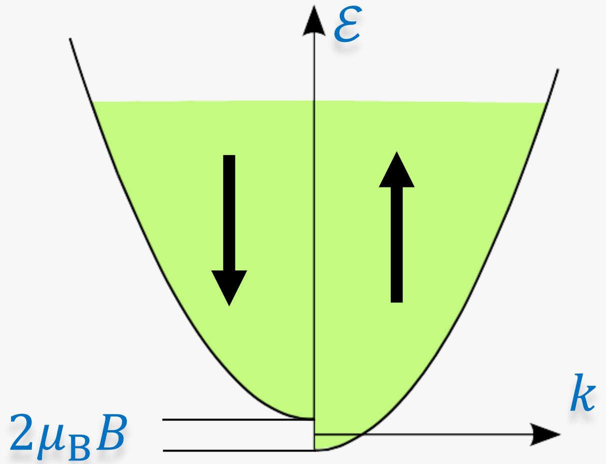
- Dzyaloshinskii-Moriya



- Heterostructures



Stoner criterium

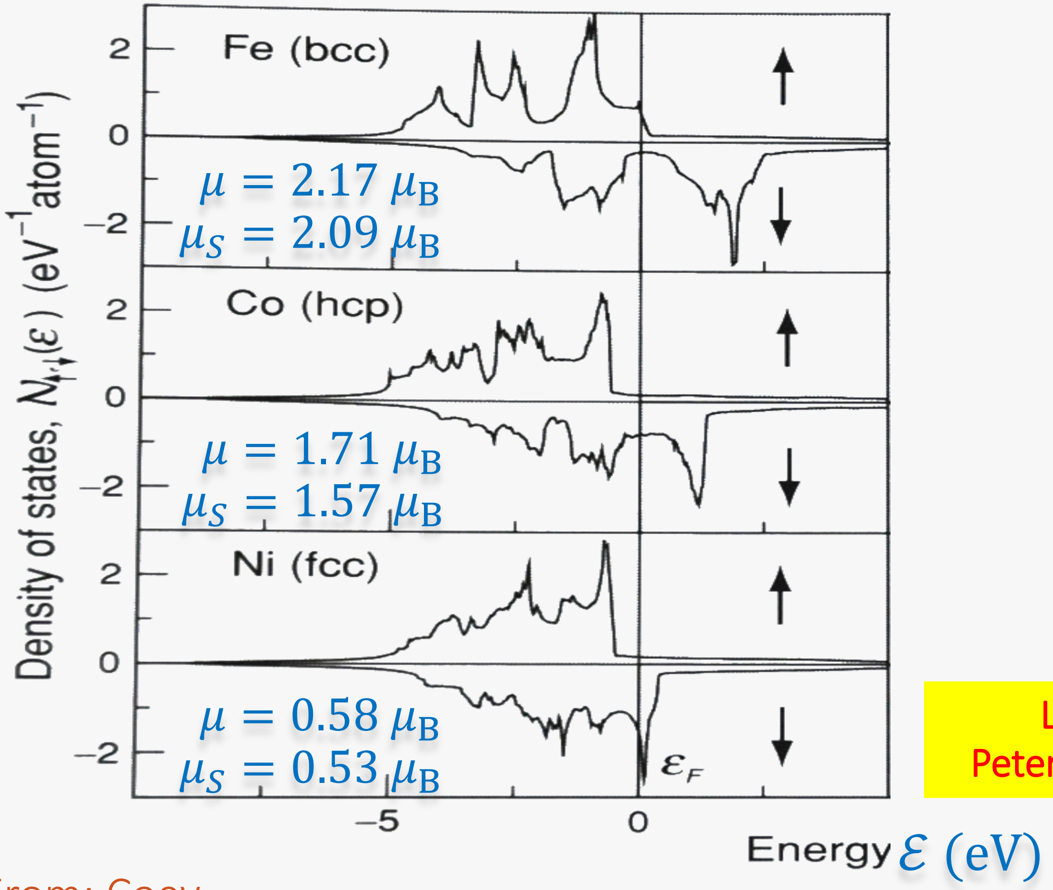


- Cost in kinetic energy
- Gain in Coulomb interaction

Criterion for ordering: $I\rho_{\uparrow,\downarrow}(\mathcal{E}_F)>1$

Lecture
Heike Herper

Spin-polarized band structure



From: Coey

Lecture
Peter Oppeneer

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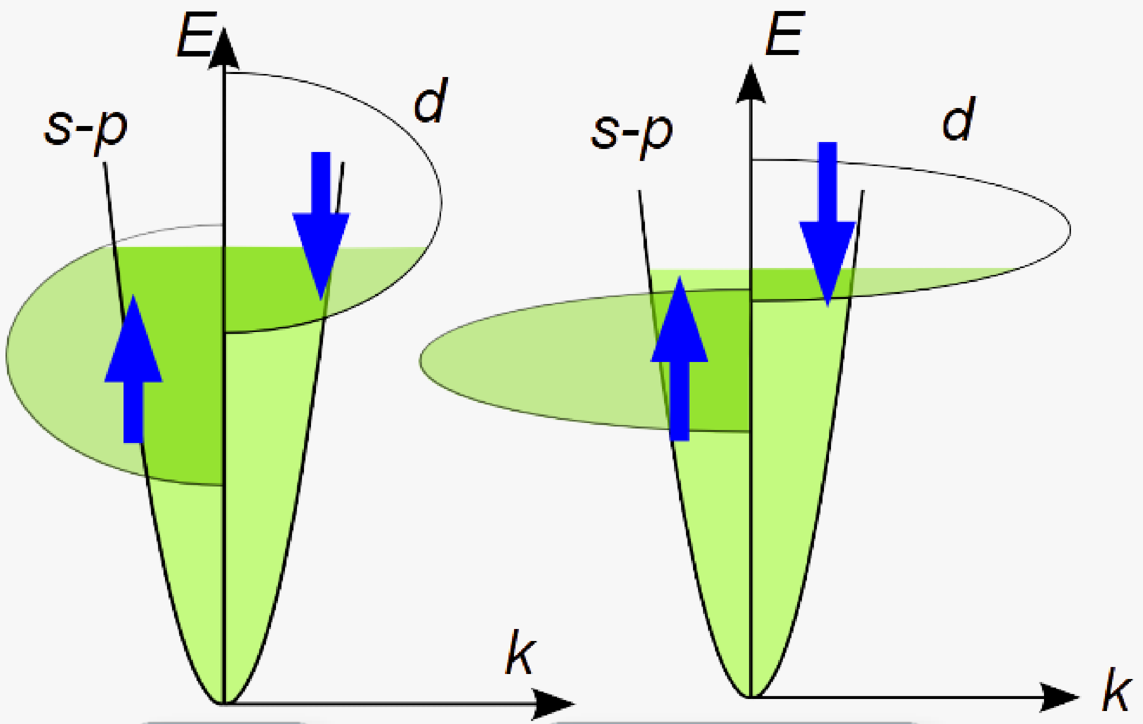
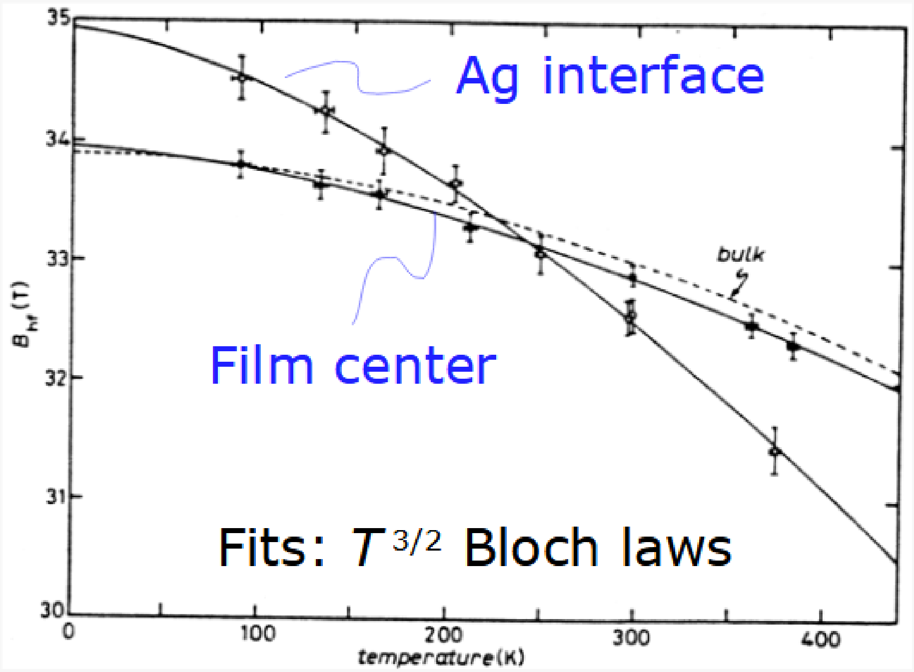
Simple picture: band narrowing at surfaces



Bulk

At a surface

Experiment Ag/Fe(110)/W(110)



U. Gradmann et. al.

Mössbauer spectroscopy

Lecture Marco Coisson

- Surface moments are often 20-30% larger than in the bulk
- However, decay faster with temperature

Lecture Bertrand Dupé

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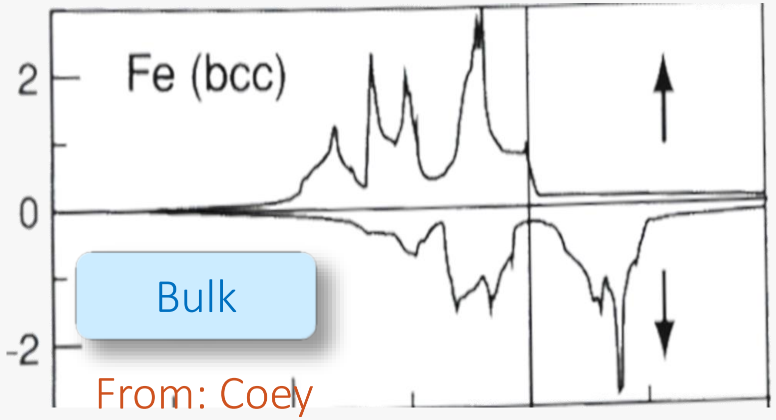
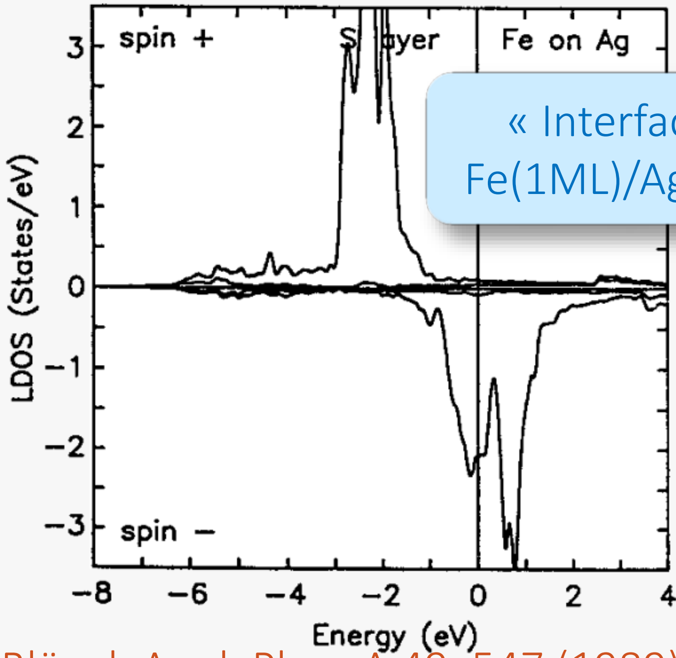
Band narrowing and enhanced moment – DFT



Bulk

From: Coey



« Interface »
Fe(1ML)/Ag(001)

S. Blügel, Appl. Phys. A 49, 547 (1989)

Band narrowing and enhanced moment – DFT

Magnetic moment at a free surface

- Enhancement of moment depends of crystal surface
- Lower coordination -> More band narrowing and enhanced moment

M [μ_B]	Cr (bcc)	Fe (bcc)	Co (hcp)	Ni (fcc)
(100)	2.55	2.88	1.85	0.68
(110)	—	2.43	—	0.74
(111) (0001)	—	2.48	1.70	0.63
Bulk	±0.60	2.13	1.62	0.61

Most packed surface

Most open surface

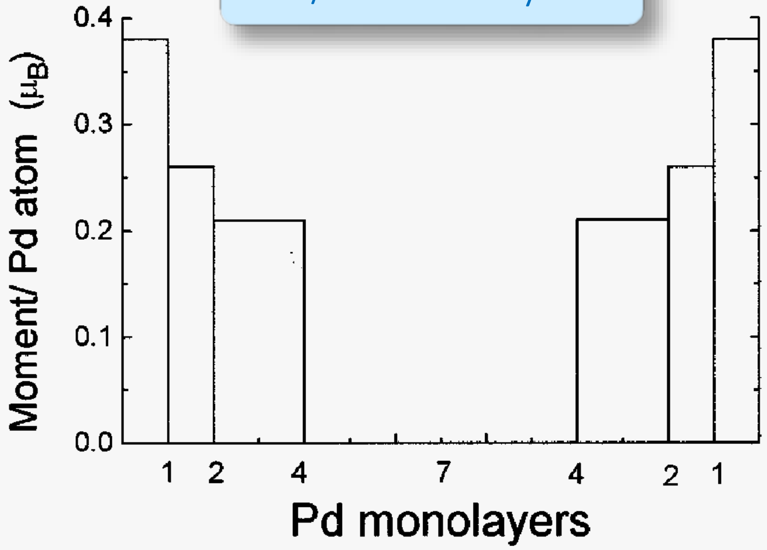
Lecture ESM2024
Stefan Blügel

Moments and orbitals – Induced magnetic moment

Experiments (XMCD)

Lecture
Stuart Cavill

Fe/Pd multilayers



J. Vogel et al., Phys. Rev. B 55, 3663 (1997)

DFT simulations

3d/Pd interface

Table 3. Induced moments M_1 and M_2 in the first and second layer of the Pd substrate. The values (in μ_B) refer to the ferromagnetic configuration of the 3*d*-monolayers M^F_{OL} on Pd(001)

	V	Cr	Mn	Fe	Co	Ni
M_1	−0.01	0.17	0.30	0.32	0.33	0.24
M_2	0.00	0.03	0.11	0.17	0.24	0.20

S. Blügel, Appl. Phys. A 49, 547 (1989)

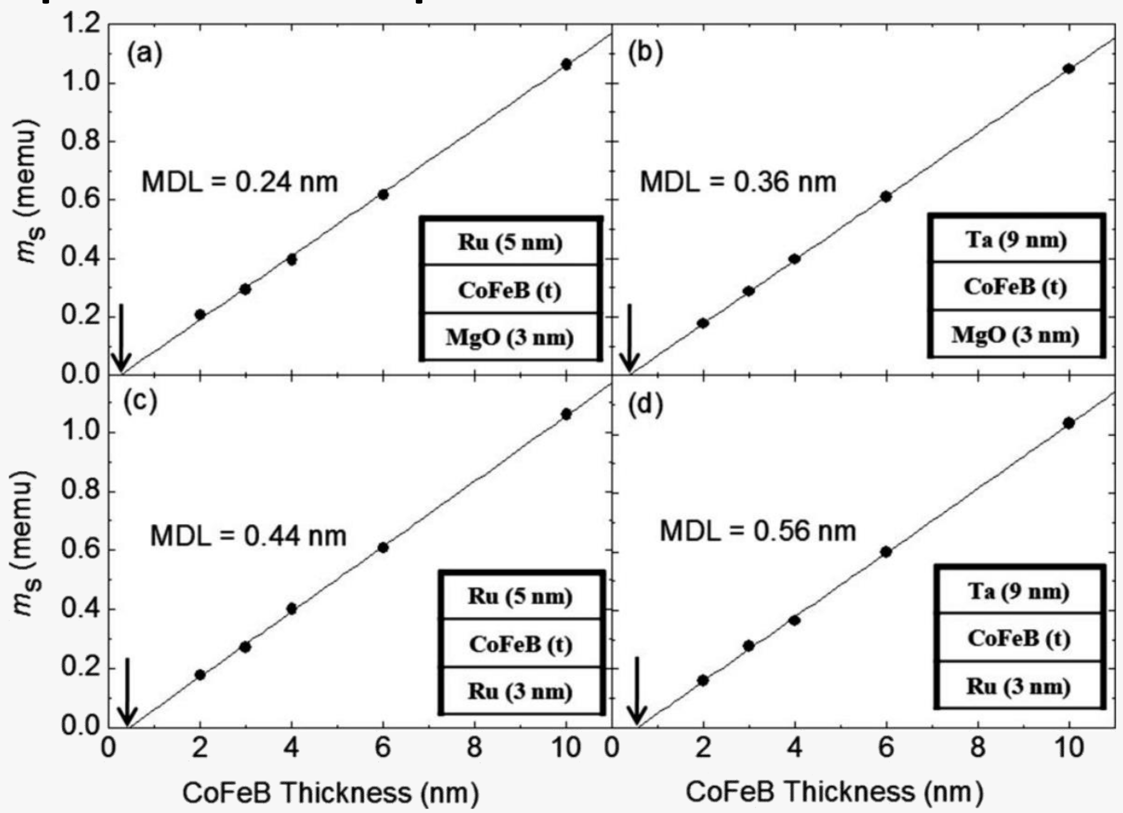
- The magnetic 3d metal polarizes the first layers of the interface material
- Polarization depends on magnetic susceptibility (eg, Pd versus Pt)
- **Magnetic properties (anisotropy, DMI etc.) induced both in 3d and interface material**

Interface = active for the property

MISTRAL AI: *An interface is the atomic-scale boundary…*

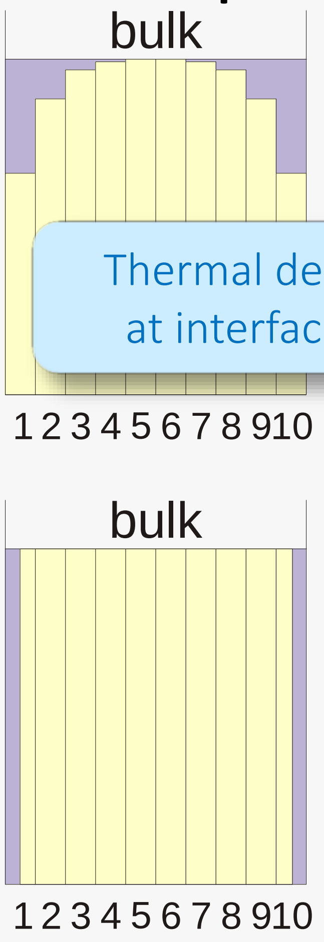
Moments and orbitals – Dead layers

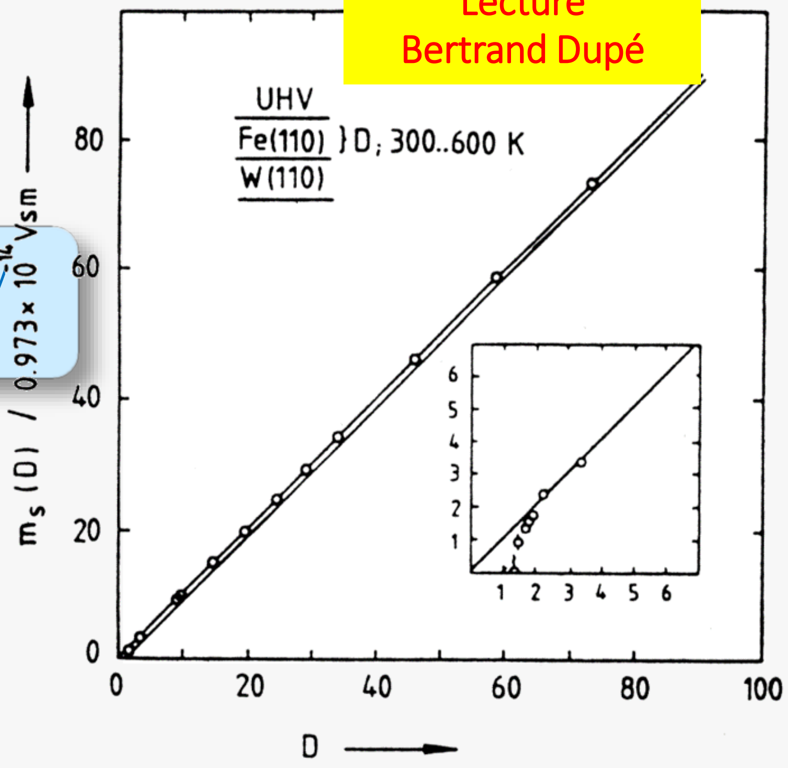
Experimental example



"Missing" moment for finite thickness interpreted as "dead" layer

Beware of possible bias





Lecture Bertrand Dupé

- Apparent: $+0.14\ \mu_B$
- Corrected from spin waves: $+0.42\ \mu_B$

- Dead layers may result from roughness, intermixing, alloying…
- Estimation from M(T) requires zero-temperature extrapolation

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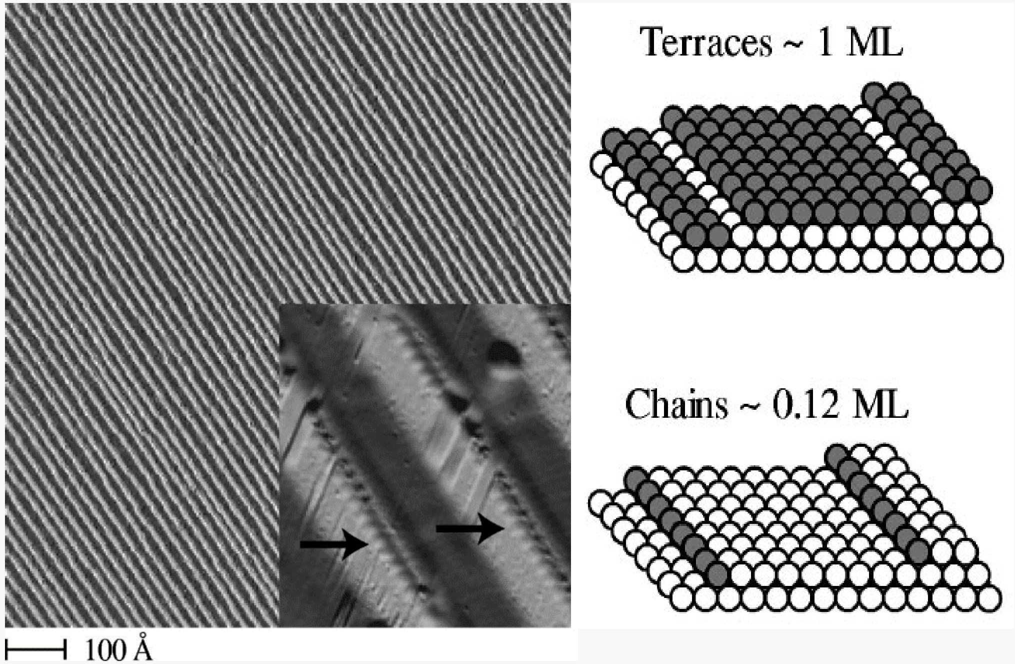
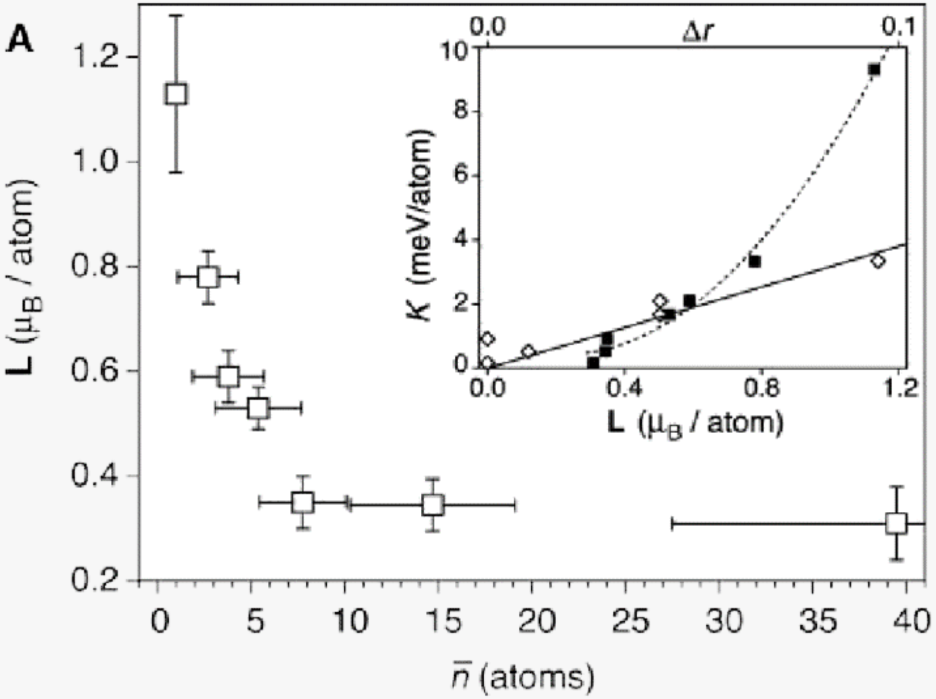
Example of system: sub-monolayer Co/Pt(997)



A. Dallmeyer et al., Phys.Rev.B 61(8), R5153 (2000)

Example of system: Co/Pt(111)



P. Gambardella et al., Science 300, 1130 (2003)

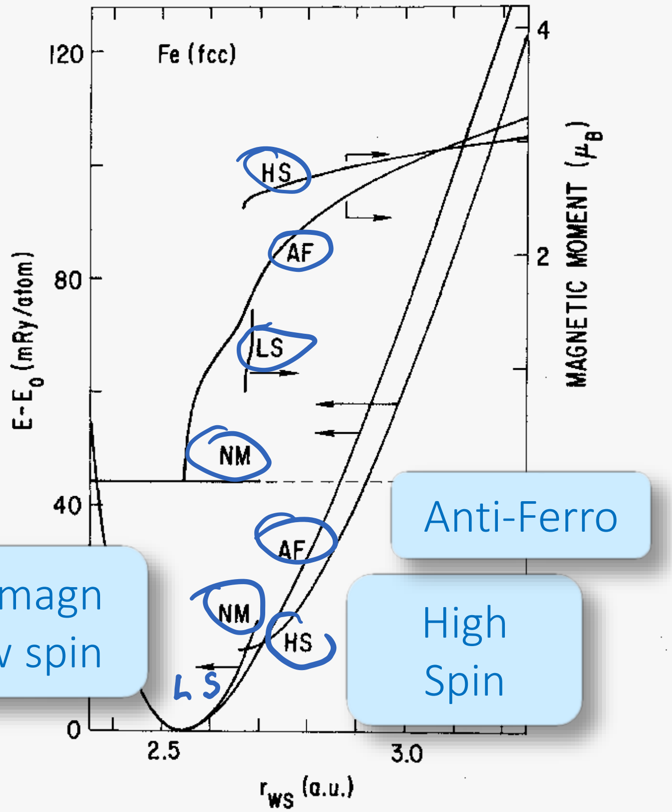
Conclusions

- From bulk to atoms: considerable increase of orbital moment
- 2 atoms closer to wire than 1 atom
- bi-atomic wire closer to surface than wire

Moments and orbitals – Change of magnetic order

Theory (bulk)

- fcc γ-Fe for T>1185K: non-magnetic
- ‘ground-state’: sensitive on strain

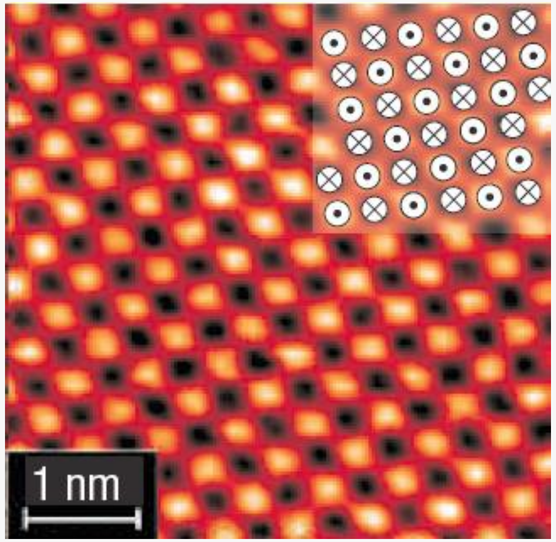


V. L. Moruzzi et al., PRB39, 6957 (1989)

See also: O.K. Andersen, Physica B 86, 249 (1977)

(Some) experiments in low dimensions

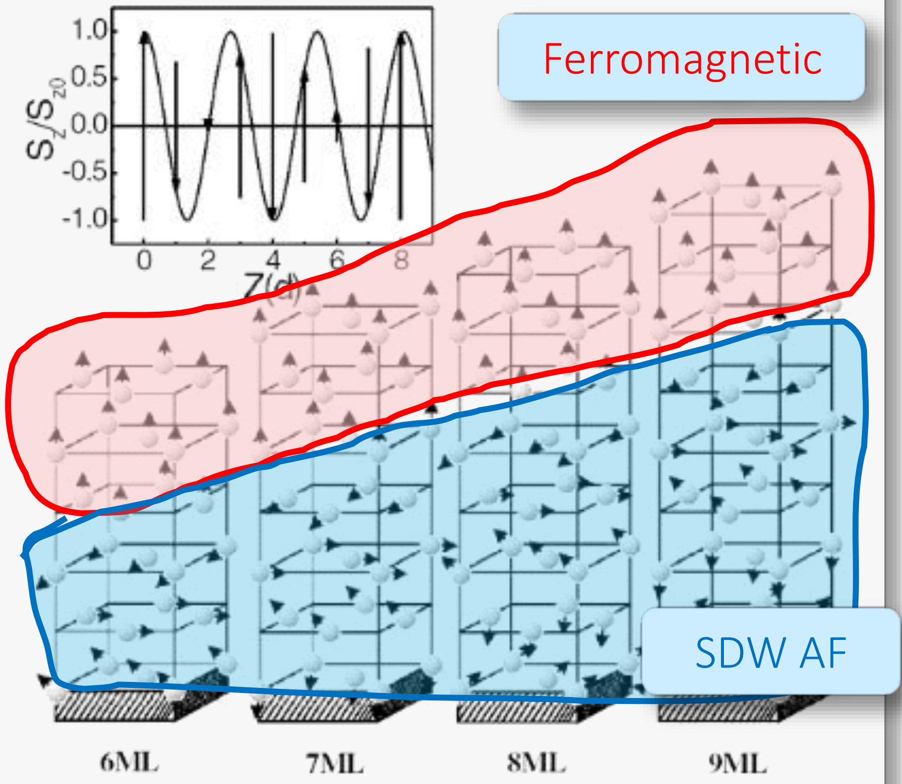
AF Fe(1ML)/W(001)



Antiferromagnetic domain (SP-STM)

M. Bode et al., Nat. Mater. 5, 477-481 (2006)

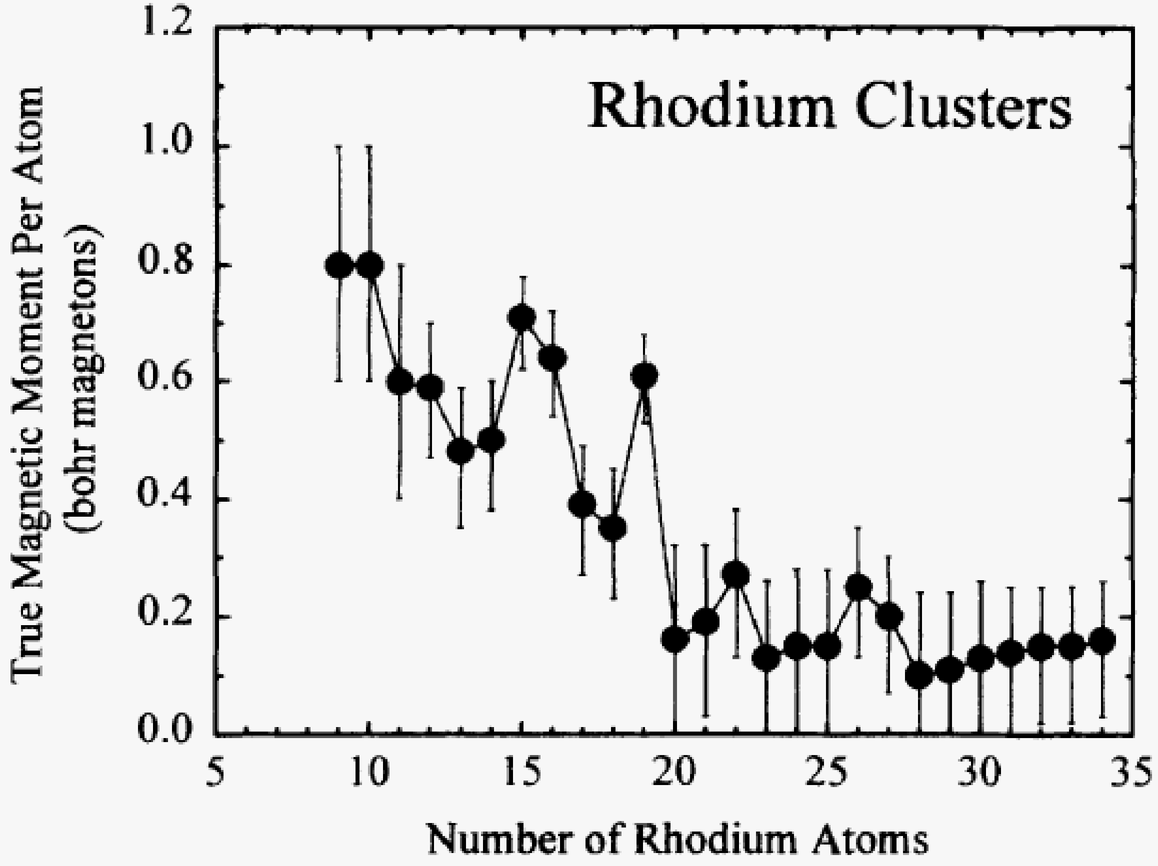
Spin-density-wave AF fcc Fe(001)



D. Qian et al., PRL87, 227204(2001)

See also V. Cros et al., Europhys. Lett. 49, 807 (2000)

Rh turning magnetic in small clusters



A. J. Cox et al., Magnetism in 4d-transition metal clusters, Phys. Rev. B 49, 12295 (1994)

Physics

- Narrowing of band
- Stoner criterium fullfilled
- Quantum size effects

Moments and orbitals – Quizz

Which phenomena depend on the electronic properties at the very interface?

1. Perpendicular magnetic anisotropy
2. Tunnel magneto-resistance
3. Shape anisotropy
4. Spin-orbit torques

Moments and orbitals – Quizz answers

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Which phenomena depend on the electronic properties at the very interface?

1. Perpendicular magnetic anisotropy — Strain/Magnetostriction, structural changes etc.
2. Tunnel magneto-resistance — Yes, but quantum size effect or electronic structure or barrier can matter
3. Shape anisotropy — See next part…
4. Spin-orbit torques — Rashba: yes – SHE + torque: no

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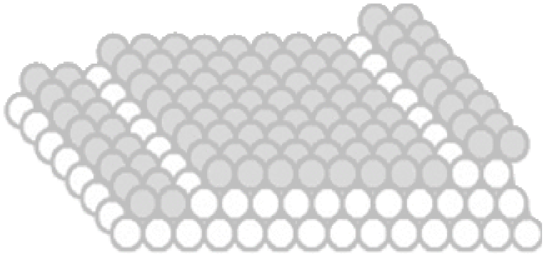
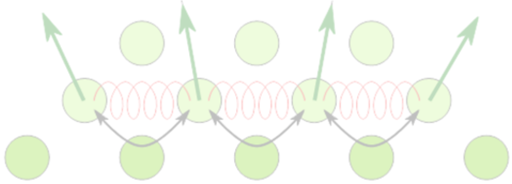
- Moments and orbitals

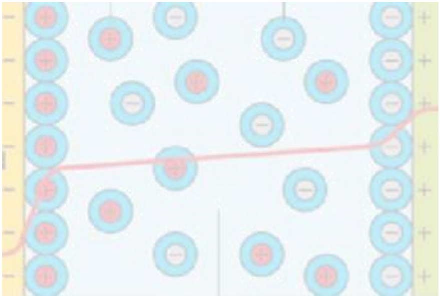


- Magnetic anisotropy

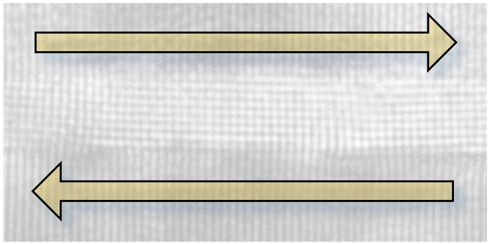
- Dzyaloshinskii-Moriya



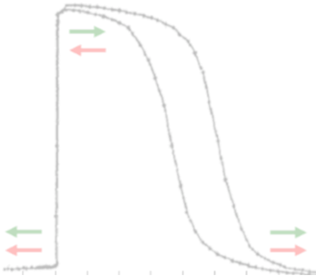
- Electric field effects



- Magneto-Transport

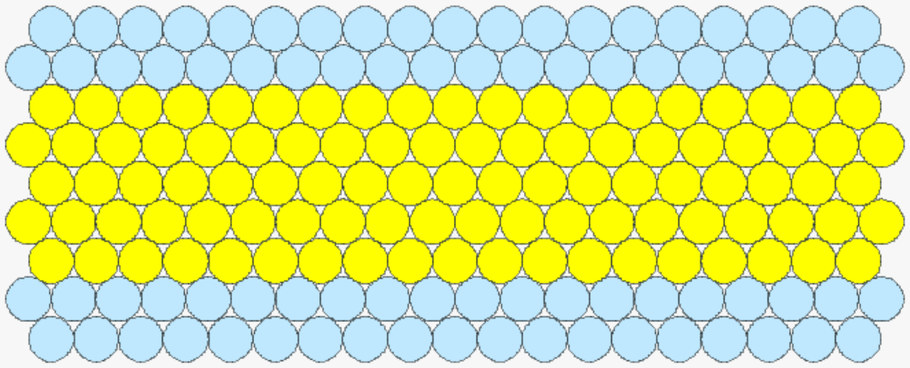


- Heterostructures



- Ordering and critical phenomena
  Bertrand Dupe
- Domains and domain walls
  Lukas Körber
- Magnetic anisotropy
  Franzisca Scheibel
- Electronic transport
  Peter Oppeneer

Simple picture: interfacial magnetic anisotropy



- Breaking of symmetry for surface/interface atoms
- Brings a correction to magnetocrystalline anisotropy

$$E_s = K_{s,1}\cos^2\theta + K_{s,2}\cos^4\theta + \cdots$$

L. Néel, J. Phys. Radium 15, 15 (1954),
Superficial magnetic anisotropy and orientational superstructures

This surface energy, of the order of 0.1 to 1 erg/cm2, is liable to play a significant role in the properties of ferromagnetic materials spread in elements of dimensions smaller than 100Å.

Visionary !!!

Seminal experimental hint

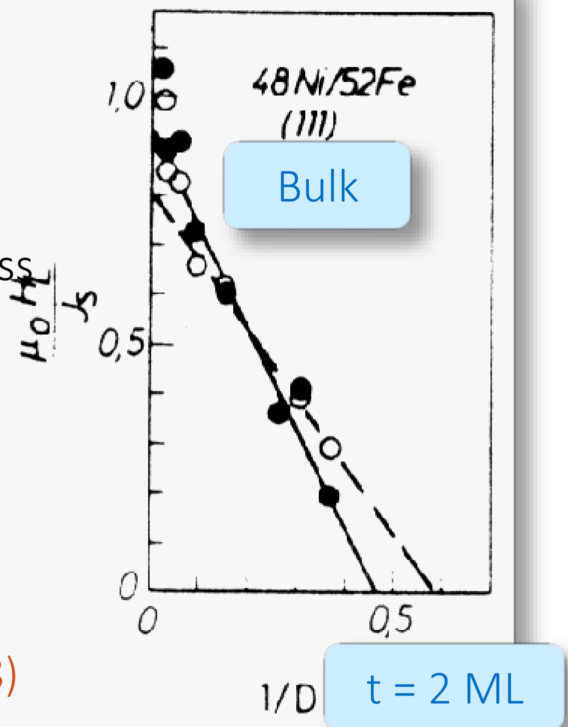
- Total anisotropy energy

$$\mathcal{E}(t) = K_V t + 2K_s$$

- Anisotropy per unit thickness

$$E(t) = K_V + \frac{2K_s}{t}$$

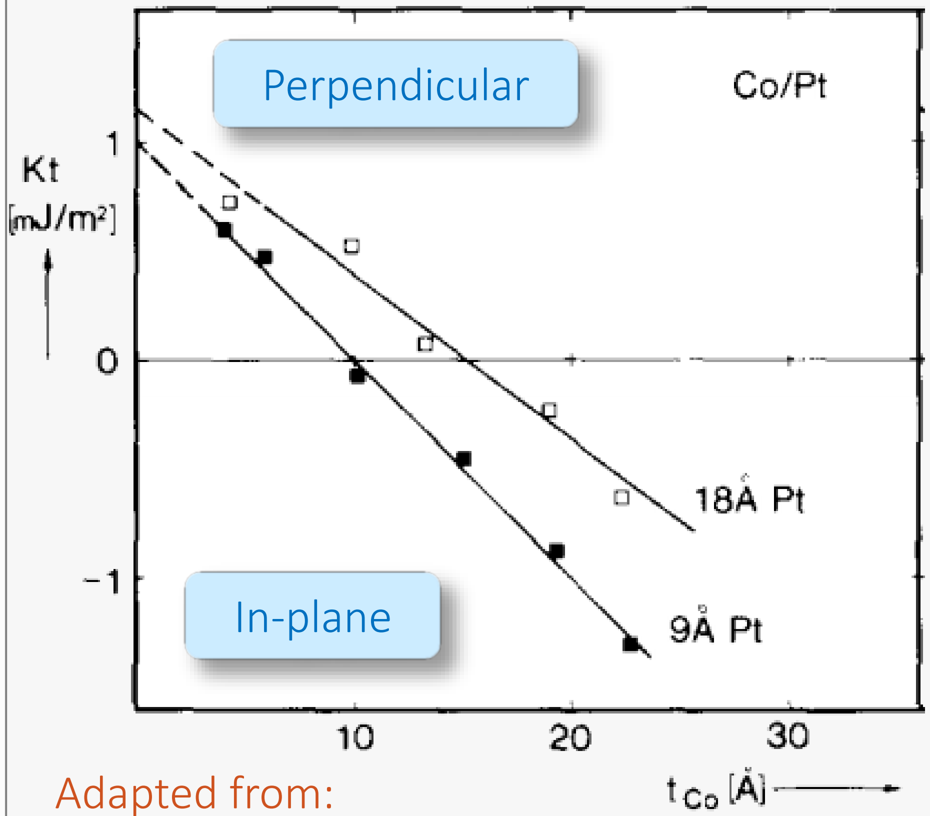
U. Gradmann and J. Müller,
Phys. Status Solidi 27, 313 (1968)



Lecture
Franzisca Scheibel

Magnetic anisotropy – Device relevance

Example of perpendicular magnetization



Adapted from:

F. J. A. den Broeder, JMMM 93, 562 (1991)

Note dependance on Pt thickness
→ Story is not so simple as interfacial anisotropy

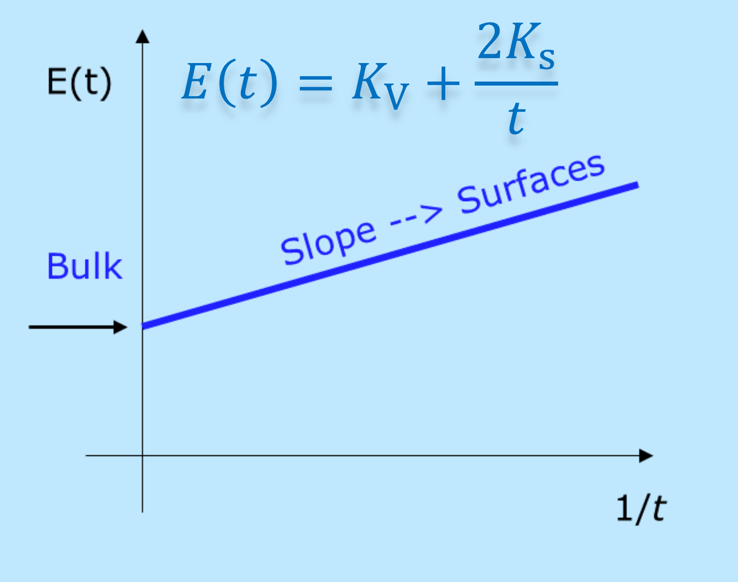
Figures

- Magnitude around $1\ \mathrm{mJ/m^2}$
- May promote perpendicular magnetization below thickness 1nm or so
- 80's & 90's: in contact with high spin-orbit materials (Au, Pt …)
- Since: Al_2O_3, MgO, graphene…

Device relevance

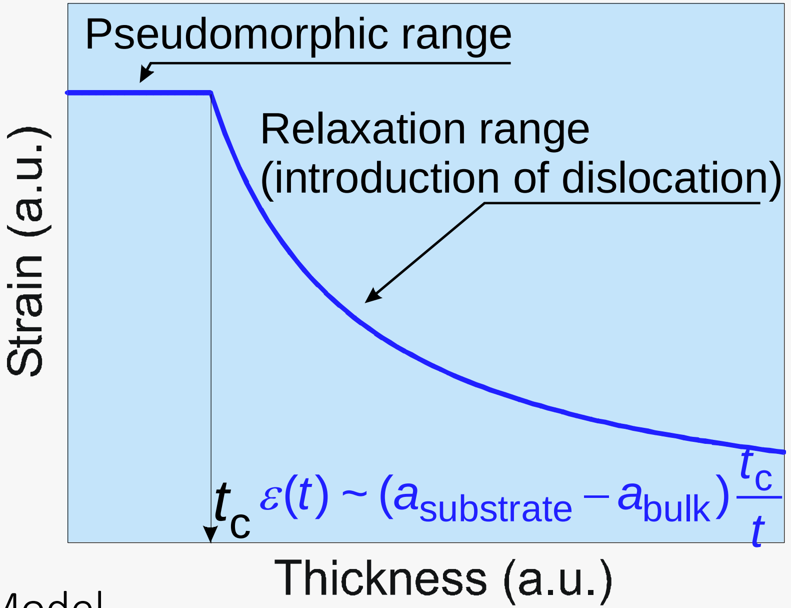
- Provide larger energy barriers than IP anisotropy
- Better scalable at small technological nodes
- Lower write current lower for a given energy barrier
- Interface with oxide provides compatibility with tunnel magneto-resistance

Surface anisotropy alone



→ Bulk and surface anisotropy infered from intercept with *y* axis and slope

Inverse magnetostriction in films



Model

W. A. Jesser, Phys. Stat. Sol. 19, 95 (1967)

Experiments

U. Gradmann, Appl. Phys.3, 161 (1974)

→ Induces a 1/t variation of anisotropy, similar to interface contribution

C. Chappert and P. Bruno., JAP64, 5736 (1988)

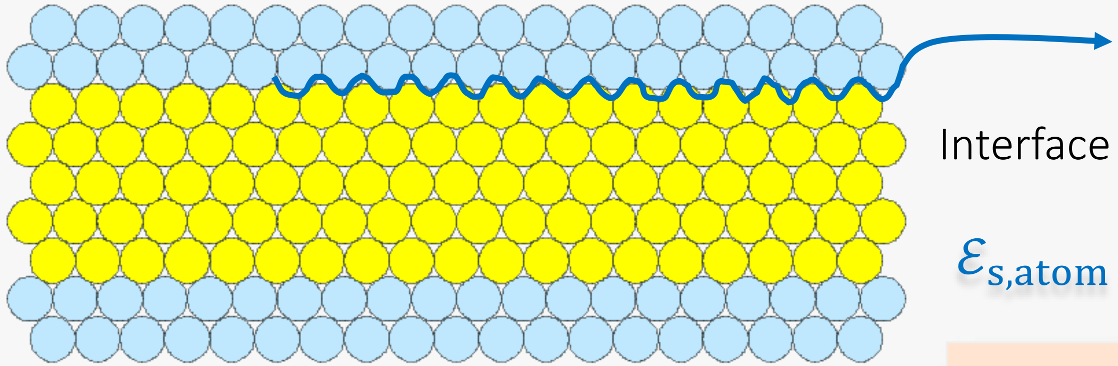
Other effects…

- Interface roughness and intermixing
- Thickness-dependent thermal decay (when measured at T > 0K)
- Non-linearity of magneto-elastic coupling coefficients

D. Sander, Rep. Prog. Phys. 62, 809 (1999)

U. Gradmann, Magnetism in ultrathin transition metal films, in Handbook of magnetic materials, vol. 7, Buschow, K. H. J. (Ed.), Elsevier (1993)

Surface contribution to shape anisotropy



Interface dipolar anisotropy (per interface)

$$\mathcal{E}_{\mathrm{s,atom}} = -\mathrm{k_s}\delta\left(\frac{1}{2}\mu_0 M_s^2\right)\cos^2(\theta)$$

- Decreases slab demag coeff 1
- Change is large for open surface

Surface	k_s
fcc(111)	0.0344
fcc(001)	0.1178
hcc(110)	0.0383
bcc(001)	0.2187
hcp(0001)	0.0338

H.J.G. Draaisma et al., JAP 64, 3610 (1988)

Notes

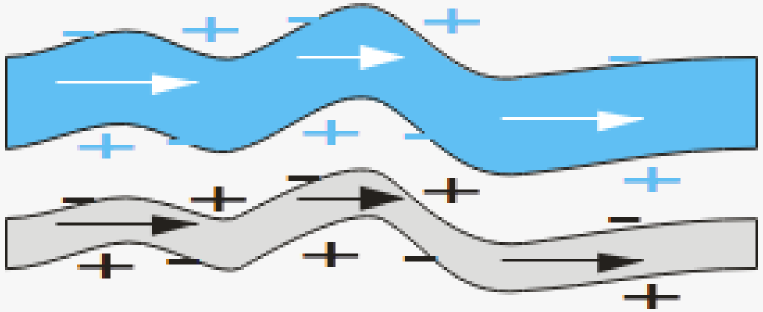
- Included in Néel's pair interaction model from 1954 !
- Specific case of the dipolar crystalline anisotropy
- This effect is expected to be large in VdW materials, due to the large difference of in-plane versus out-of-plane distance between magnetic ions

P. Bruno, Physical origins and theoretical models of magnetic anisotropy, Ferienkurse des Forschungszentrums Jülich, Ch.24 (1993)

Lecture
Anders Bergman

Magnetic anisotropy – Roughness and shape anisotropy

2D surfaces – Orange-peel coupling



- Physics: surface roughness induces surface charges
- Induces non-zero in-plane demag coefficient
- Two stacked layers are coupled

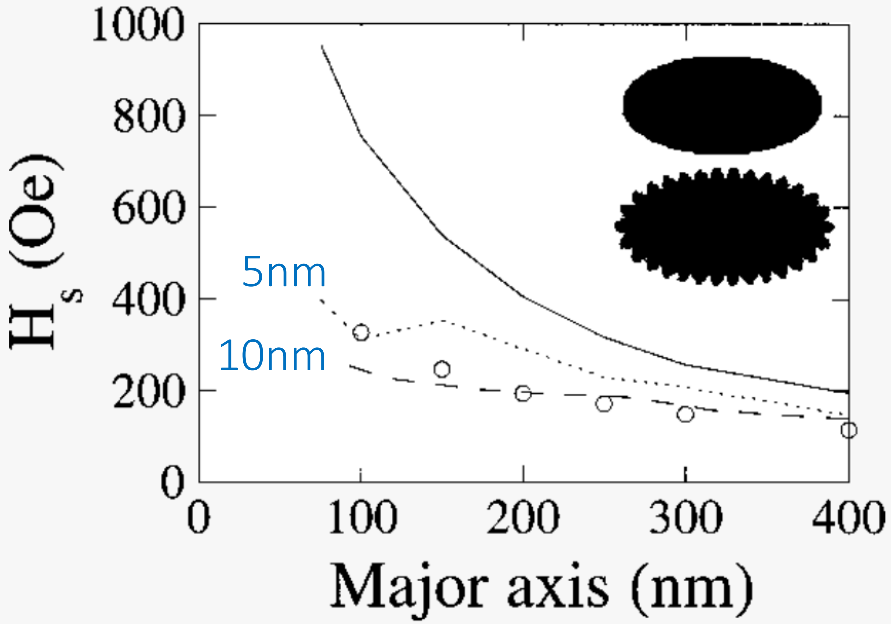
Seminal, in-plane (valid for thick films)
L. Néel, C. R. Acad. Sci. 255, 1676 (1962)

In-plane, for any thickness
J. C. S. Kools et al., J. Appl. Phys. 85, 4466 (1999)

Out-of-plane, for any thickness
J. Moritz et al., Europhys. Lett. 65, 123 (2004)

- **May need to be compensated to avoid coupling (eg: in memories, sensors…)**

1D boundaries – Decreased demag coefficients



- Dipolar fields are short-ranged in 2D
- Edge roughness efficiently reduces demag fields (scales with film thickness)

R. P. Cowburn et al., J. Appl. Phys. 87, 7067 (2000)

- **May significantly reduce energy barriers**

Magnetic anisotropy – Quizz

Which statements are true ?

1. Perpendicular magnetic anisotropy is purely interfacial

2. Shape anisotropy is affected by roughness

3. Any film turns perpendicular if sufficiently thin

4. The demag coefficient of a single-layer 2D material is 1

Magnetic anisotropy – Quizz answers

spintec
SPIN IN ELECTRONICS

Which statements are true ?

1. Perpendicular magnetic anisotropy is purely interfacial — Strain/Magnetostriction, structural changes, non-magn material etc.
2. Shape anisotropy is affected by roughness — Dipolar crystalline anisotropy
3. Any film turns perpendicular if sufficiently thin — Ks may be of wrong sign, or too small
4. The demag coefficient of a single-layer 2D material is 1 — Magnetization is undefined

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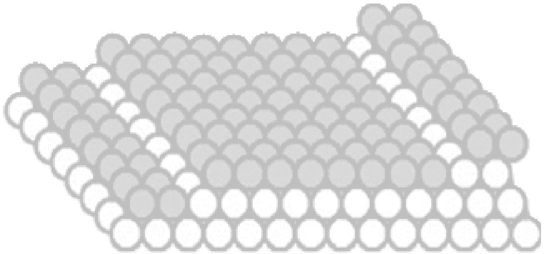
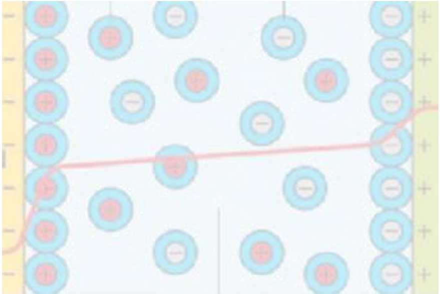
- Moments and orbitals

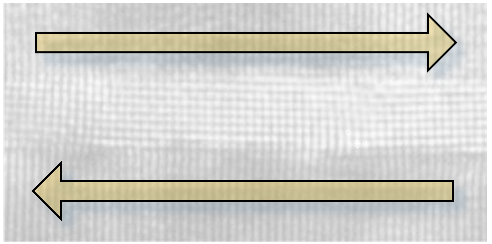


- Electric field effects

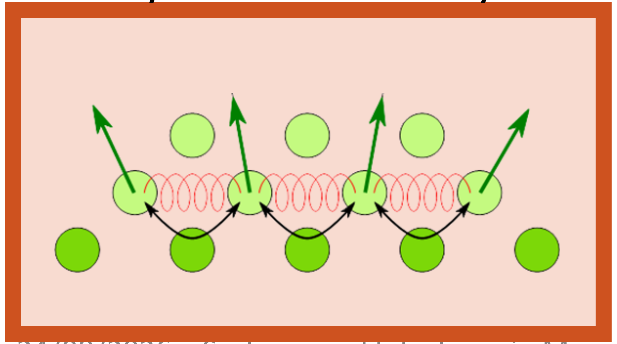


- Magnetic anisotropy

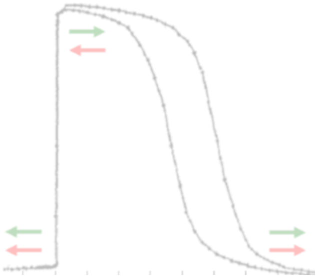
- Magneto-Transport



- Dzyaloshinskii-Moriya



- Heterostructures

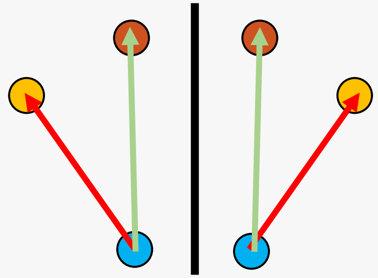


Dzyaloshinskii-Moriya interaction – Chirality

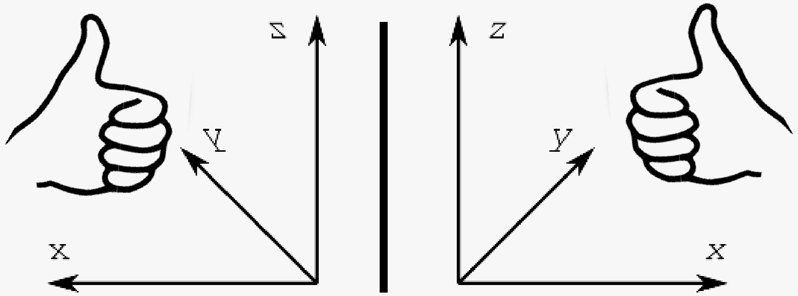
Definition

An object that cannot be superimposed onto itself, following a mirror symmetry

- Two vectors do not allow chirality (the image can be flipped 180°)

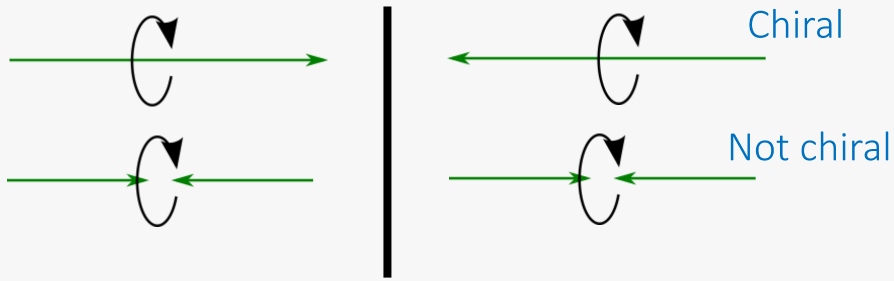


- Three vectors are required for chirality



(Counter-)examples

- Not all curling structures are chiral

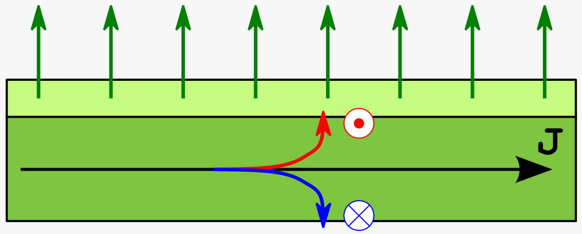


- Competition or promotion with chiral physical effects, i.e., those involving a vector product

LLG equation

$$\frac{d\mathbf{m}}{dt} = -|\gamma_0|\mathbf{m}\times\mathbf{H} + \alpha\mathbf{m}\times\frac{d\mathbf{m}}{dt}$$

Lecture Lukas Körber



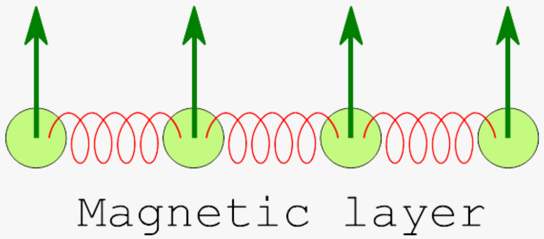
Spin-orbit torques

Lecture Peter Oppeneer

- Loss of inversion symmertry
- Interfaces allow chiral effects

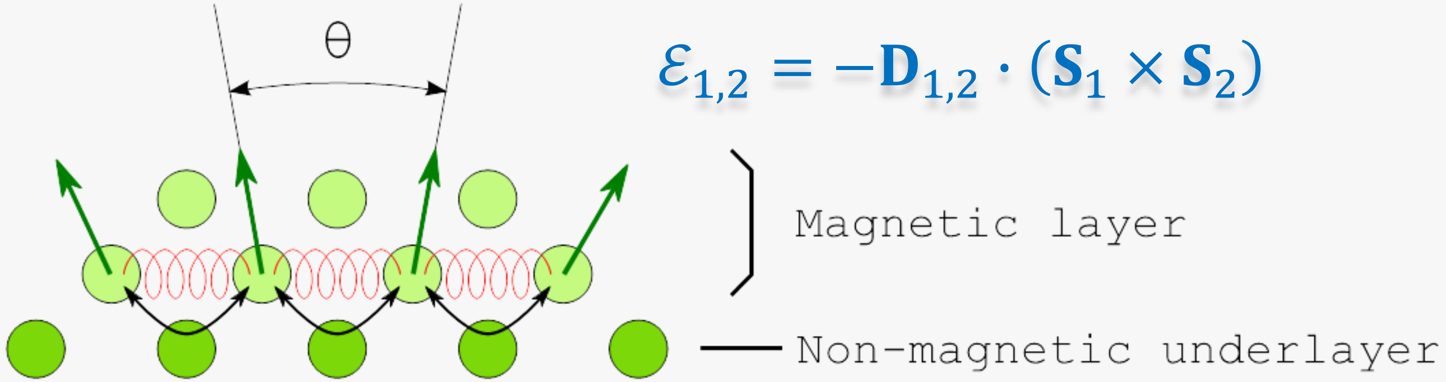
Magnetic exchange

$$\mathcal{E}_{1,2} = -J_{1,2}\,\mathbf{S}_1 \cdot \mathbf{S}_2$$

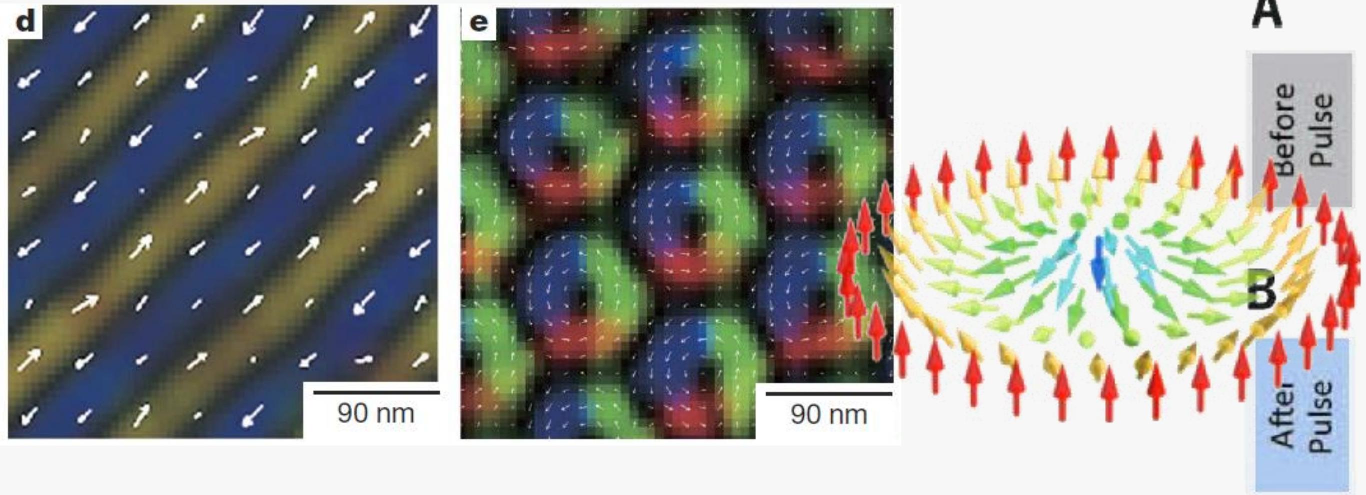


The Dzyaloshinskii-Moriya interaction (DMI)

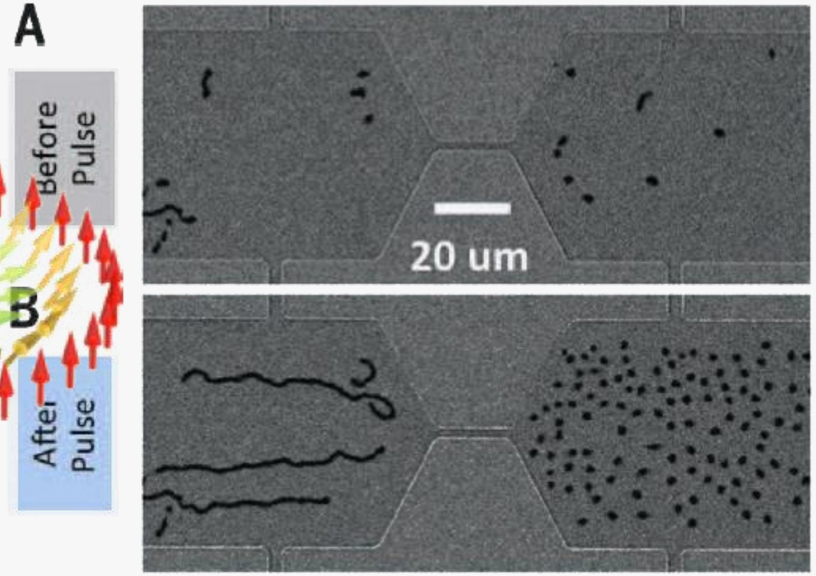
$$\mathcal{E}_{1,2} = -\mathbf{D}_{1,2} \cdot (\mathbf{S}_1 \times \mathbf{S}_2)$$



Chiral magnetization textures: spirals and skyrmions



X. Z. Yu et al., Nature 465, 901 (2010)

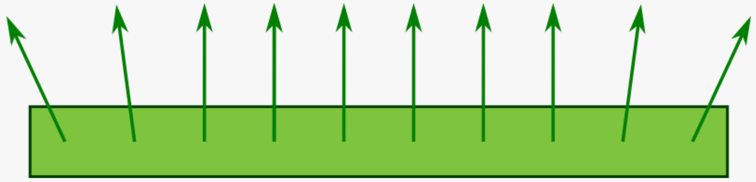


W. Jiang et al., Science 349, 283 (2015)

Lecture Lukas Körber

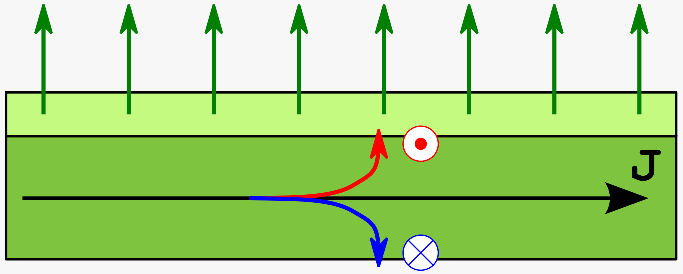
Physics of edge tilting

- Second-order cost in magnetic anisotropy to deviate from perpendicular magnetization
- First-order gain in DMI for a lateral magnetization gradient



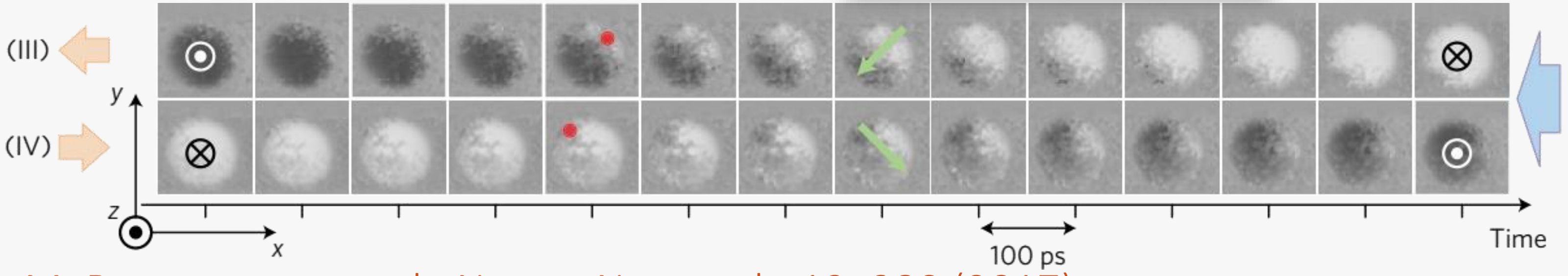
Magnetization tilt at edges

Significance: deterministic edge nucleation with SOT



- Spin-orbit torque + DMI edge tilt induce nucleation at a specific location

Time-resolved TXM



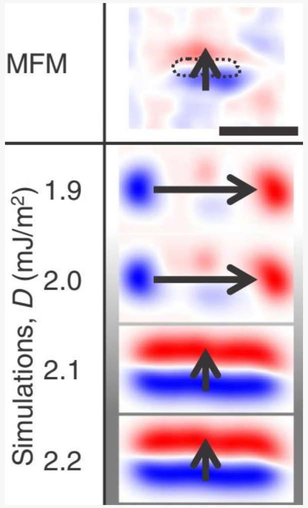
M. Baumgartner et al., Nature Nanotech. 12, 980 (2017)

Significance: contribution to in-plane shape anisotropy

- Tilt only at edges perpendicular to magnetization
- Tilt induces a gain of energy, competing with demag

Magnetization rotates along the short axis for string-enough DMI or small-enough size

M. Cubukcu et al? Phys. Rev. B 93, 020401 (2016)



Which statements are true ?

1. A Pt\Co\Pt film can display DMI

2. DMI matters only for perpendicularly-magnetized films

Dzyaloshinskii-Moriya interaction – Quizz answers

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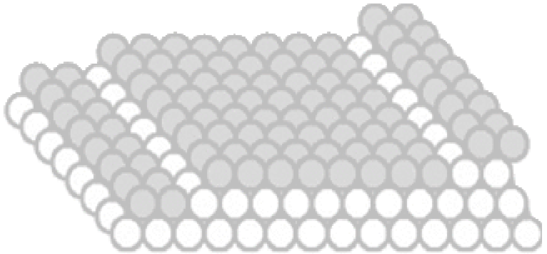
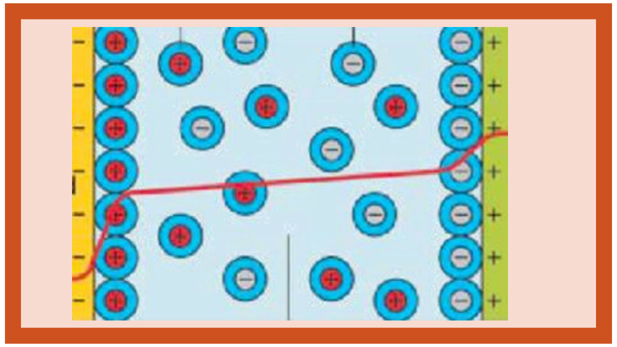
Which statements are true ?

1. A Pt\Co\Pt film can display DMI — Growth can induce an asymmetry between the top and bottom interfaces (structure, alloying…)
2. DMI matters only for perpendicularly-magnetized films — Yes, but quantum size effect or electronic structure or barrier can matter

- Moments and orbitals

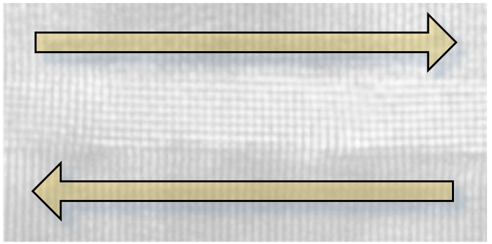


- Electric field effects

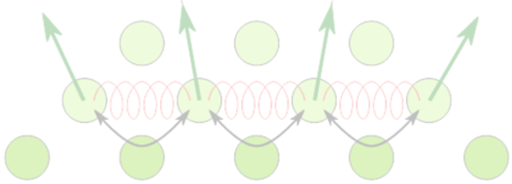


- Magnetic anisotropy

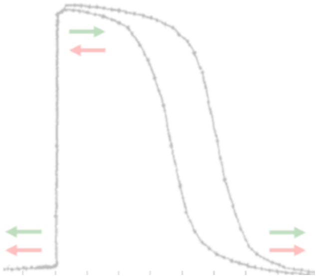
- Magneto-Transport



- Dzyaloshinskii-Moriya



- Heterostructures

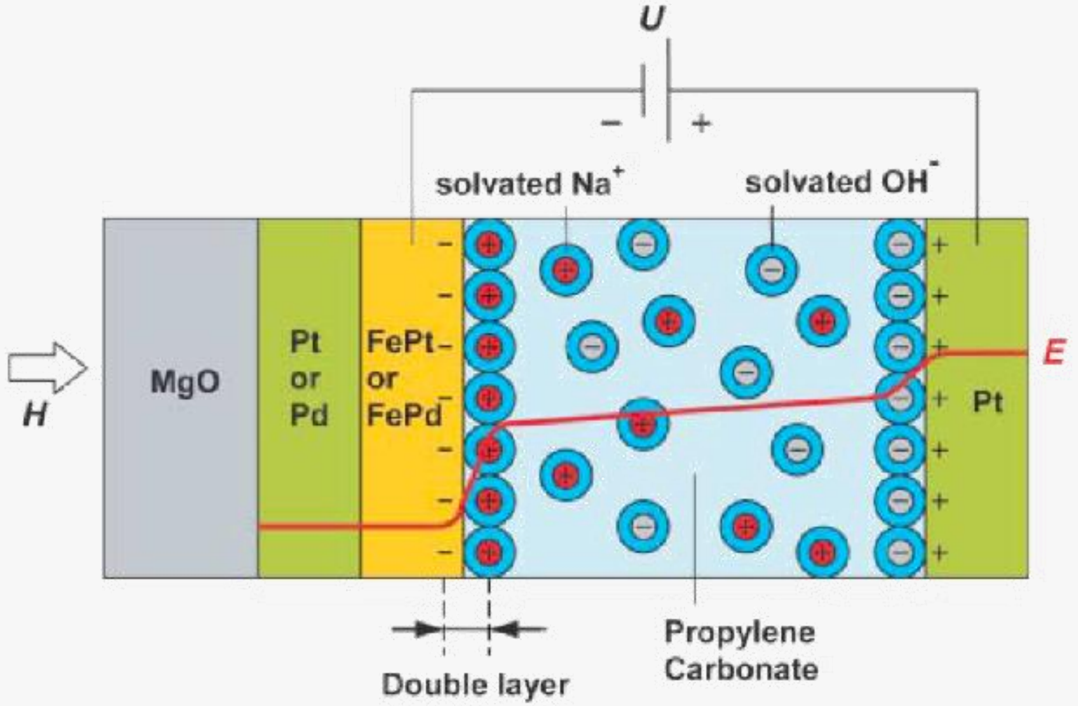


Covered in other lectures

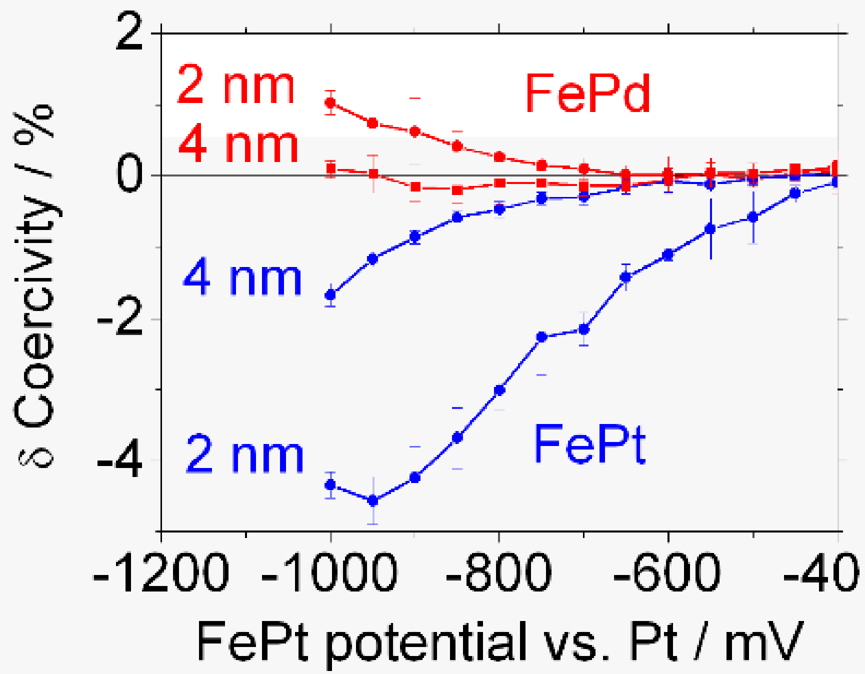
- Ordering and critical phenomena
  Bertrand Dupe
- Domains and domain walls
  Lukas Körber
- Magnetic anisotropy
  Franzisca Scheibel
- Electronic transport
  Peter Oppeneer

Seminal report

- Enhanced E-field thanks to electrolyte



- Slight (relative) change of coercivity



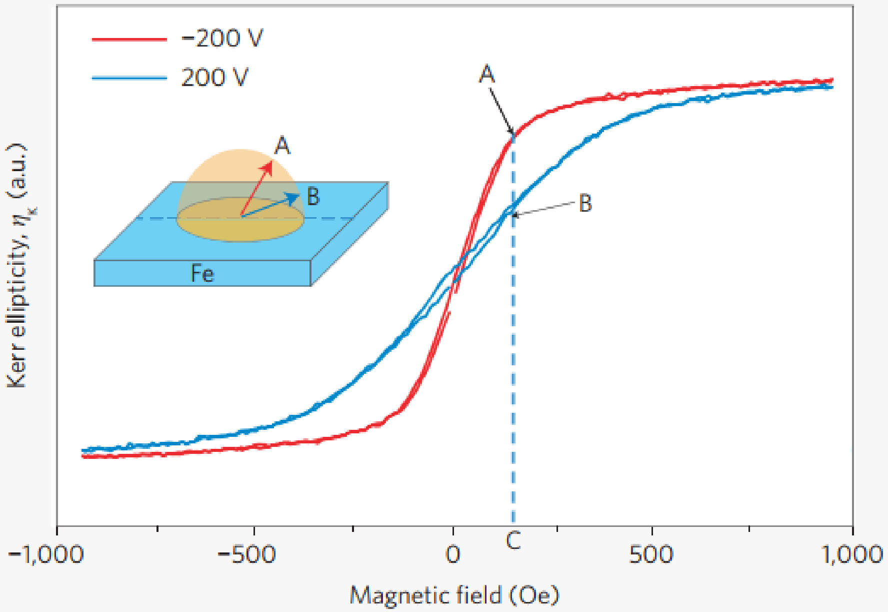
- Effect was not expected for metals, due to short screening length
- Relative change of coercivity is weak as coercivity is large

M. Weisheit et al., Science 315, 349 (2007)

Electric field – Control of magnetic anisotropy (VCMA)

Progress

Au\Fe(2-4ML)\MgO



T. Murayama et al., Nat. Nanotech. 4, 158 (2009)

- Considering a system close to the spin-reorientation transition enhances the relative response
- Pure electric effect: weak and reversible
- Ion migration (magneto-ionic effect): strong and remanent

Function/Device relevance

- Excite magnetization: precessional switching or ferromagnetic resonance

  Y. Shiota et al., Nat. Mater. 11, 39 (2012)

  T. Nozaki et al., Nat. Phys. 9, 491 (2012)

- Electric-field dc bias to favor magnetization switching with spin-transfer torque:
  VCMA operation of MRAM reduces power consumption

  Y. T. Liu et al., J. Appl. Phys. 122, 133907 (2017)

Electric field – Control of DMI

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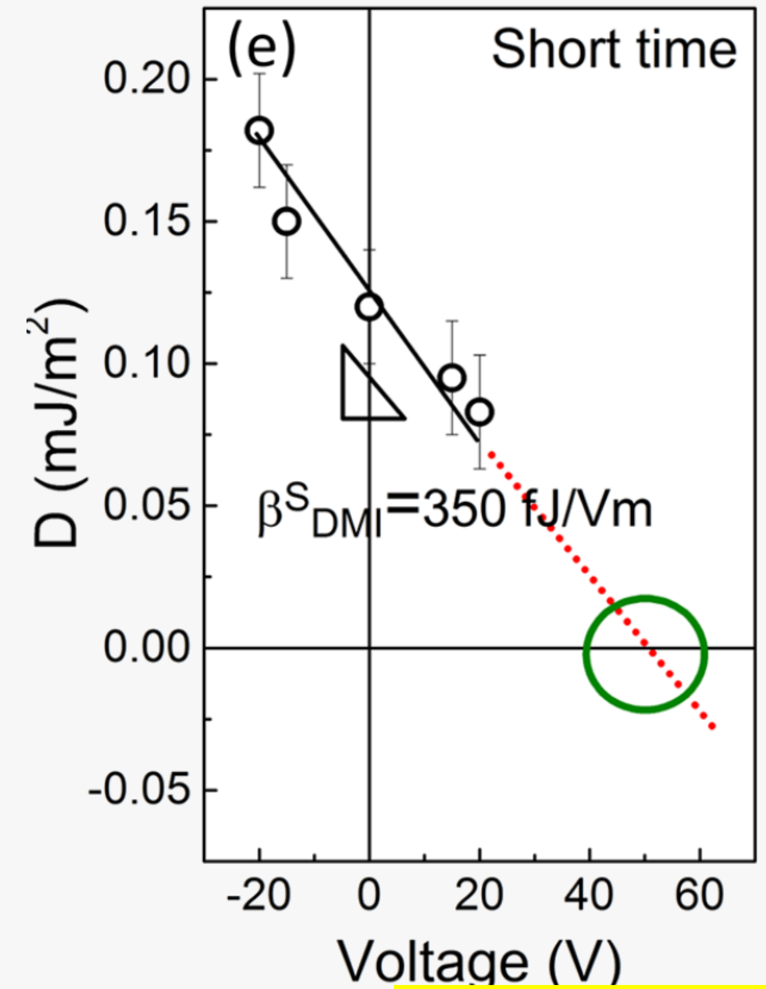
Control of DMI

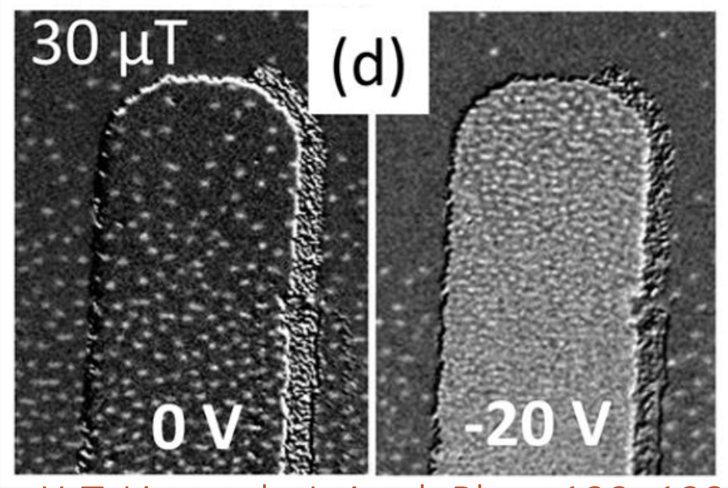
Ta\CoFeB\TaOx



BLS spectroscopy

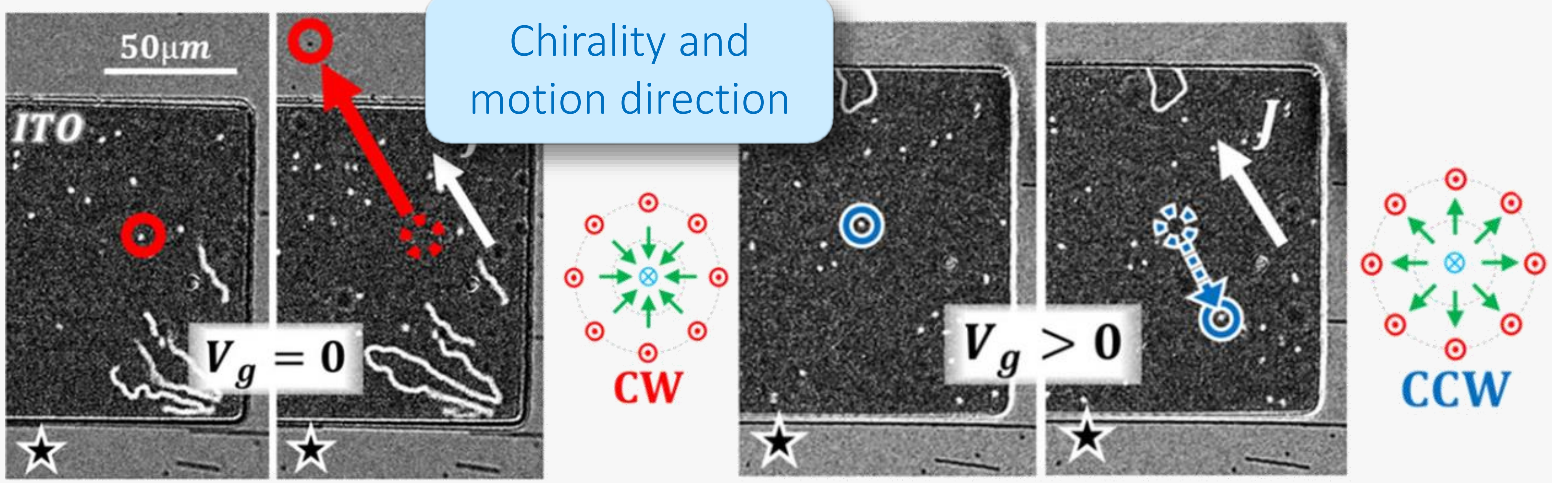
Lecture
Marco Coisson

Functionality : control of skyrmions



Nucleation / Annihilation

Y. T. Liu et al., J. Appl. Phys. 122, 133907 (2017)



Chirality and motion direction

C. E. Fillion et al., Nat. Comm. 13, 5257 (2022)

Electric field – Quizz

Which statements are true ?

1. Electric-field effects are not remanent
2. Electric field effects inject current in the layer

Electric field – Quizz answers

Which statements are true ?

1. Electric-field effects are not remanent — They are, in the case of ionic migration
2. Electric field effects inject current in the layer — Dipolar crystalline anisotropy

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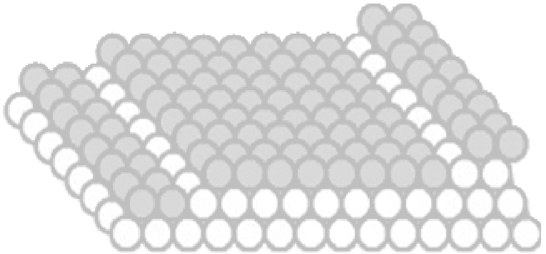
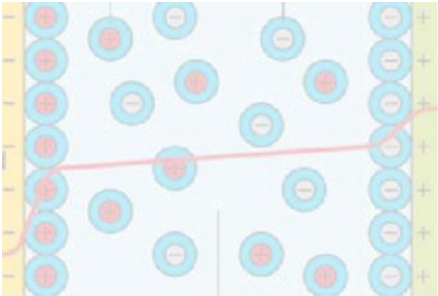
- Moments and orbitals

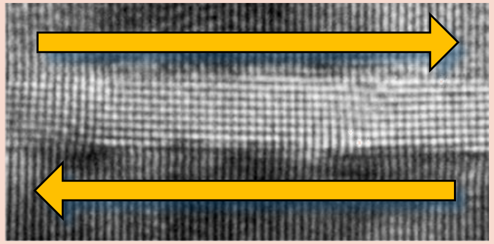


- Electric field effects

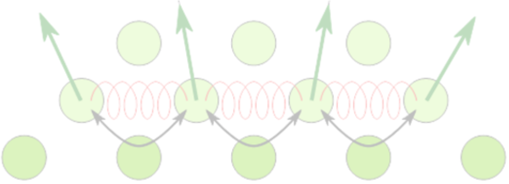


- Magnetic anisotropy

- Magneto-Transport



- Dzyaloshinskii-Moriya



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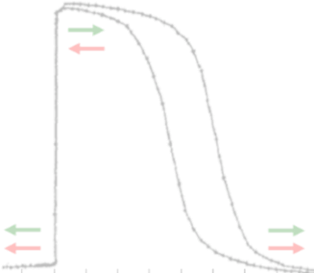
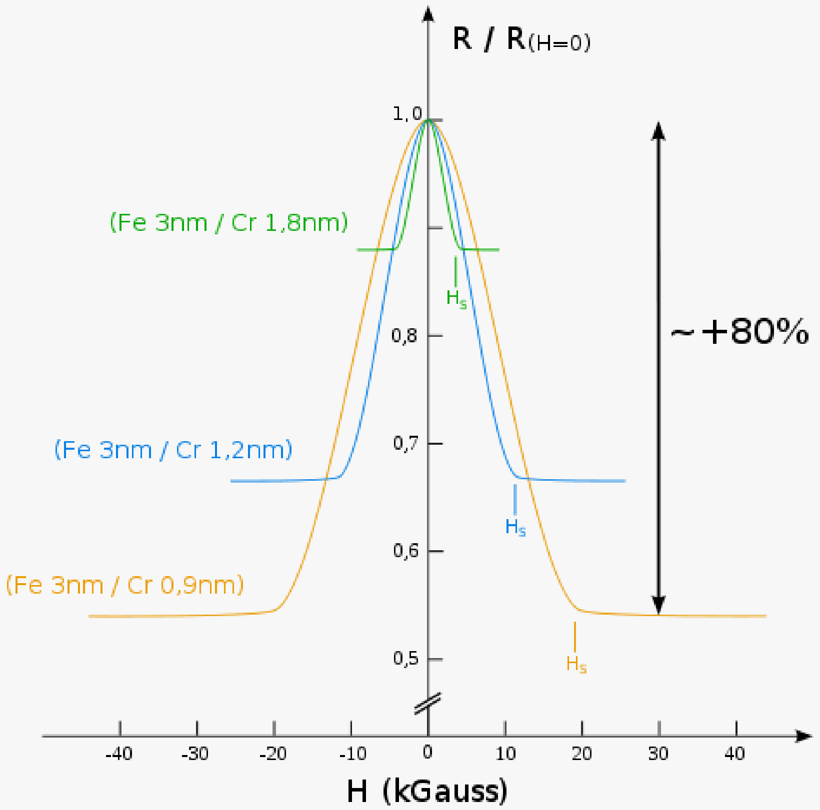


Giant magneto-resistance



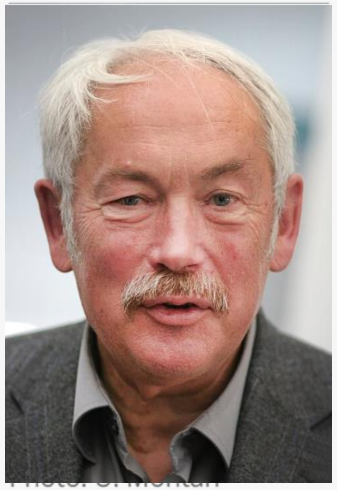
A.Fert et al, PRL (1988);

P.Grunberg et al, patent (1988) +PRB (1989)

The Nobel Prize in Physics 2007

Albert Fert

Prize share: 1/2



Peter Grünberg

Prize share: 1/2

The Nobel Prize in Physics 2007 was awarded jointly to Albert Fert and Peter Grünberg *"for the discovery of Giant Magnetoresistance"*

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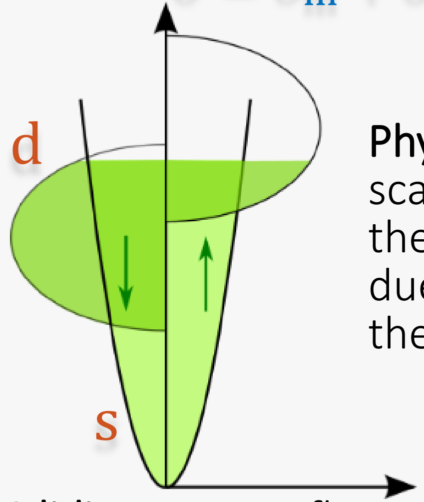
Two-current model

Mott 1930

- **Model**: electrons with spin up and down contribute to two independent conduction channels $\sigma = \sigma_\mathrm{m} + \sigma_\mathrm{M}$



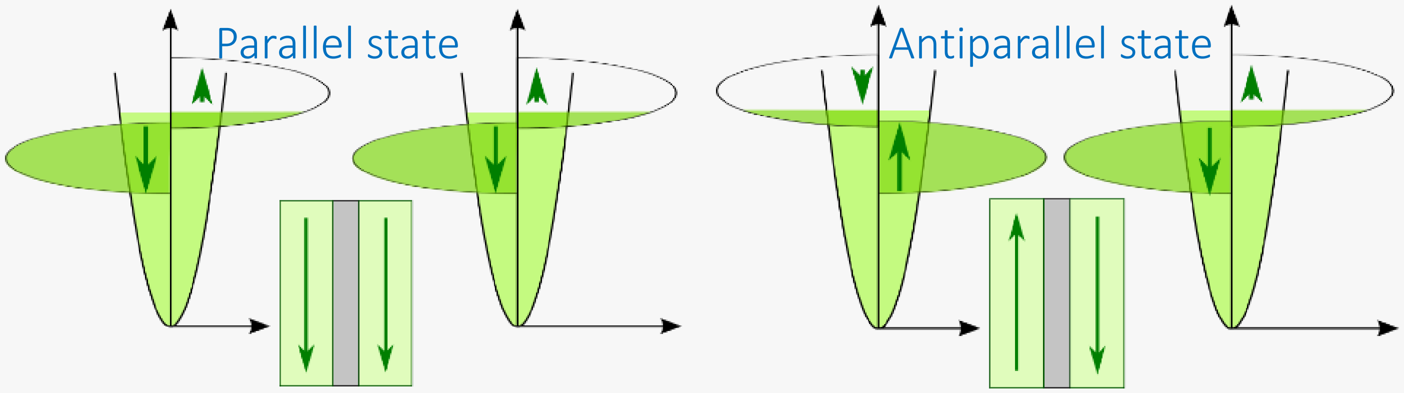
Physics: the s-d scattering is different in the two spin channels, due to the splitting of the d bands.

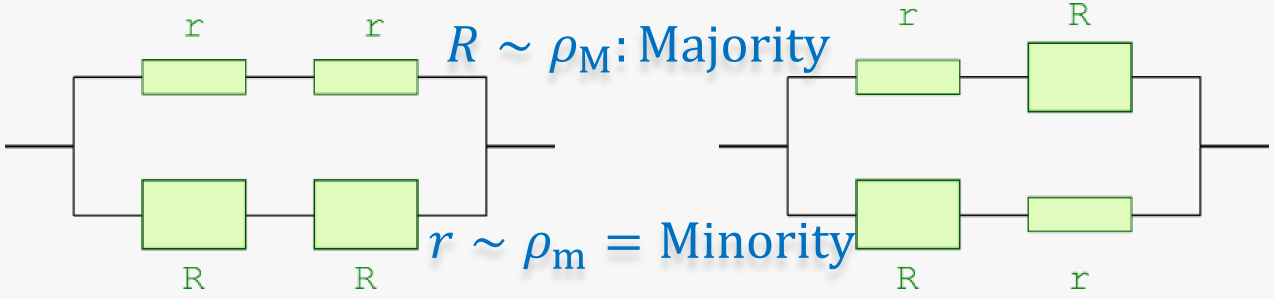
- **Validity**: no spin-flip, rather low temperature (no magnons and phonons)

- **Define**: asymmetry of resistivity $\alpha = \dfrac{\rho_\mathrm{m}}{\rho_\mathrm{M}} = \dfrac{\sigma_\mathrm{M}}{\sigma_\mathrm{m}}$

$$\rho = \frac{1}{\sigma} = \frac{\rho_\mathrm{M}\rho_\mathrm{m}}{\rho_\mathrm{M} + \rho_\mathrm{m}} = \frac{\alpha}{1+\alpha^2}$$

Handwaving model for GMR





$R \sim \rho_\mathrm{M}$: Majority

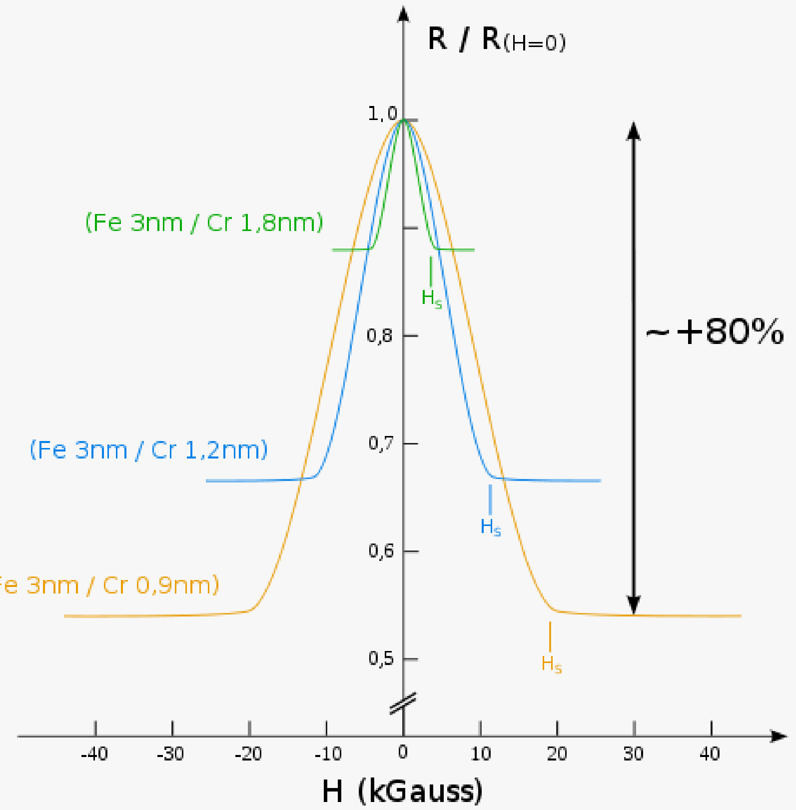
$r \sim \rho_\mathrm{m}$ = Minority

$$R_\mathrm{P} = \frac{2rR}{r+R}$$

$$R_\mathrm{AP} = \frac{r+R}{2}$$

$$\mathrm{GMR} = \frac{R_\mathrm{AP} - R_\mathrm{P}}{R_\mathrm{P}} = \frac{(\alpha-1)^2}{4\alpha}$$

Example (Seminal, 1986)

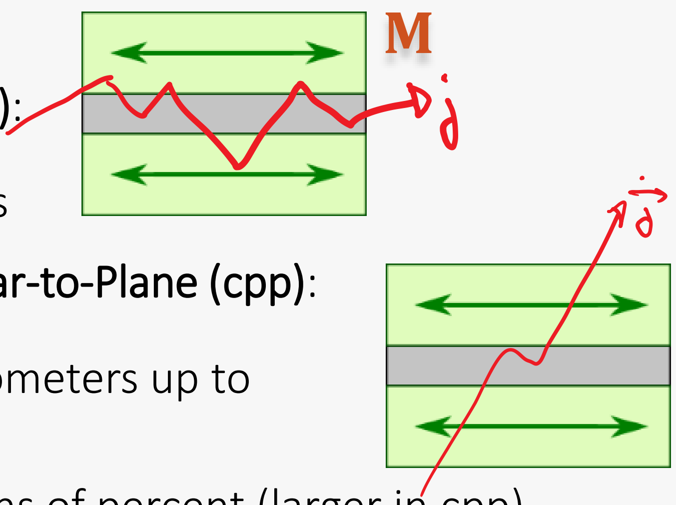


A.Fert et al, PRL (1988);

P.Grunberg et al, patent (1988) +PRB (1989)

Facts

- **Current-In-Plane (cip)**: mean free path → A few nanometers
- **Current-Perpendicular-to-Plane (cpp)**: spin diffusion length → Hundreds of nanometers up to micrometers
- Magnitude: a few tens of percent (larger in cpp)

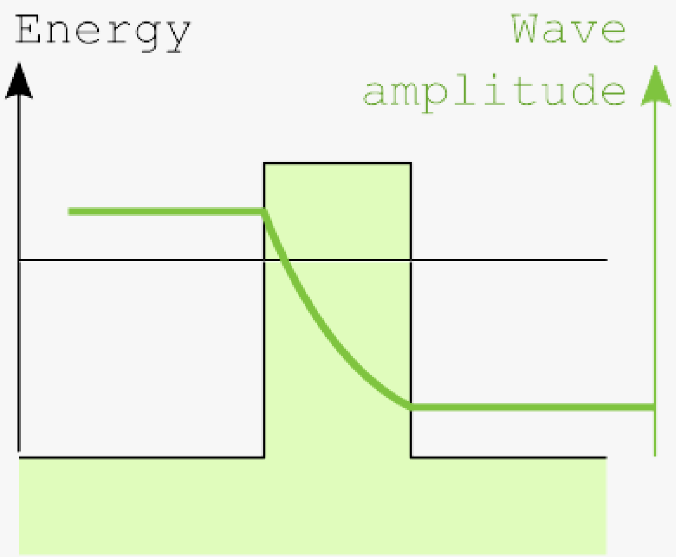


Spin accumulation

- Electrons with minority spin accumulate in front of a ferromagnetic layer (cpp geometry)
- May be modeled by spin-dependent potential and diffusion equations
- Possible implementation of lateral spin valves and GMR

Magneto-transport – Tunnel Magneto-Resistance

Tunneling transport

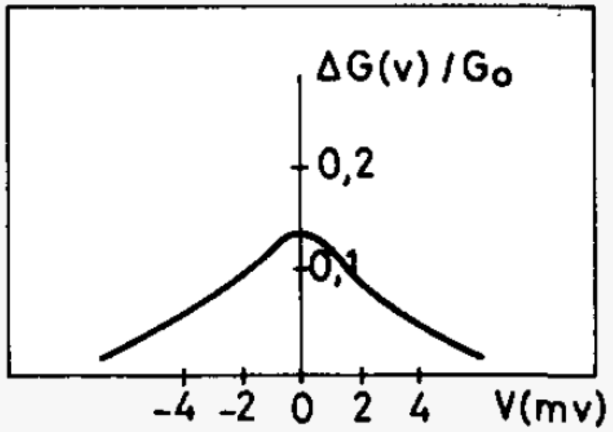


- Exponential decay of wave functions in the barrier

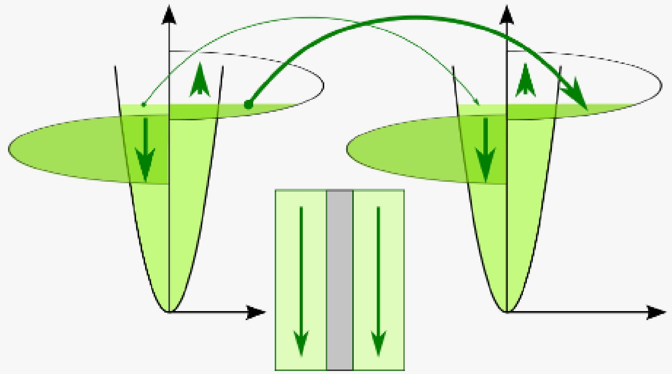
- Used in high sensitivity sensors, memory reading, HDD head…
- TMR should be bound to circa 50 % (3d ferromagnets)

Tunneling Magneto-resistance

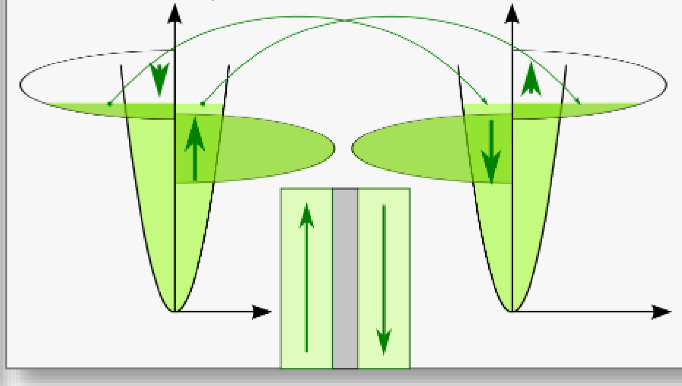
- Discovery at 4K in Fe/Ga/Fe thin-film stacks
  M. Julliere, Phys. Lett. 54A, 3, 225 (1975)
- Revival at 300K in F / Al_2O_3 / F stacks
  J. S. Moodera, Phys. Rev. Lett. 74, 3273 (1995)



Parallel state (P)



Antiparallel state (AP)



- Define polarization at the Fermi level

$$P = \frac{D_{\mathrm{Maj}} - D_{\mathrm{Min}}}{D_{\mathrm{Maj}} + D_{\mathrm{Min}}}$$

- Define the TMR ratio

$$\mathrm{TMR} = \frac{R_{\mathrm{AP}} - R_{\mathrm{P}}}{R_{\mathrm{P}}} = \frac{2P^2}{1 - P^2}$$

Need to name differently spins up/down, versus minority/majority

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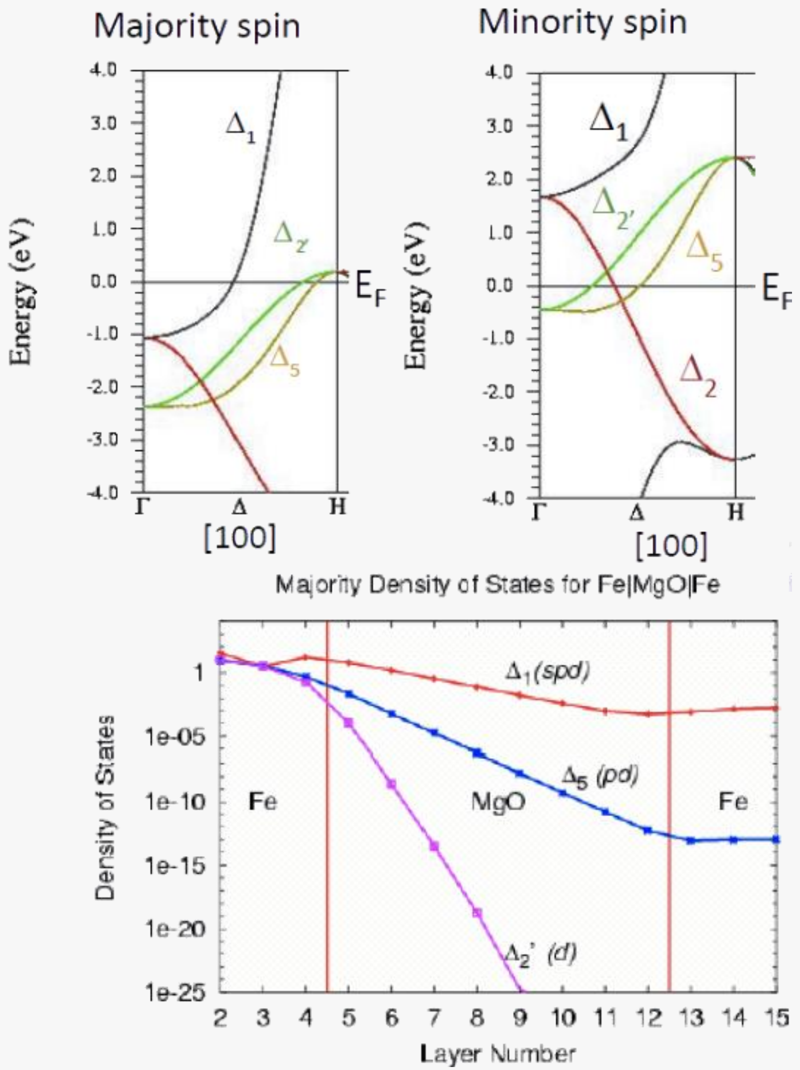
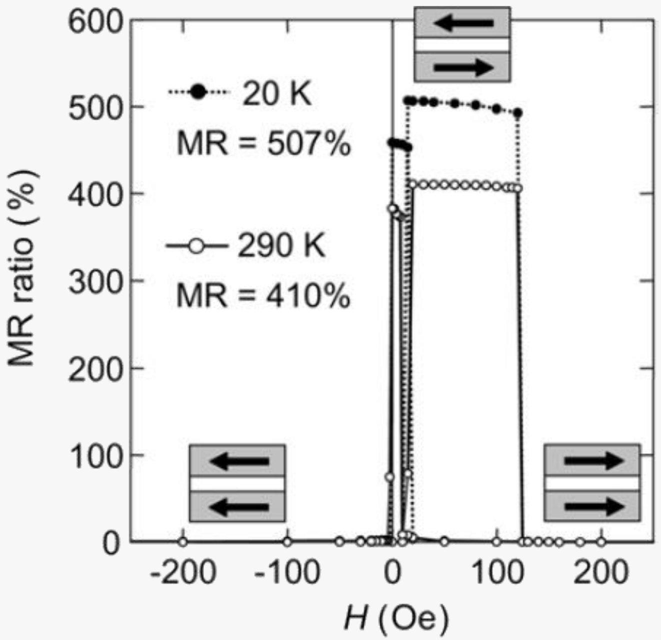
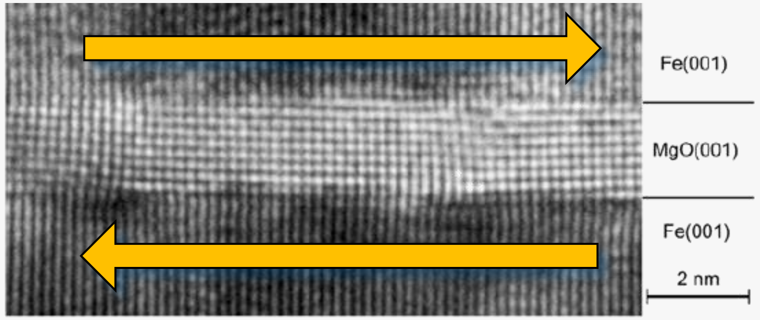
Prediction of spin filtering for Fe/MgO/Fe



F. Butler et. al., Phys. Rev. B 63, 220403 (2001)

Realization of spin filtering for MgO(001) barriers





S. Yuasa, J. Phys. D 40, R337 (2007)

500% TMR ratio !

- Interfacial structural effect: crystallization of CoFe with suitable (001) texture from amorphous CoFeB
- Not a transistor, yet enough to discriminate On/Off states
- Magnetic Tunnel Junctions (MTJs) are the key building block of solid-state magnetic memories

Spin-transfer torque: theoretical prediction

$$P_{\mathrm{trans}} = P \frac{J}{|e|} \mu_{\mathrm{B}}$$

$$\frac{\mathrm{d}\mathbf{m}_2}{\mathrm{d}t} = -|\gamma_0| \mathbf{m}_2 \times \mathbf{H}_{\mathrm{eff}} + \alpha \mathbf{m}_2 \times \frac{\mathrm{d}\mathbf{m}_2}{\mathrm{d}t} - \frac{P_{\mathrm{trans}}}{M_2} \mathbf{m}_2 \times (\mathbf{m}_2 \times \mathbf{m}_1)$$

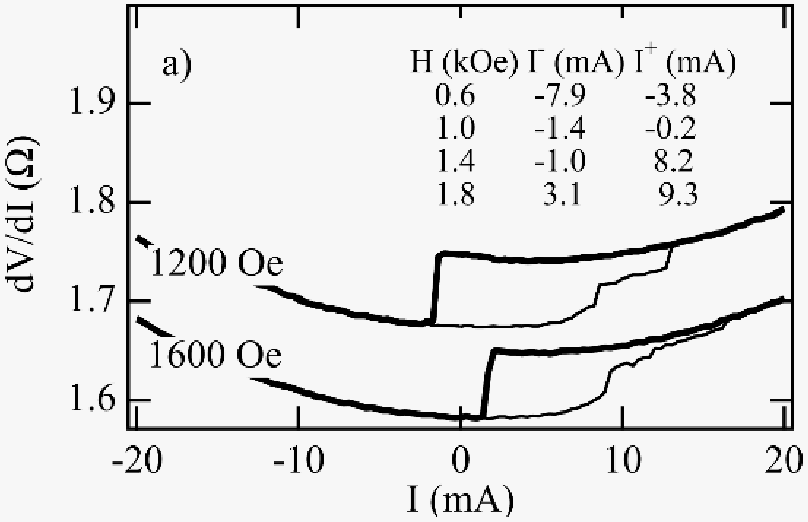
J. C. Slonczewski, J. Magn. Magn. Mater. 159, L1-7(1996)

- Can be viewed as the reverse effect of Giant Magnetoresistance

spintec SPIN IN ELECTRONICS

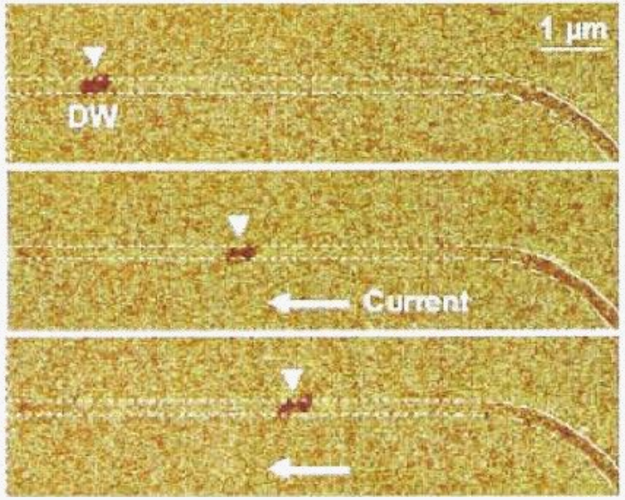
Spin-transfer torque: experiments

Magnetization switching



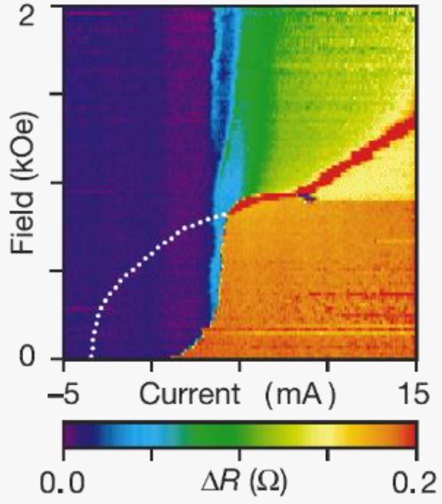
Katine 2000

Domain-wall motion



Yamaguchi 2004 $j \approx 10^{12}\ \mathrm{A/m^2}$

Oscillator



Kiselev 2003

New physics deeply rooted in condensed matter magnetism!

- Magnetization switching with charge current
- Domain-wall motion with charge current
- Precessional dynamics with charge current

A booster for applications

- Simplifies architectures
- Scalable to smaller nodes
- Robust writing

Which statements are true ?

1. Giant magneto-resistance is larger than tunneling magneto-resistance

2. The electric current required for Spin-Transfer torque is similar to magnetization value, i.e., $\approx 10^6\ \mathrm{A/m^2}$

3. Magnetization can be switched forth and back by opposite pulses of current

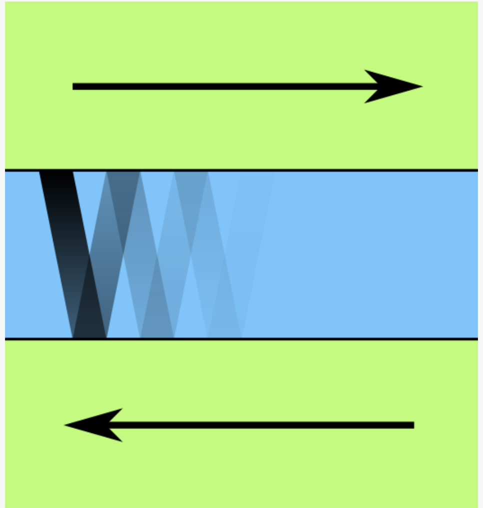
Which statements are true ?

1. Giant magneto-resistance is larger than tunneling magneto-resistance — No, record values show the reverse
2. The electric current required for Spin-Transfer torque is similar to magnetization value, i.e., $\approx 10^6\ \mathrm{A/m^2}$ — No, is $\approx 10^{12}\ \mathrm{A/m^2}$ Besides, units are different !
3. Magnetization can be switched forth and back by opposite pulses of current — Yes !

Table of contents

spintec
SPIN IN ELECTRONICS

Spin-dependent quantum confinement



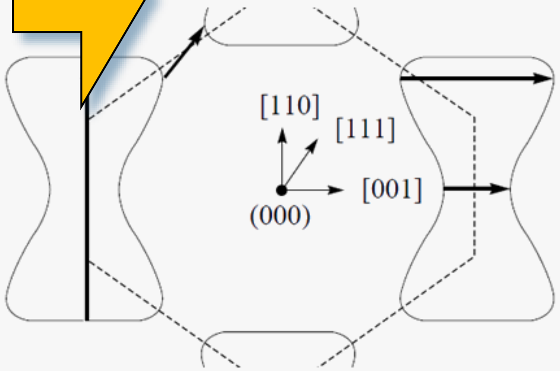
- Forth & back phase shift

$$\Delta\varphi = qt + \varphi_A + \varphi_B$$

- Spin dependence:

$$r_A, \varphi_A, r_B, \varphi_B$$

Oscillating constructive and destructive interferences with spacer thickness



Cu Fermi surface

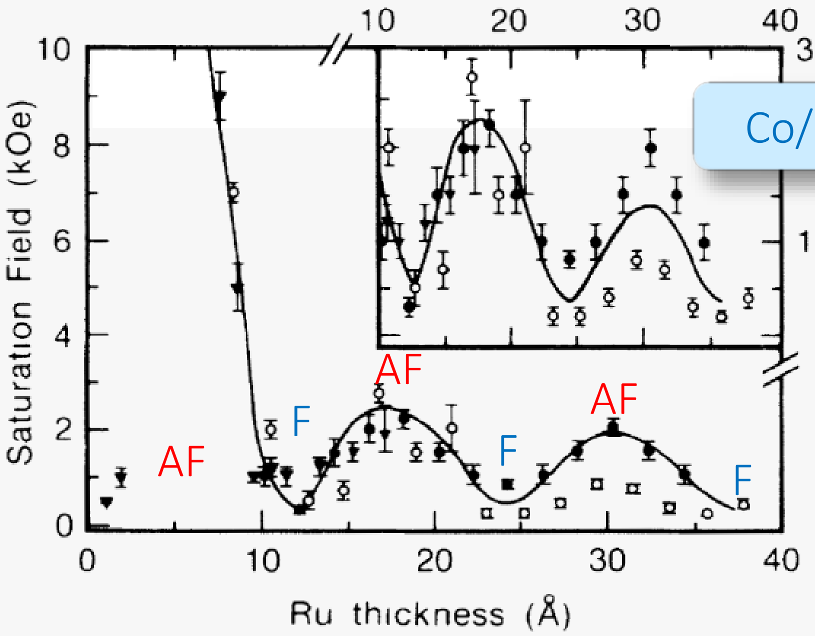
- Importance of nesting
- Depends on crystal direction

P. Bruno, J. Phys. Condens. Matter 11, 9403 (1999)

Coupling strength

$E_s(t) = J(t)\cos\theta$ with unit: $\mathrm{J/m^2}$ $\theta = \langle \mathbf{m}_1, \mathbf{m}_2 \rangle$

$$J(t) = \frac{A}{t^2}\sin(q_\alpha t + \Psi)$$

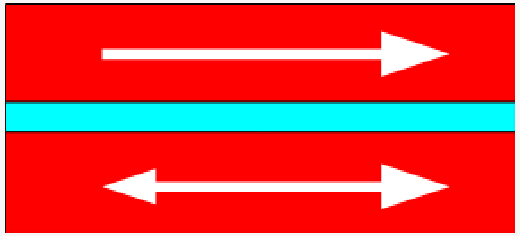


S. S. P. Parkin et al., PRL64, 2304 (1990)

- RKKY = Ruderman-Kittel-Kasuya-Yoshida
- A function quantum effect at room temperature !
- Crucial to couple magnetic layers in stacks

spintec SPIN IN ELECTRONICS

RKKY Synthetic Ferrimagnets (SyF) – Basics



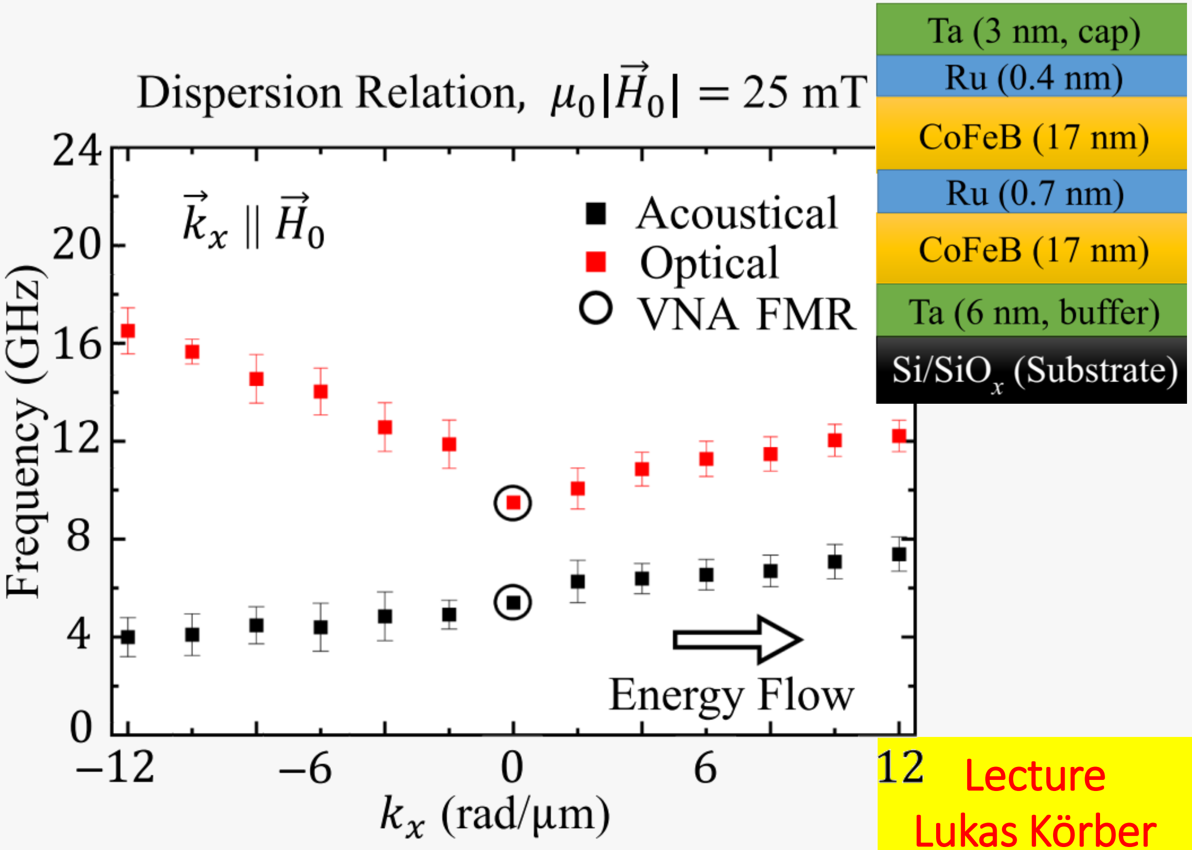
- Crude phenomenology

$$M = \frac{|e_1 M_1 - e_2 M_2|}{e_1 + e_2} \qquad K = \frac{e_1 K_1 + e_2 K_2}{e_1 + e_2}$$

$$\Rightarrow \quad H_c \approx \frac{e_1 M_1 H_{c,1} + e_2 M_2 H_{c,2}}{|e_1 M_1 - e_2 M_2|}$$

- Enhances coercivity
- Reduces cross-talk in dense arrays

Functionality relevance: non-reciprocity of spin waves



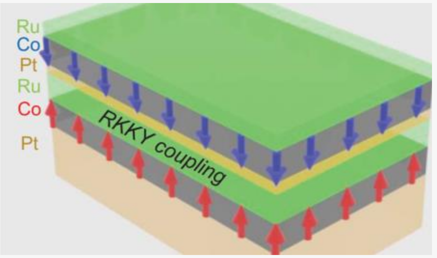
Lecture
Lukas Körber

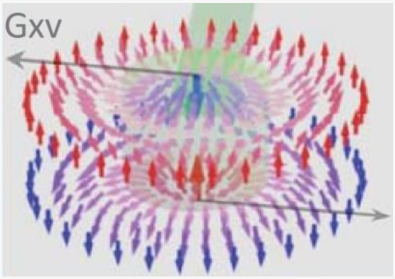
F. Millo et al., Phys. Rev. Appl. 20, 054051 (2023)

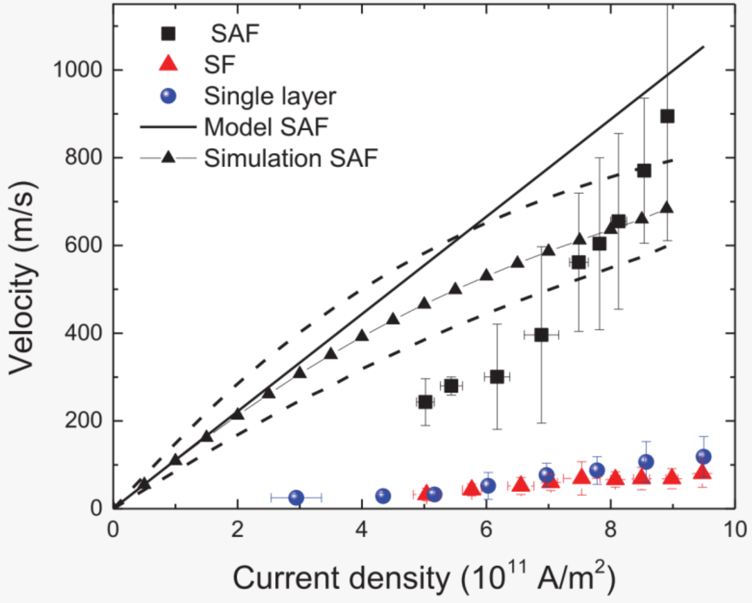
Functionality relevance: magnetization dynamics

- Precessional frequency enhanced in antiferromagnets
  -> Faster speed of domain walls and skyrmions
- Compensated skyrmions
  -> Suppression of Skyrmion Hall effect

Lecture
Anders Bergman



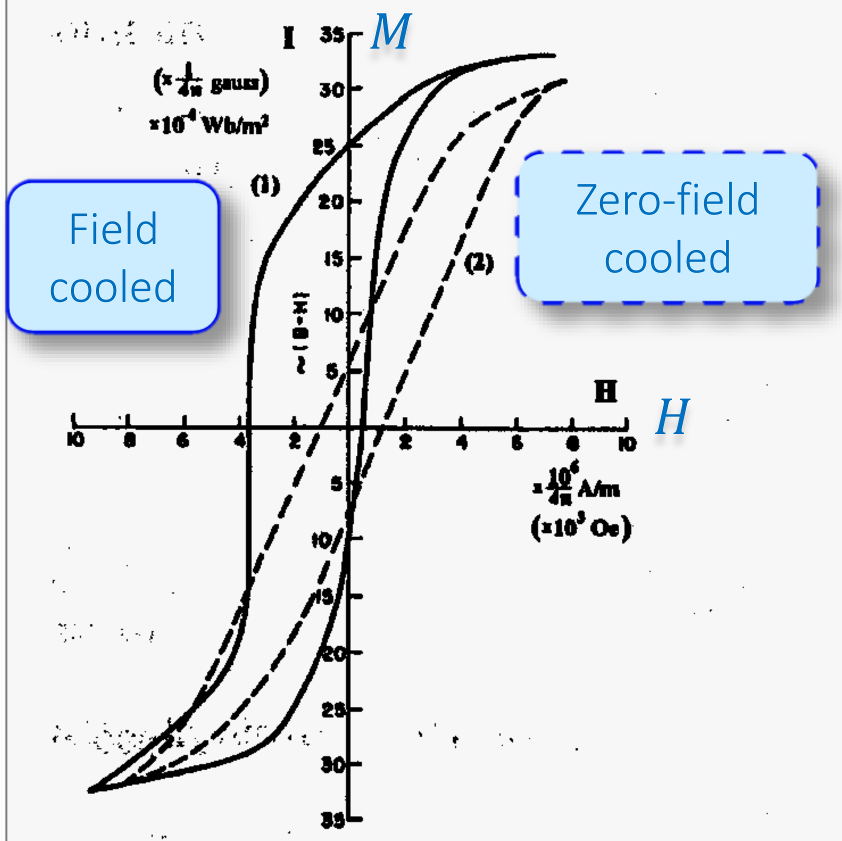




V. T. Pham et al., Science 384, 307 (2024)

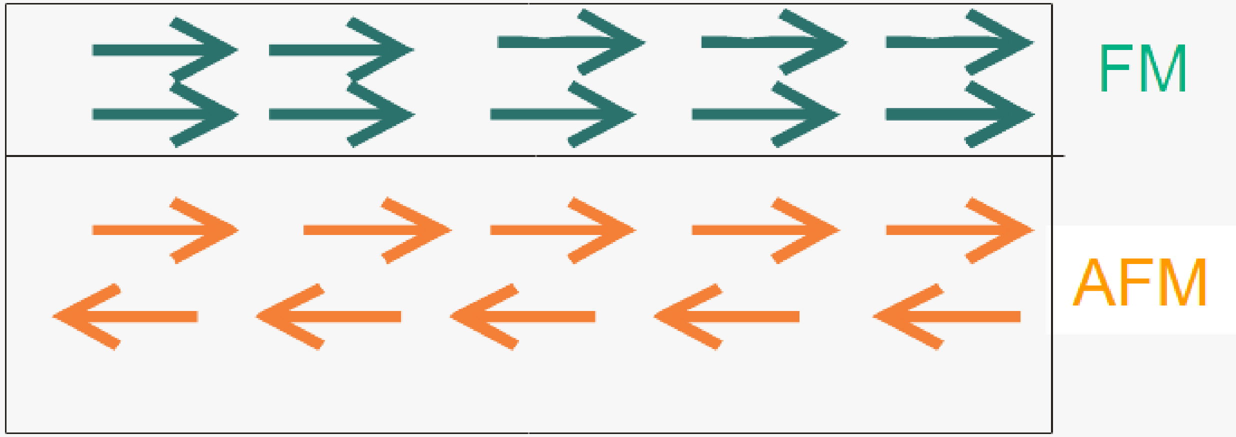
Heterostructures – Exchange bias

Seminal investigation



Meiklejohn and Bean, Phys. Rev. 102, 1413 (1956), Phys. Rev. 105, 904, (1957)

Physics and functionnalities



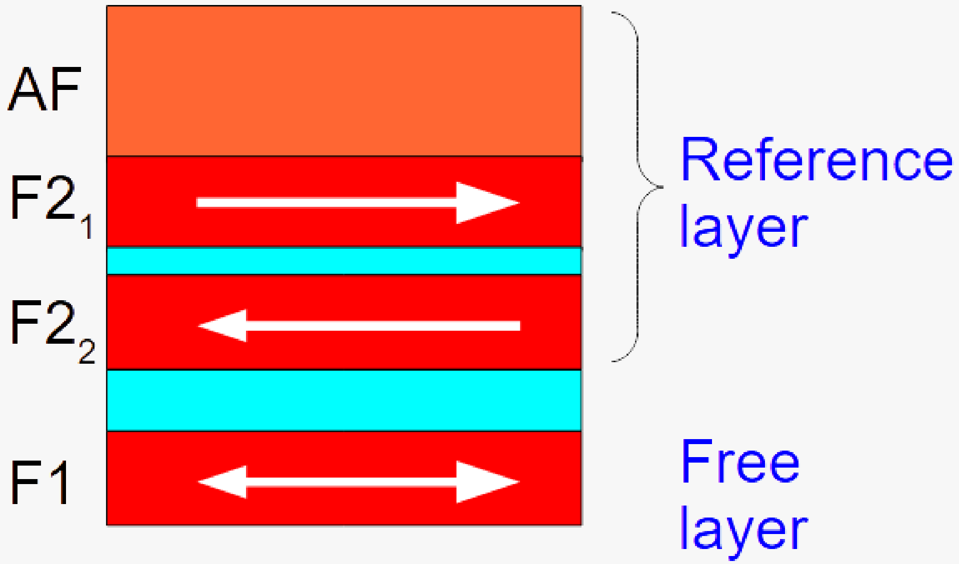
- Field-shift of hysteresis loop
- Increase of coercivity
- Crucial to design reference layer in memories

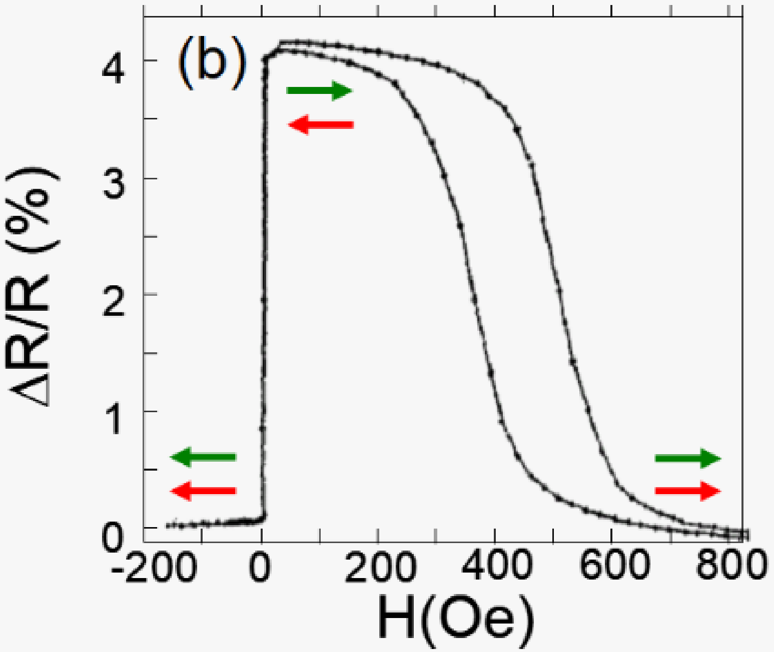
Exchange bias, J. Nogués and Ivan K. Schuller, J. Magn. Magn. Mater. 192 (1999) 203

Exchange anisotropy—a review, A E Berkowitz and K Takano, J. Magn. Magn. Mater. 200 (1999)

Spin valves

- "Free" and reference layers





B. Diény et al., J. Magn. Magn. Mater. 93, 101 (1991)

1956

Wikipedia, CC-BY-SA

- Spin-valves are key elements in magneto-resistive devices (sensors, memories)
- Control Ru thickness within the Angström !

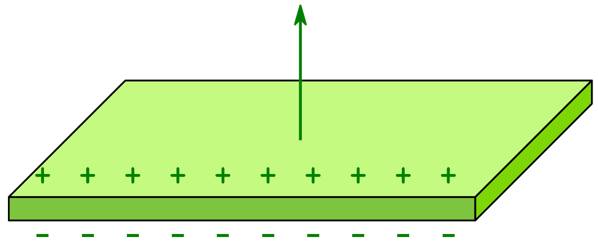
Today, 2.5" HDD

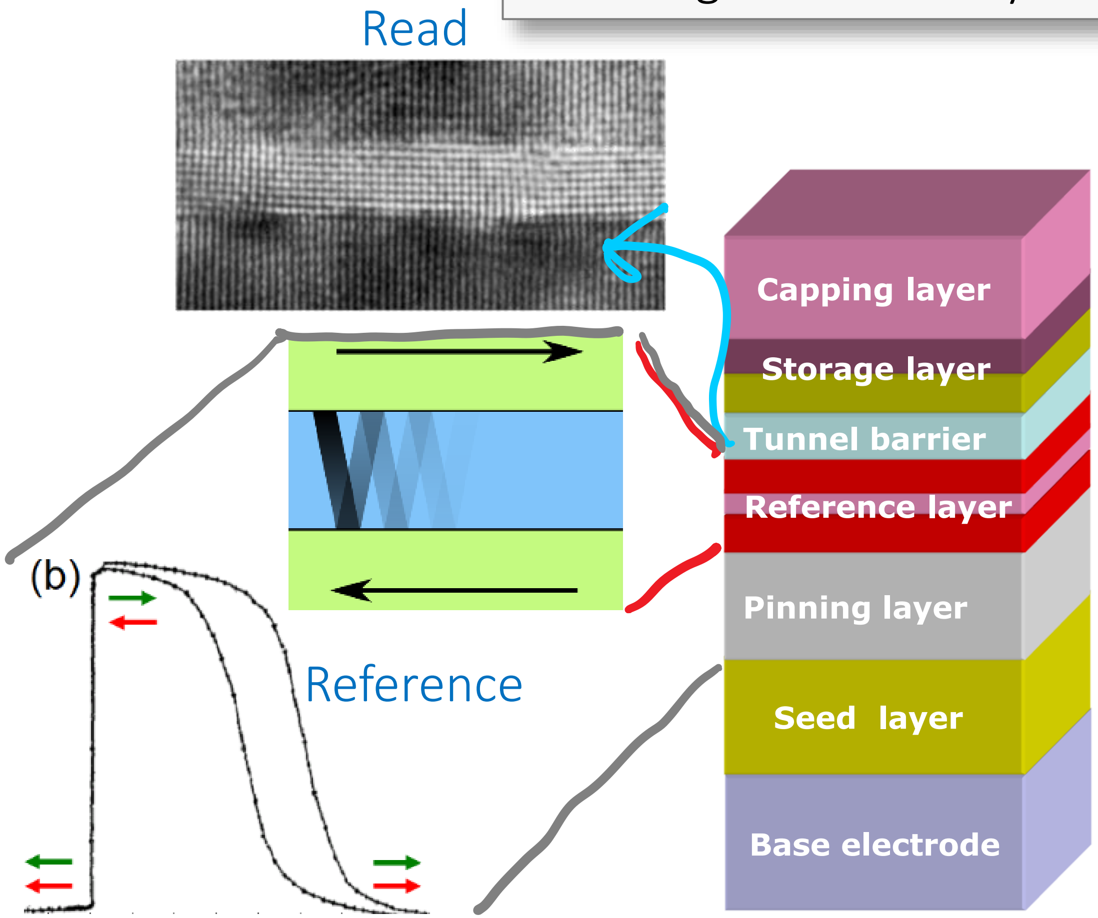
Wikipedia, CC-BY-SA

Solid-state magnetic cells

- Magnetic field sensors
- Magnetic memory bit (MRAM)

Enhance stability





Protects MTJ during process

NiFe(3) / CoFe(2) : Stores data (2 stable states)
Interfacialdusting enhancing TMR

MgO (1.1) : Defines cell R & TMR

CoFeB(2) / Ru(0.8)/CoFe(2) : SAF, immune to external fields
Imbalance of moment compensates for orange-peel coupling through MgO

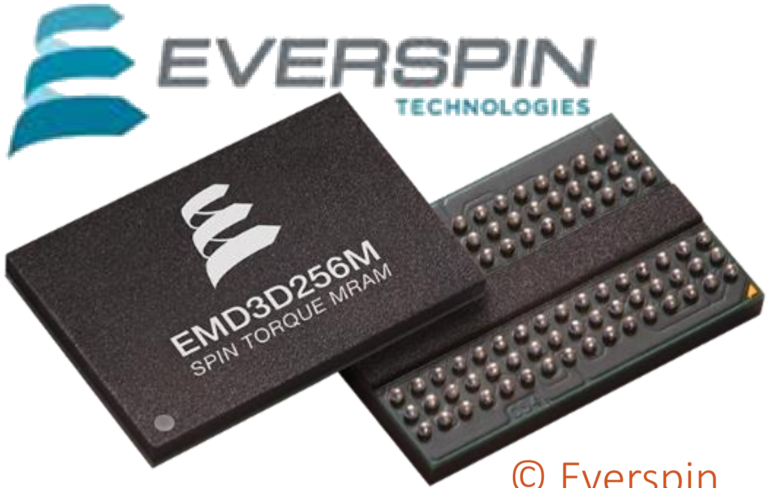
PtMn(20) : AF layer sets direction of reference layer

Ta(5) or NiFeCr(10) : Promotes texture of critical layers

Contact to select transistor + diffusion barrier

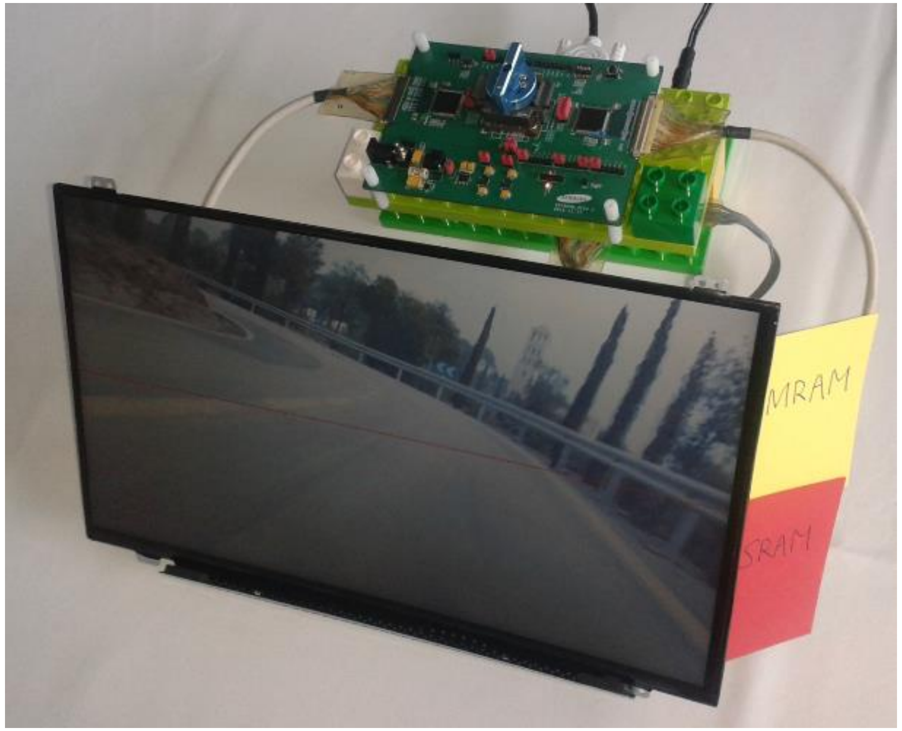
Heterostructures – MRAM, the emergence

Spintronics enters the ITRS roadmap in 2015



© Everspin

1Gb in production.



Demo at the 7th MRAM (STT MRAM) Global Innovation Forum (Zurich, June 2016)

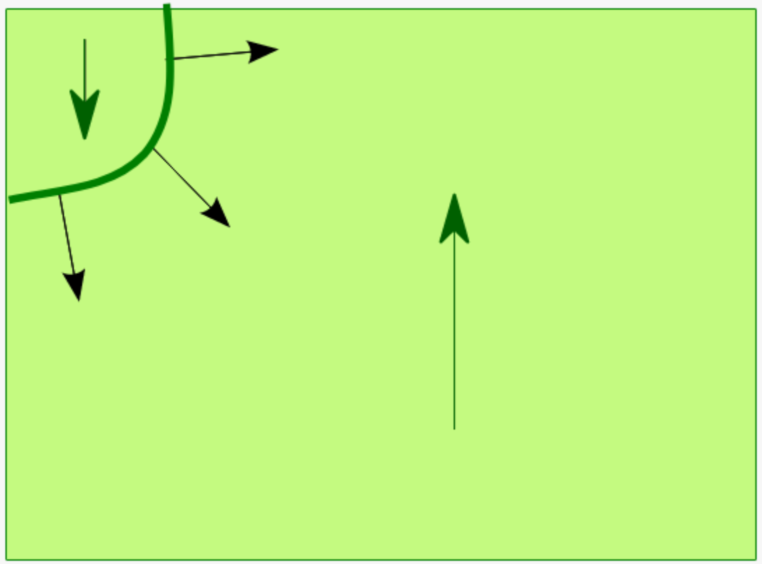
https://www.linkedin.com/company/mram-info/
https://www.mram-info.com

Heterostructures – MRAM on the market

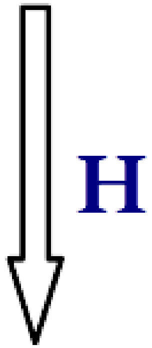
EVERSPIN TECHNOLOGIES
NEC
intel
TDK
Avalanche Technology
IBM
GLOBAL FOUNDRIES
Spin Transfer Technologies
tsmc
RENESAS
Everywhere you imagine.
Micron
CROCUS Technology
Blossoming future
SAMSUNG
SONY
FUJITSU
antaios
TOWERJAZZ
GRANDIS
TEL
QUALCOMM
TOSHIBA
Hprobe
KEYSIGHT TECHNOLOGIES
SINGULUS
APPLIED MATERIALS
hynix
Canon CANON ANELVA CORPORATION
CAPRES A/S
COPENHAGEN APPLIED RESEARCH

How are domain walls involved in magnetization reversal?

Coercivity determined by nucleation

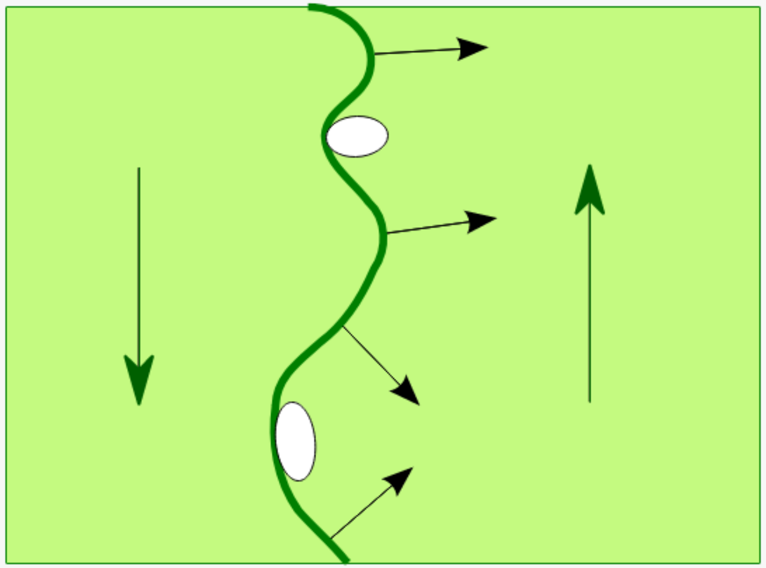


- Concept of nucleation volume
- Physics has some similarity with that of the Stoner-Wohlfarth model for small particles



Lecture
Oscar Grånäs

Coercivity determined by propagation



- Physics of surface/string in heterogeneous landscape
- Modeling necessary

Brown paradox

In most (extended systems): $H_c \ll \dfrac{2K}{\mu_0 M_s}$

(Micromagnetic) modeling

Exhibit analytic, nevertheless realistic models for magnetization reversal

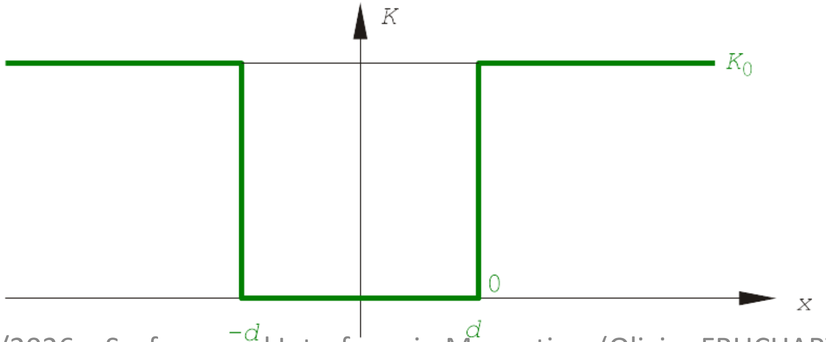
PHYSICAL REVIEW VOLUME 119, NUMBER 1 JULY 1, 1960

Reduction in Coercive Force Caused by a Certain Type of Imperfection

A. AHARONI
Department of Electronics, The Weizmann Institute of Science, Rehovot, Israel

(Received February 1, 1960)

As a first approach to the study of the dependence of the coercive force on imperfections in materials which have high magnetocrystalline anisotropy, the following one-dimensional model is treated. A material which is infinite in all directions has an infinite slab of finite width in which the anisotropy is 0. The coercive force is calculated as a function of the slab width. It is found that for relatively small widths there is a considerable reduction in the coercive force with respect to perfect material, but reduction saturates rapidly so that it is never by more than a factor of 4.



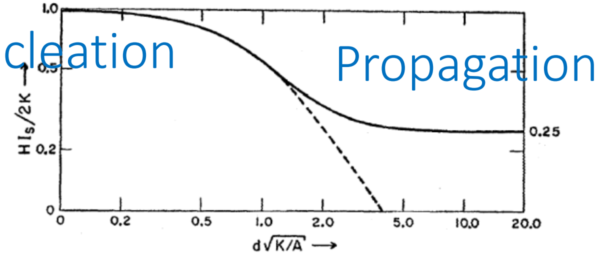


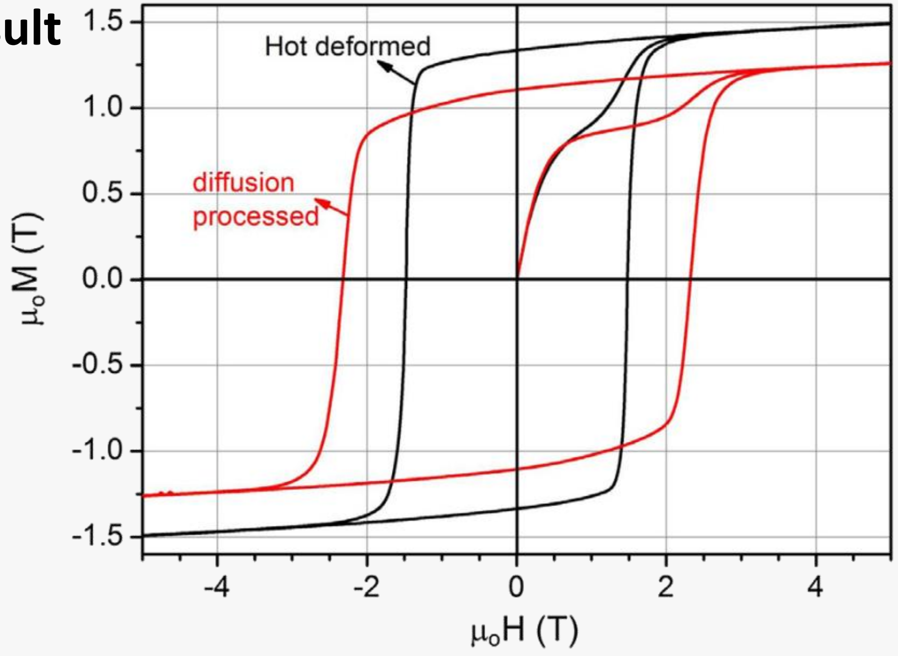
FIG. 1. The nucleation field (dashed) and coercive force (full curve) in terms of the coercive force of perfect material, $HI_s/2K$, as functions of the defect size, d.

Heterostructures – Interfaces and coercivity

Context and principle

- Brown paradox: coercivity < anisotropy
- In NdFeB, coercivity limited by nucleation
- Synthesis with Cu and Nd excess. The NdCu eutectic diffuses at grain boundaries

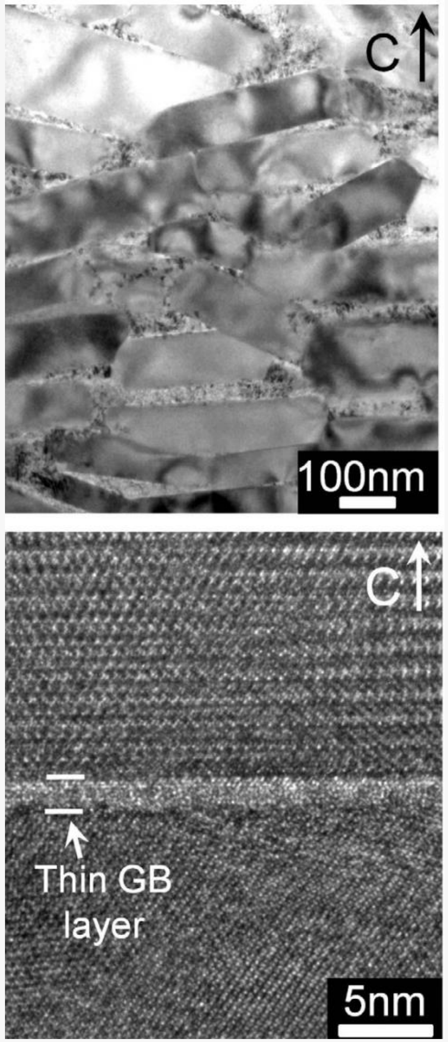
Result

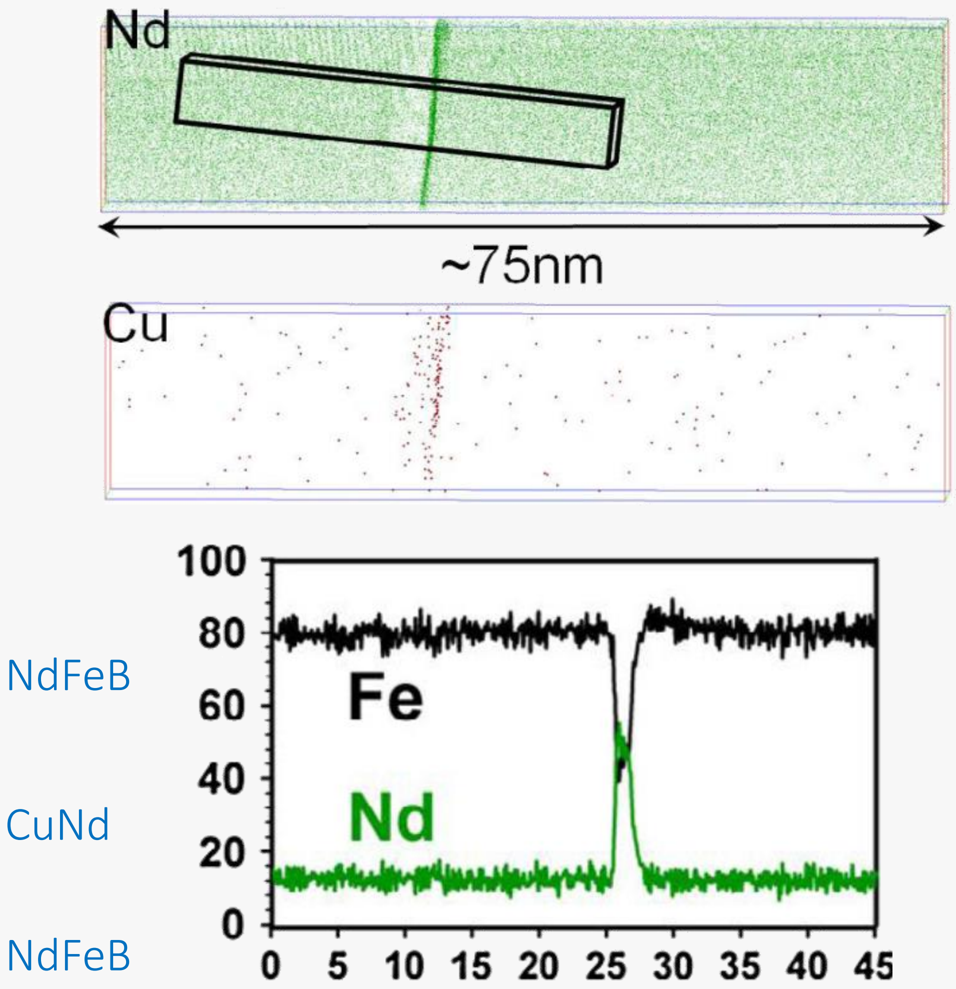


- Coercivity enhanced
- Slight reduction of magnetization

Structural analysis

Hot-deformed Nd-Fe-B magnet





H. Sepehri-Amin et al., Acta Mater. 61, 6622 (2013)

Heterostructures – Quizz

Which statements are true ?

1. RKKY coupling always favors antiferromagnetic alignement

2. The coercivity of synthetic antiferromagnets is larger than its individual layer constituents

3. Coercivity can be enhanced by smoothing interfaces

4. Magnetic Random Access Memories are still at the development stage

Heterostructures – Quizz answers

Which statements are true ?

1. RKKY coupling always favors antiferromagnetic alignement — No, it is oscillatory between positive and negative
2. The coercivity of synthetic antiferromagnets is larger than its individual layer constituents — Yes, thsi is a feature of SAF
3. Coercivity can be enhanced by smoothing interfaces — No, it is the reverse
4. Magnetic Random Access Memories are still at the development stage — No, they are already in commercial products

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Flagship Conference: Overseeing of JEMS

Awards: Young Scientist, Dominique Givord Award

Foster community actions: STF, magnetometry, industry, sponsorship action (deadline 30-01 & 31-07)

Young scientists: European School (ESM), networking

Communication: Website, newsletter, social media, calendar of events, job market

EMA – Quizz

Which statements are true ?

1. Are you a member of EMA?
2. Will you promote EMA and its membership programme when back home?
3. Will you consider attending JEMS 2027 in Prague?
4. Will you consider low(er) carbon-footprint options for attending your next scientific event?