Epitaxy and magnetic materials

O. Fruchart

Institut NEEL
CNRS & Univ. Grenoble - Alpes
Grenoble - France

Modern applications of magnetism

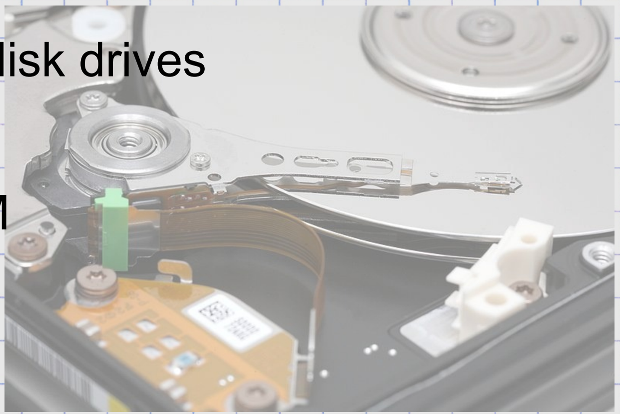
Where does 'nano' contribute ?

Sensors

- Compass
- Encoders
- Field mapping
- HDD read heads

Data storage

- Hard disk drives
- Tapes
- MRAM

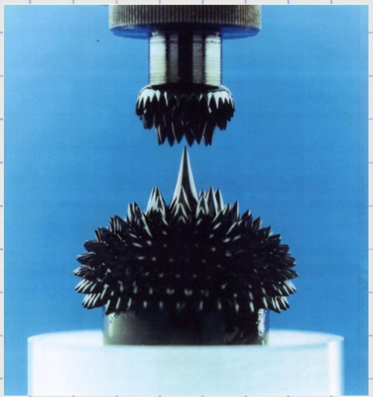


Materials

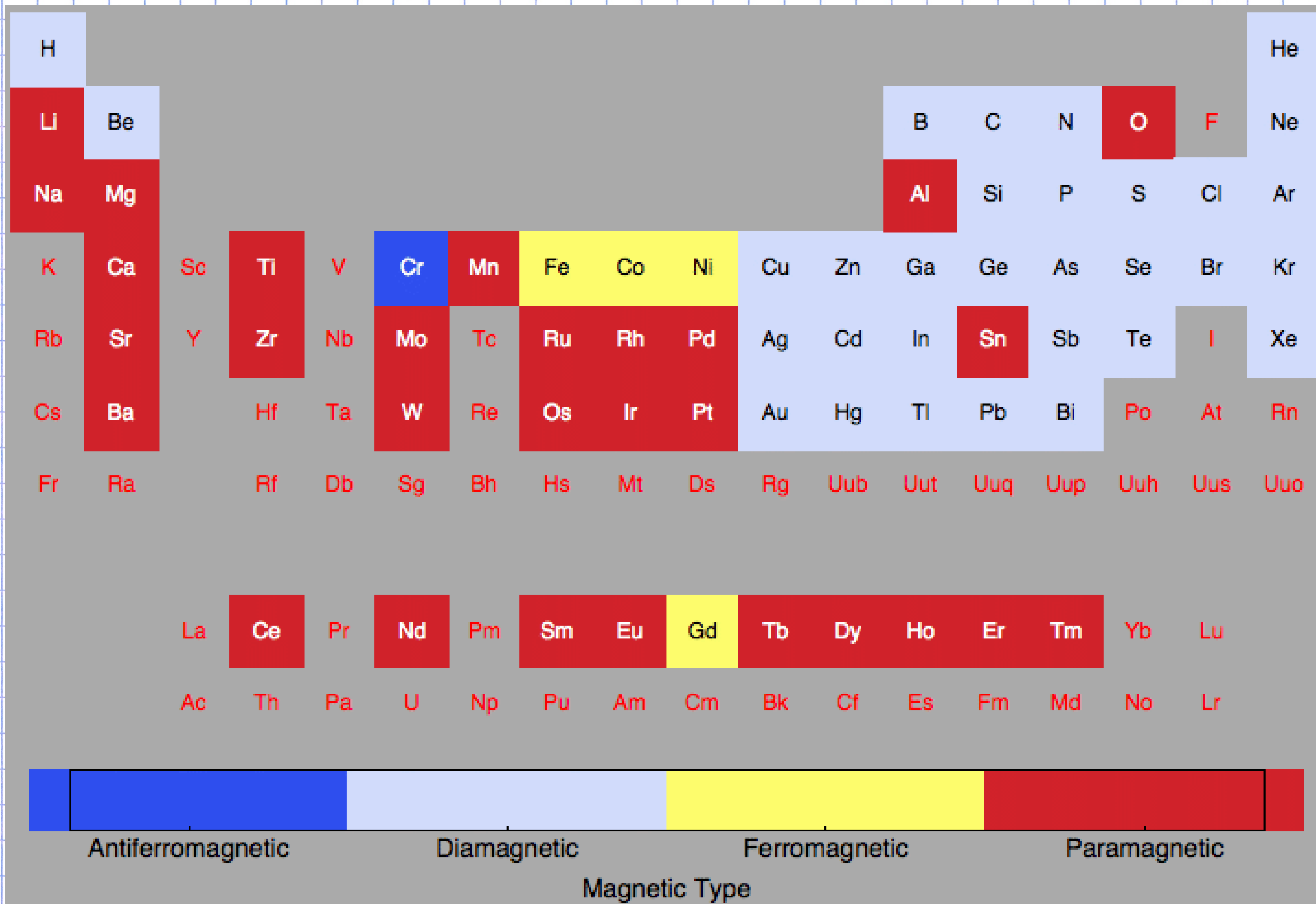
- Magnets (→ motors and generators)
- Transformers
- Magnetocaloric

Nanoparticles

- Ferrofluids
- MRI contrast
- Hyperthermia
- Sorting & tagging



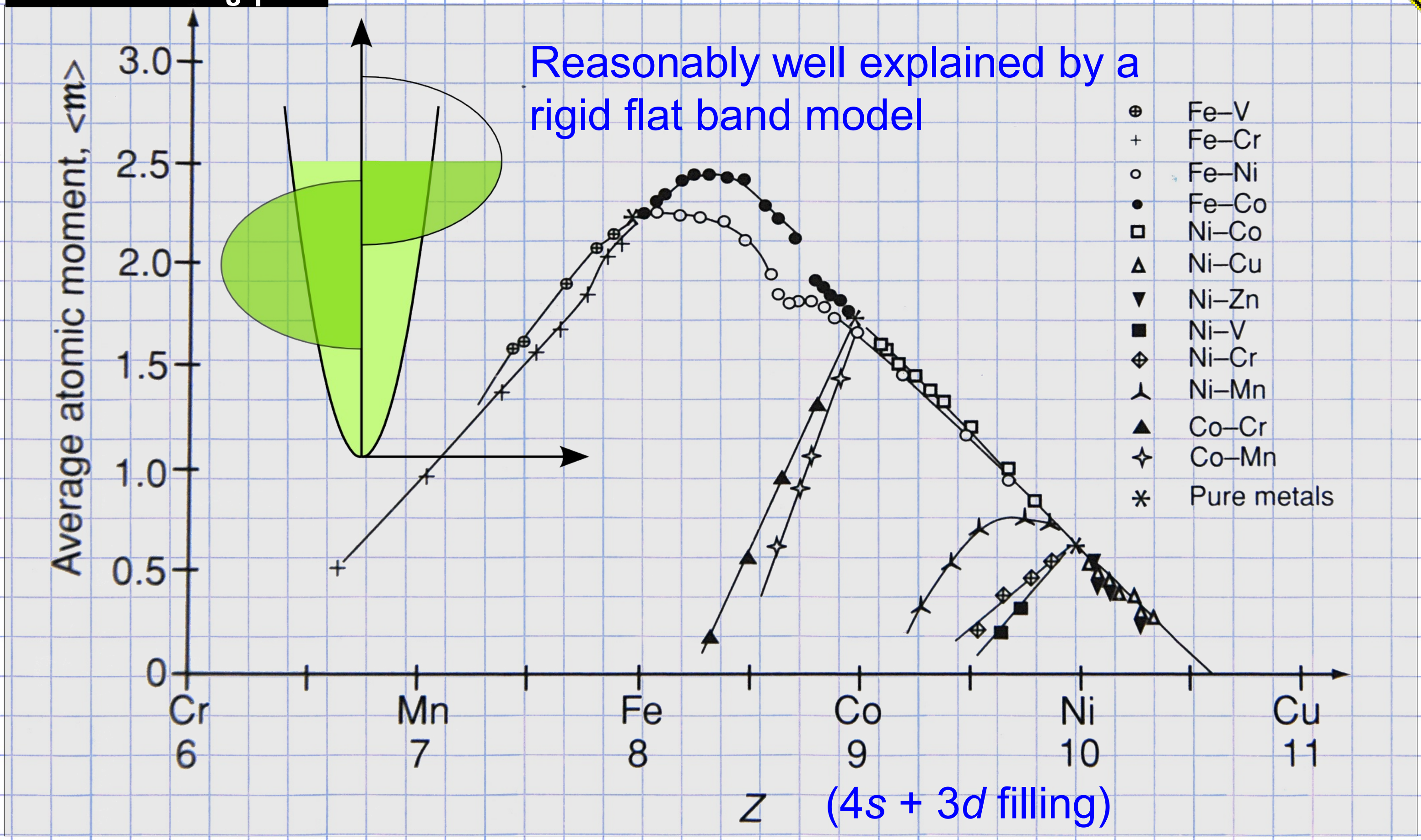
Magnetic properties of single elements at room temperature



Periodictable.com

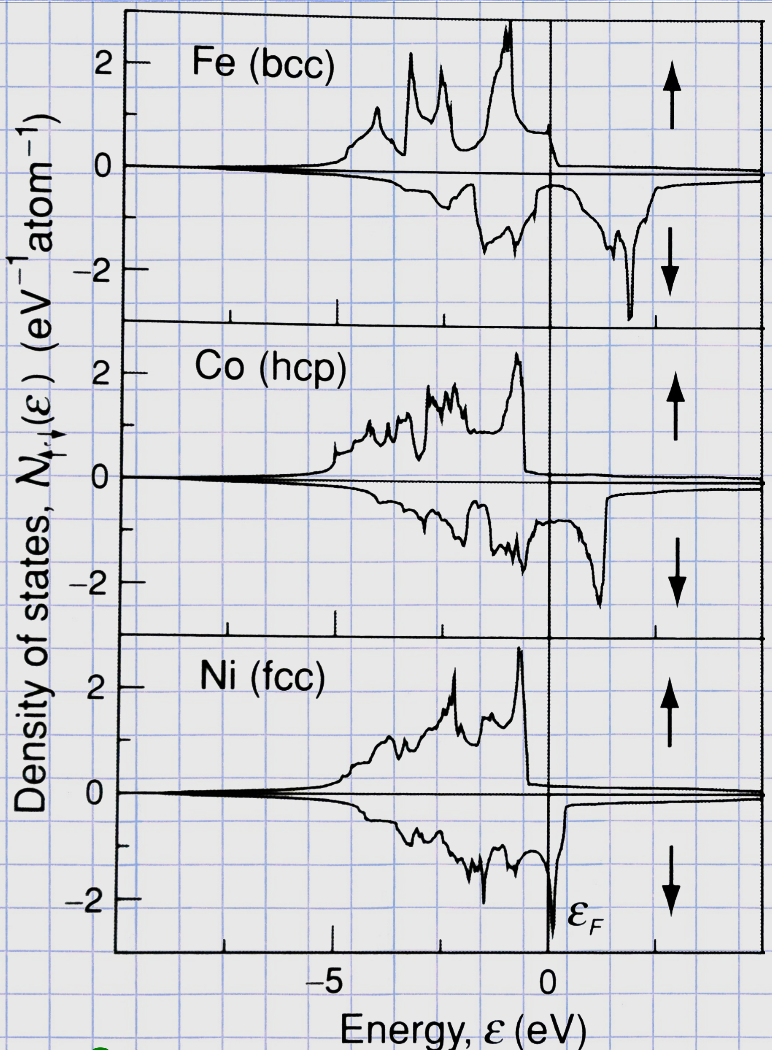
Do not use Hund's rules to estimate atomic moments

Slater-Pauling plot



From: Coey

Band structure and density of state of 3d ferromagnets

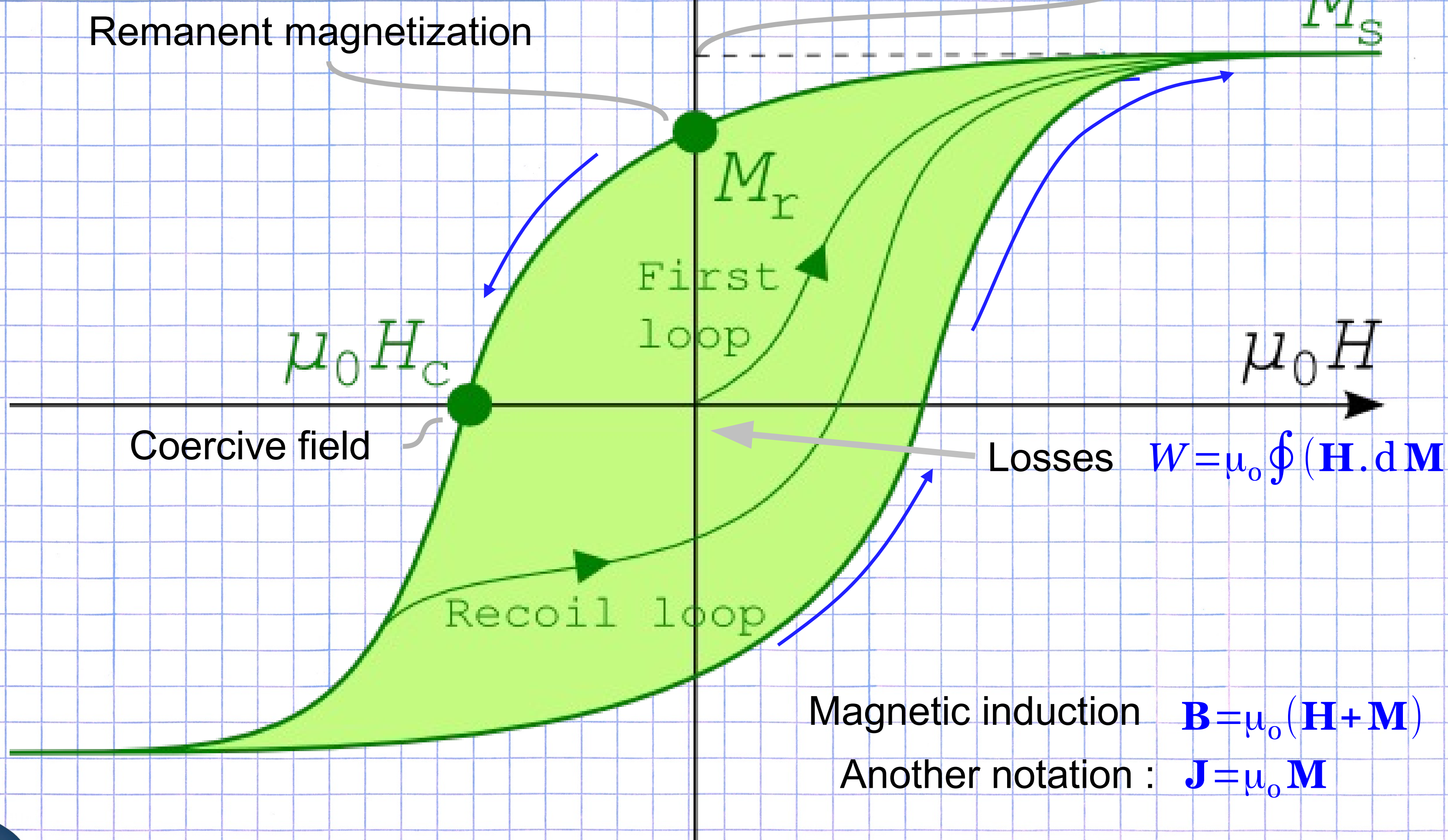


From: Coey

- Not parabolic bands
- Even simple quantities are sometimes difficult to understand
- Anisotropy of DOS → importance of epitaxy

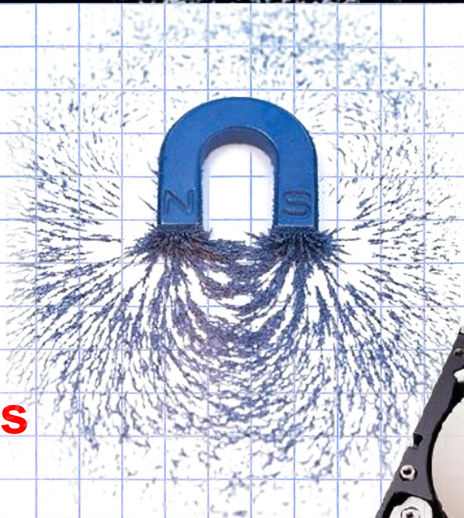
Manipulation of magnetic materials:
→ Application of a magnetic field

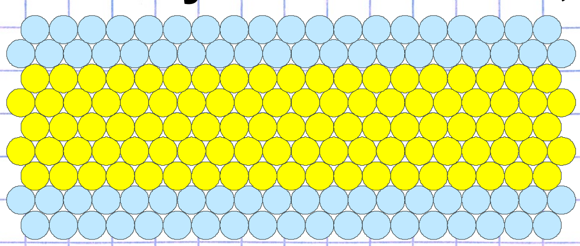
Zeeman energy: $E_Z = -\mu_0 \mathbf{H}.\mathbf{M}$

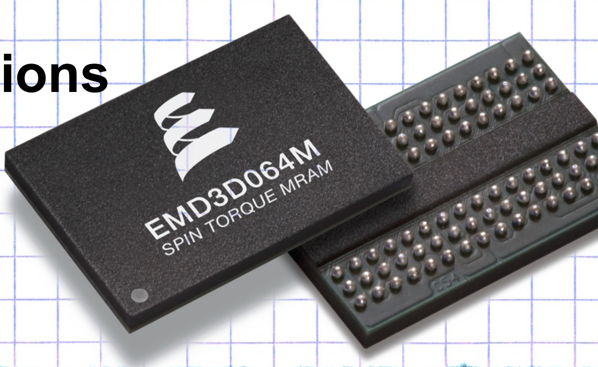


Magnetic induction $\mathbf{B} = \mu_0 (\mathbf{H} + \mathbf{M})$

Another notation : $\mathbf{J} = \mu_0 \mathbf{M}$


N
S




EMD3D064M
SPIN TORQUE MRAM

Elements of theory

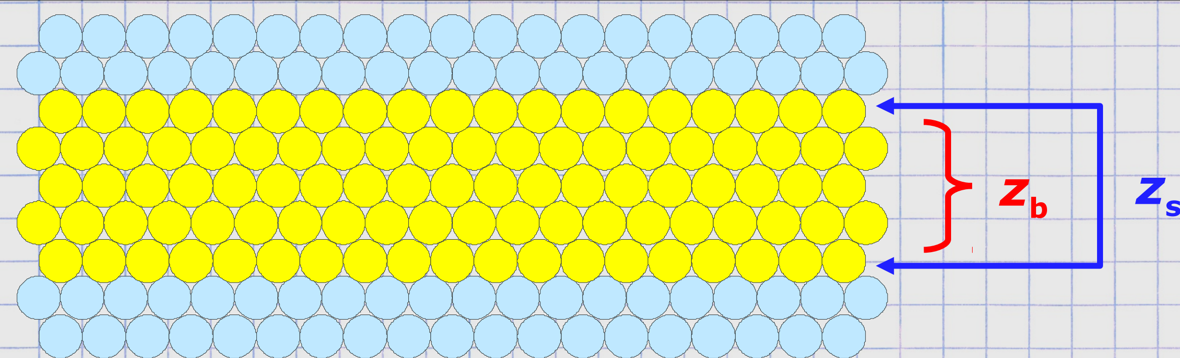
- Ising (1925). No magnetic order at T>0K in 1D Ising chain.
- Bloch (1930). No magnetic order at T>0K in 2D Heisenberg (spin-waves)
- → N. D. Mermin, H. Wagner, PRL17, 1133 (1966)
- Onsager (1944) + Yang (1951). 2D Ising model: Tc>0K

→ Magnetic anisotropy stabilizes ordering

Naïve views : mean molecular field

$$T_C = \frac{\mu_0 z n_{W,1} n g_J^2 \mu_B^2 J(J+1)}{3 k_B}$$

z neighbors



N atomic layers : $\langle z \rangle = z_b - \frac{2(z_b - z_s)}{N}$ → $\Delta T_C(t) \sim t^{-1}$

Less naïve: thickness-dependent mean molecular field

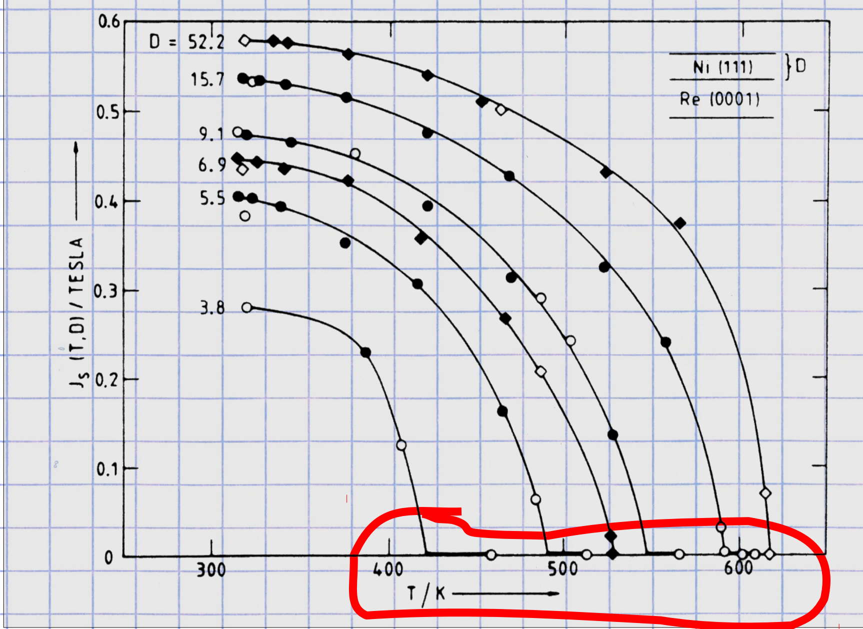
$\Delta T_C(t) \sim t^{-\lambda}$

$\lambda = 1$ **G.A.T. Allan, PRB1, 352 (1970)**

Conclusion:
Naïve views are roughly correct

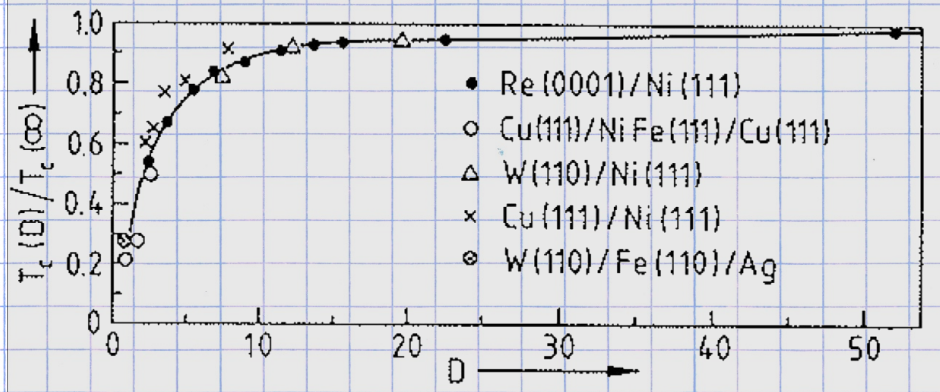
Qualitative

Ni(111)/Re(0001)



R. Bergholz and U. Gradmann, JMM45, 389 (1984)

Quantitative (molecular field)



Tc fitted with molecular field :

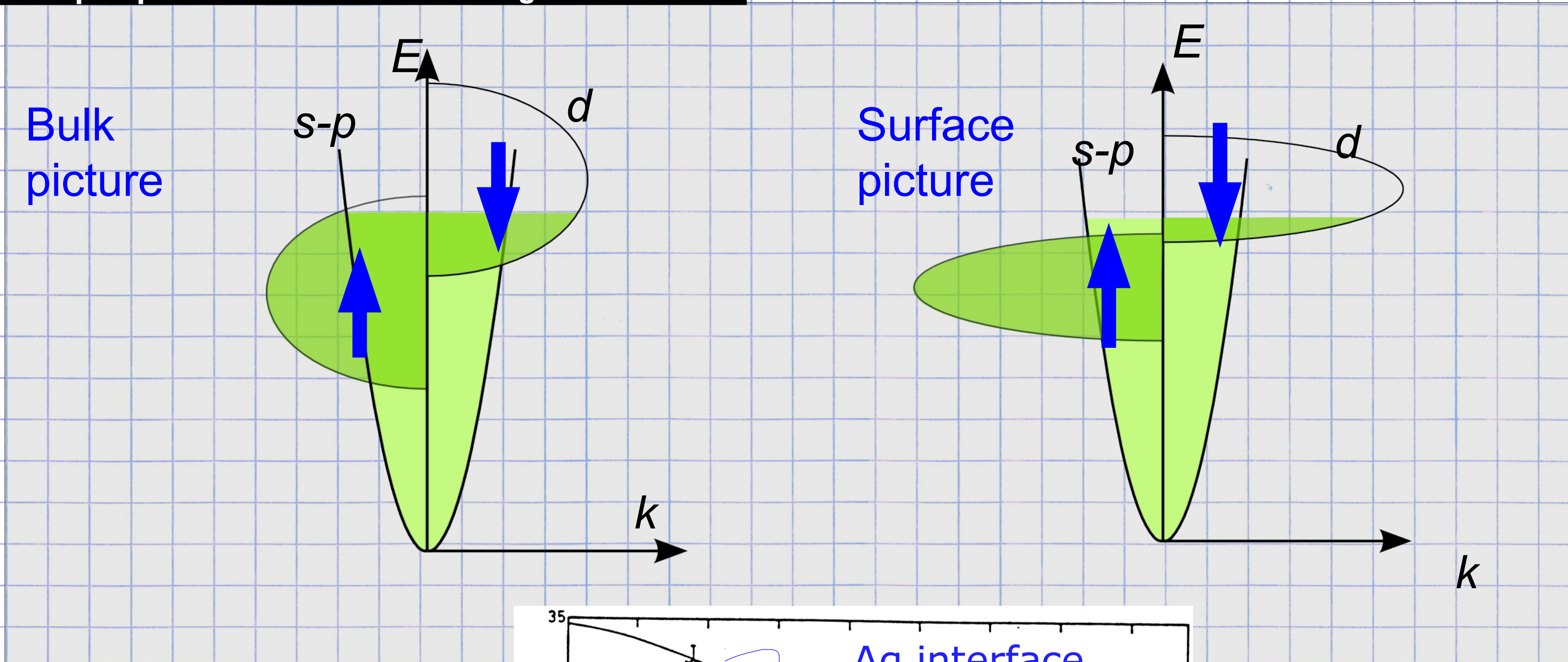
$$\Delta T_C(t) \sim t^{-1}$$

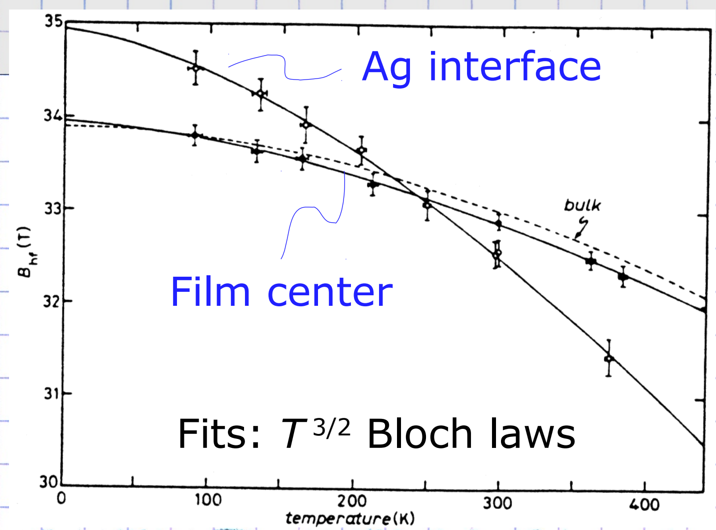
U. Gradmann, Handbook of Magn. Mater. Vol.7, ch.1 (1993)

- Ordering temperature decreases with thickness
- Noticeable below ≈ 1nm

Enhanced moment at surfaces

Simple picture: band narrowing at surfaces

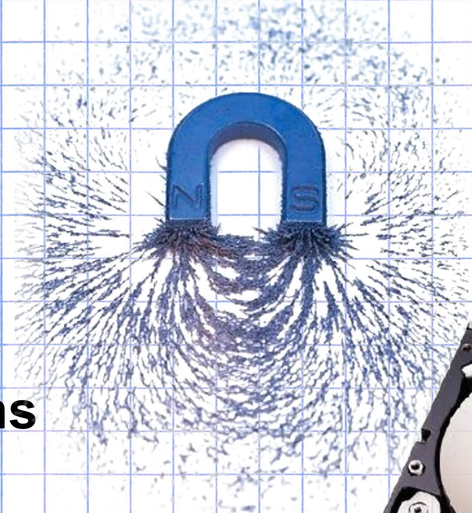


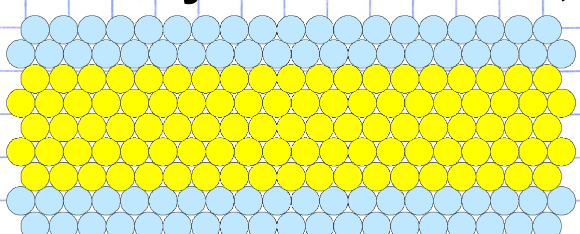


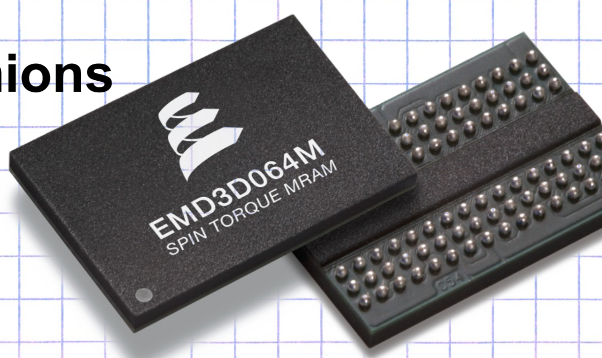
In practice:
20-30 %, however decays faster with temperature

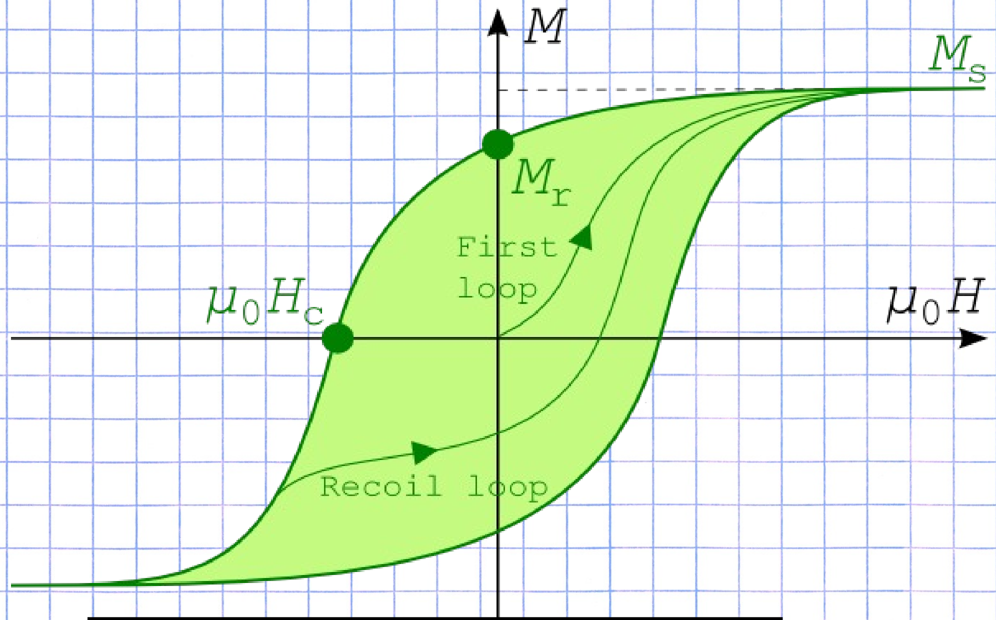
Ag/Fe(110)/W(110)

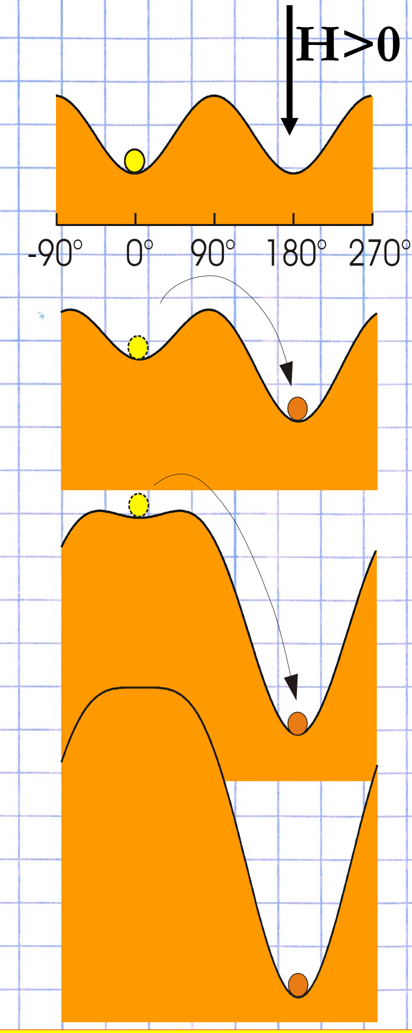
U. Gradmann et al.


N
S

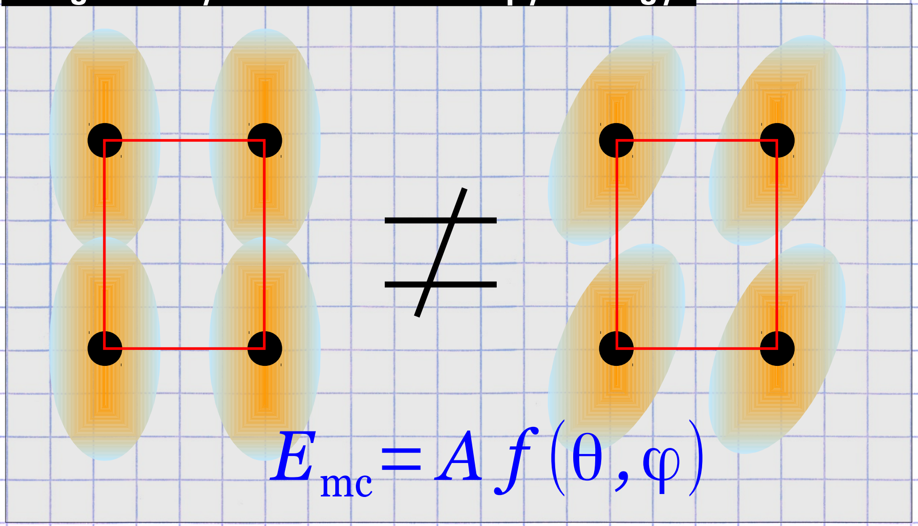



EMD3D064M
SPIN TORQUE MRAM





Magnetocrystalline anisotropy energy



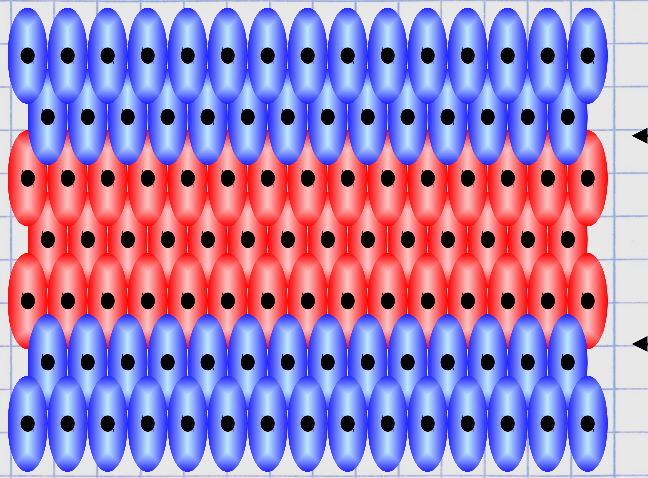
$$E_{mc} = A\, f(\theta, \varphi)$$

- Responsible for remanence
- and coercivity
- Memories, magnets

Surface anisotropy

L. Néel, J. Phys. Radium 15, 15 (1954)

« Superficial magnetic anisotropy and orientational superstructures »



Overview

Breaking of symmetry for surface/interface atoms

→ Correction to the magneto-crystalline energy

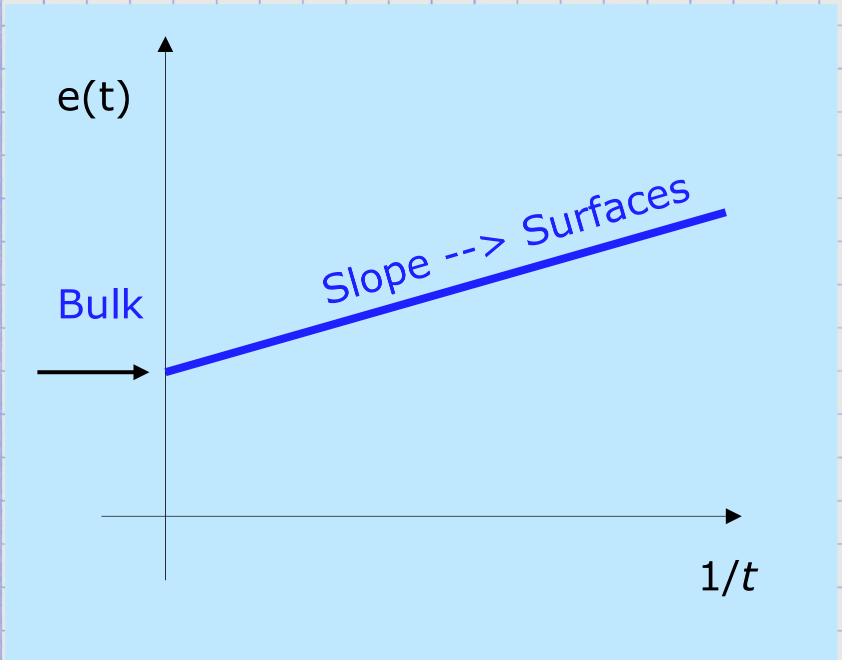
$$E_s = K_{s,1}\cos^2\theta + K_{s,2}\cos^4\theta + \ldots$$

- « 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 !

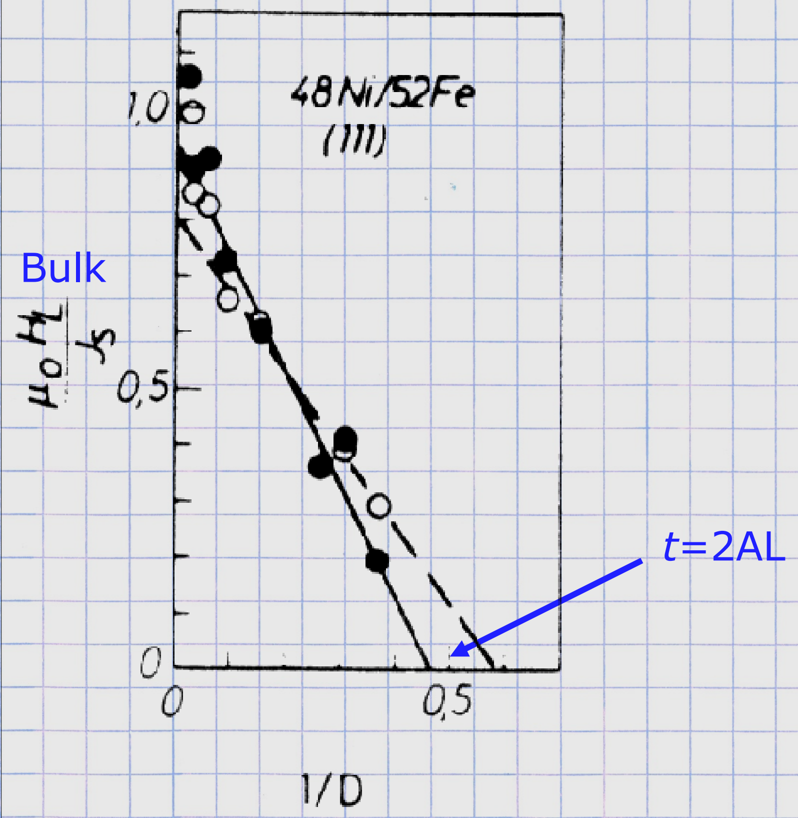
History of surface anisotropy : 1/t plot

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

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



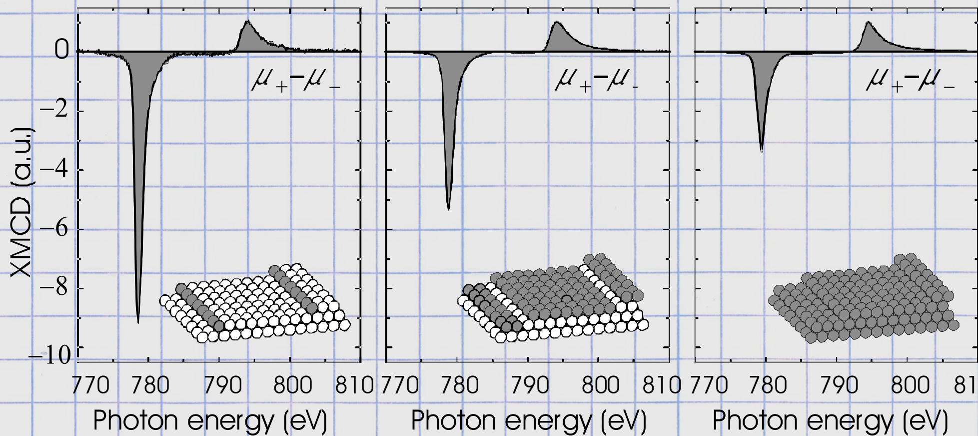
First example of perpendicular anisotropy



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

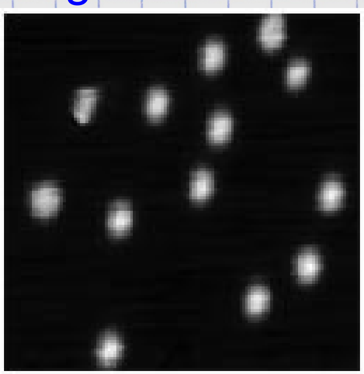
Experimental systems

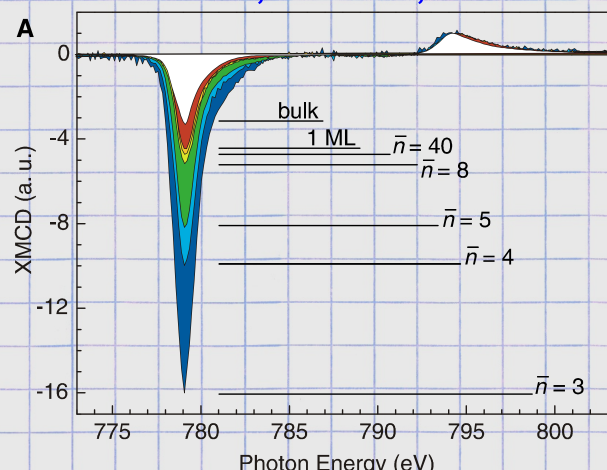
Co on vicinal Pt(111) probed by Xray dichroism



P. Gambardella et al., Nature 416, 301 (2002)

Single atoms at surface. STM, 8.5nm, 5.5K





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

Results

- Bulk Co: 40μeV/atom
- Co ML: 140μeV/atom
- Co bi-wire: 0.34meV/atom
- Co wire: 2meV/atom
- Co bi-atom: 3.4meV/atom
- Co atom: 9.2meV/atom

Dramatic dimensional effect

Practical use : past and trends

⇨ 3d (mostly Co and Co\Ni) with heavy metal (Pt, Au, Pd...). Critical thickness 1-2nm

M. T. Johnson, RPP59, 1409 (1996)

U. Gradmann, Handbook7, Bushow (1993)

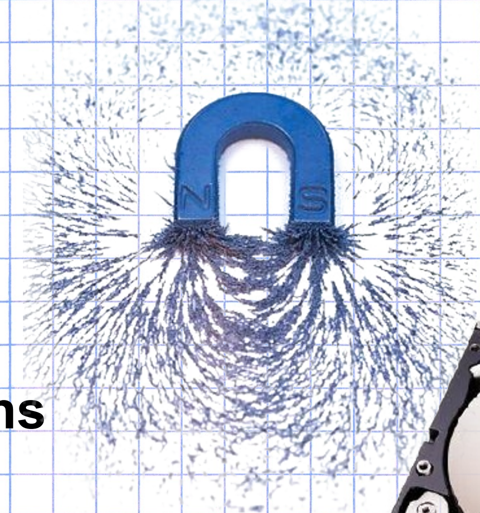
⇨ Bonding with oxide : Al_2O_3, MgO... (→ t_c up to 3.5nm)

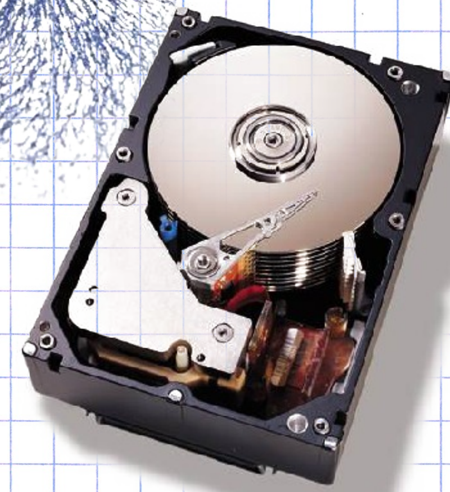
A. Manchon, JAP 103, 07A912 (2008)

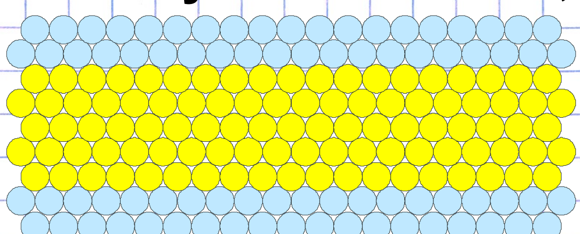
I. G. Rau, Science 344, 988 (2014)

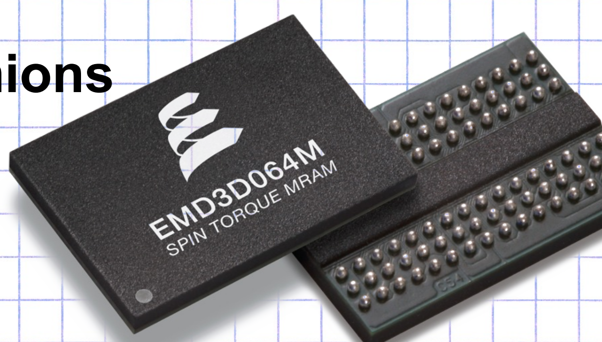
⇨ Interface with graphene

J. Coraux, J. Phys. Chem. Lett. 3, 2059 (2012)



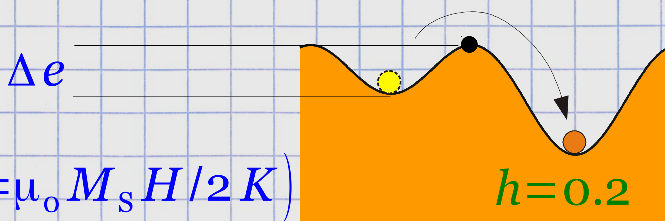





EMD3D064M
SPIN TORQUE MRAM

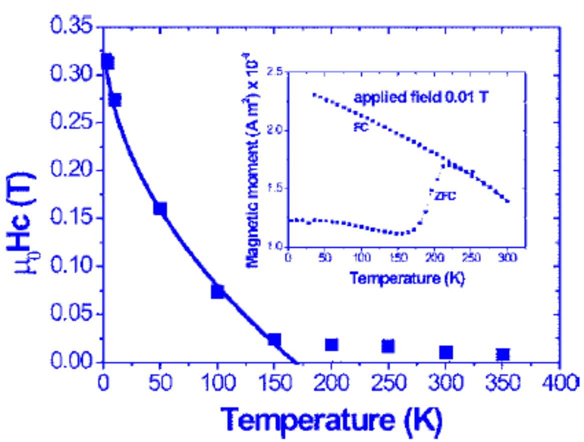
Barrier height

$$\Delta e = e(\theta_{max}) - e(0) = (1-h)^2$$



$$(h = \mu_0 M_S H / 2K)$$

J. Appl. Phys. **99**, 08Q514 (2006)



➪ Coercivity and remanence features lost for small anisotorpy or small size

Thermal activation

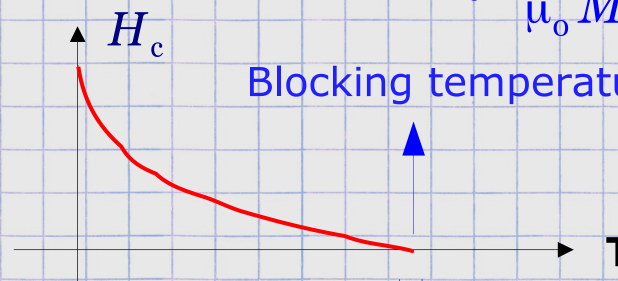
Brown, Phys.Rev.130, 1677 (1963)

$$\tau = \tau_0 \exp\left(\frac{\Delta\mathcal{E}}{k_B T}\right) \Rightarrow \Delta\mathcal{E} = k_B T \ln(\tau/\tau_0)$$

$$\tau_0 \approx 10^{-10}\ \mathrm{s}$$

Lab measurement: $\tau \approx 1\ \mathrm{s} \Rightarrow \Delta\mathcal{E} \approx 25 k_B T$

$$\Rightarrow H_c = \frac{2K}{\mu_0 M_S}\left(1 - \sqrt{\frac{25 k_B T}{KV}}\right)$$



Blocking temperature $T_b \simeq KV/25 k_B$

Blocked state ← | → Superparamagnetism

E. F. Kneller, J. Wijn (ed.) Handbuch der Physik XIII/2: Ferromagnetismus, Springer, 438 (1966)

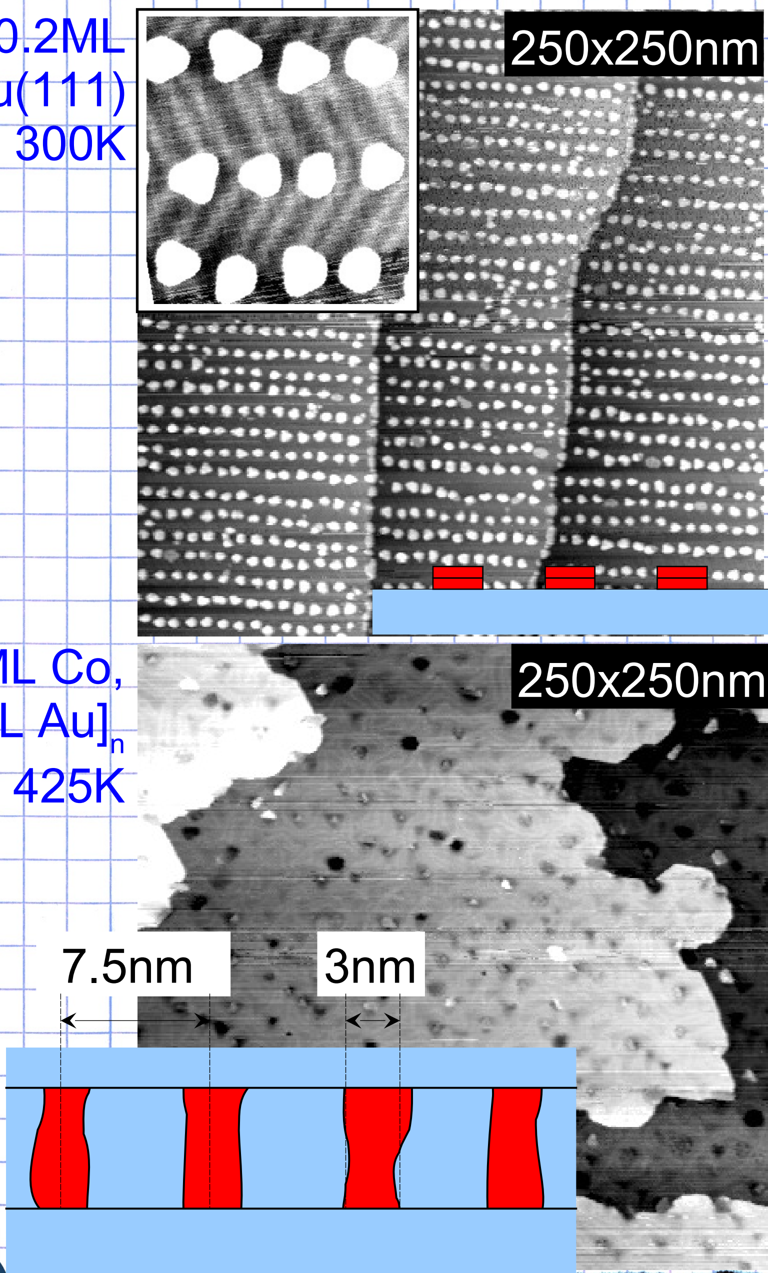
M. P. Sharrock, J. Appl. Phys. 76, 6413-6418 (1994)

Notice, for magnetic recording :

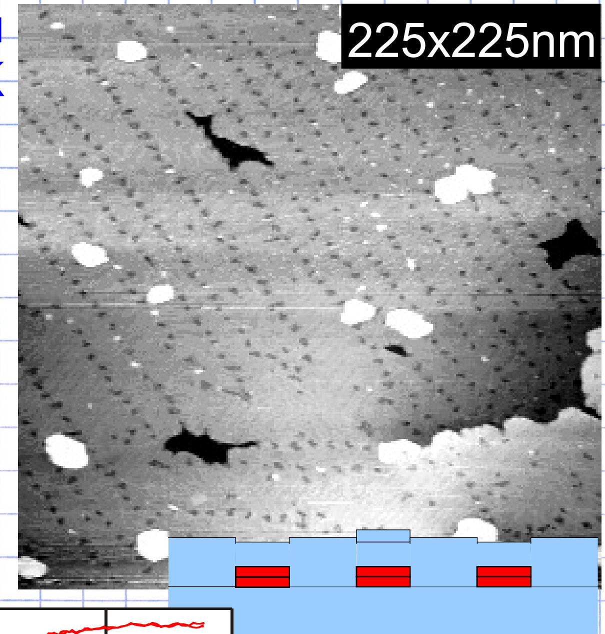
$\tau \approx 10^9\ \mathrm{s}$ $\qquad KV_b \approx 40-60 k_B T$

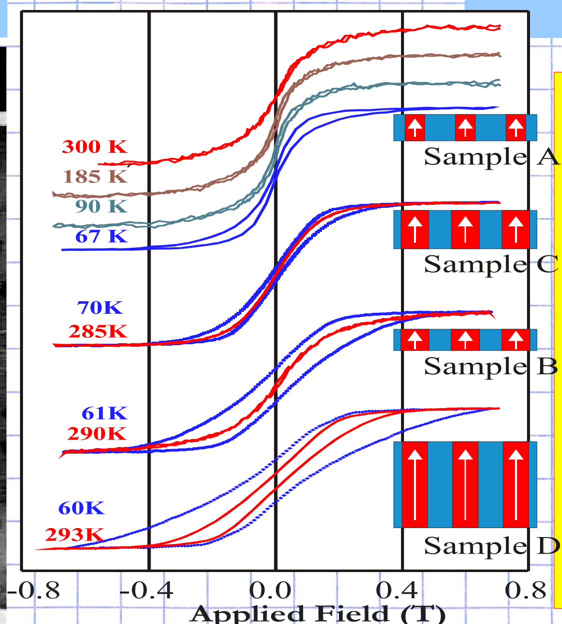
0.2ML Co/Au(111) @ 300K

+[0.1ML Co, 0.9ML Au]$_n$ @ 425K



+3.8ML Au @ 400K



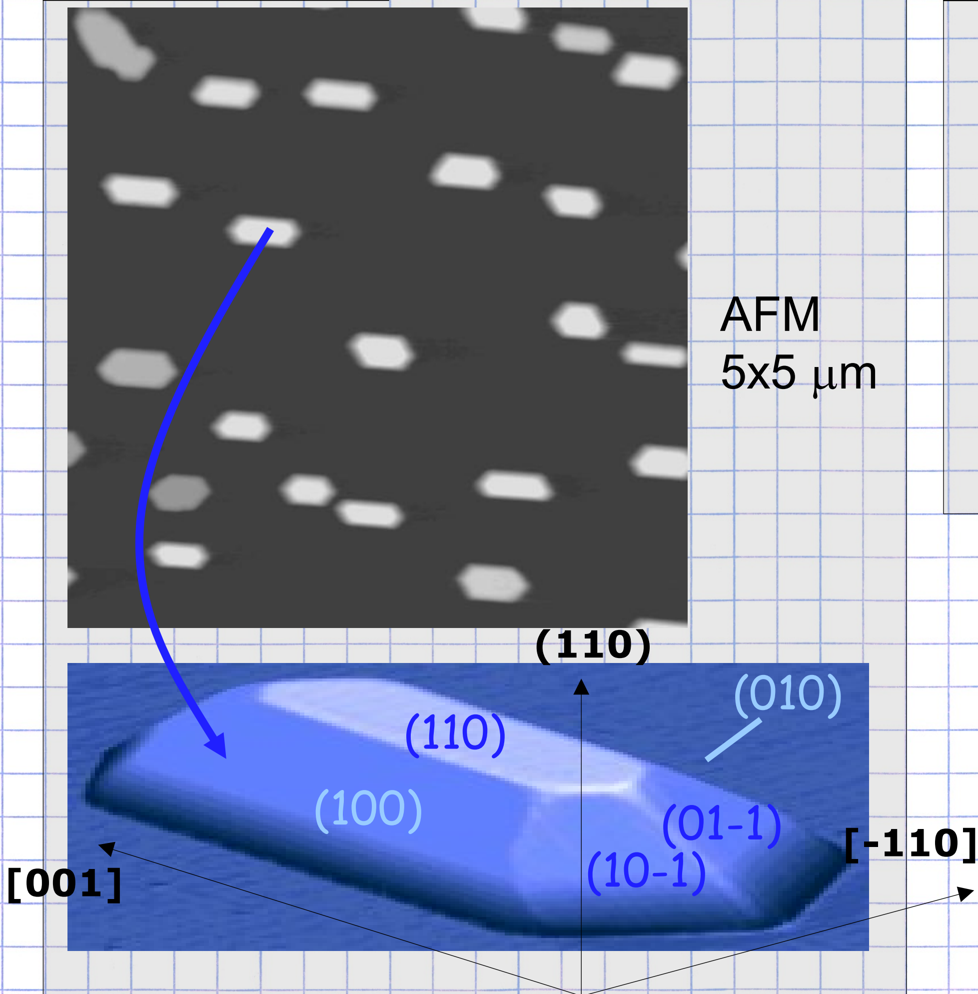


- 3D replication of 2D pattern
- Recovery of coercivity and remanence
- Similar to columns of CoCr for hard disk drives

O. Fruchart et al., PRL23 (14), 2769 (1999)

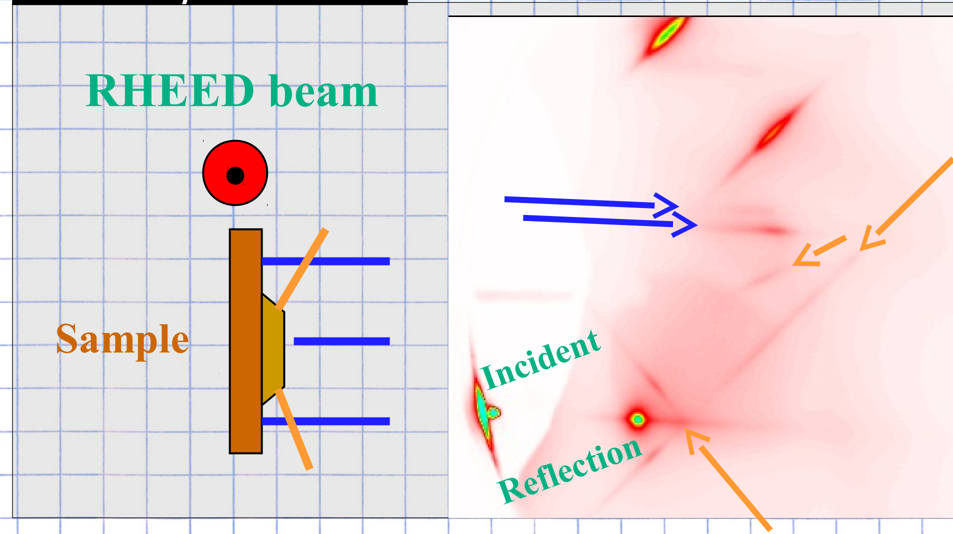
Shape in real space

$Fe/W(110)/Al_2O_3(11\text{-}20)$

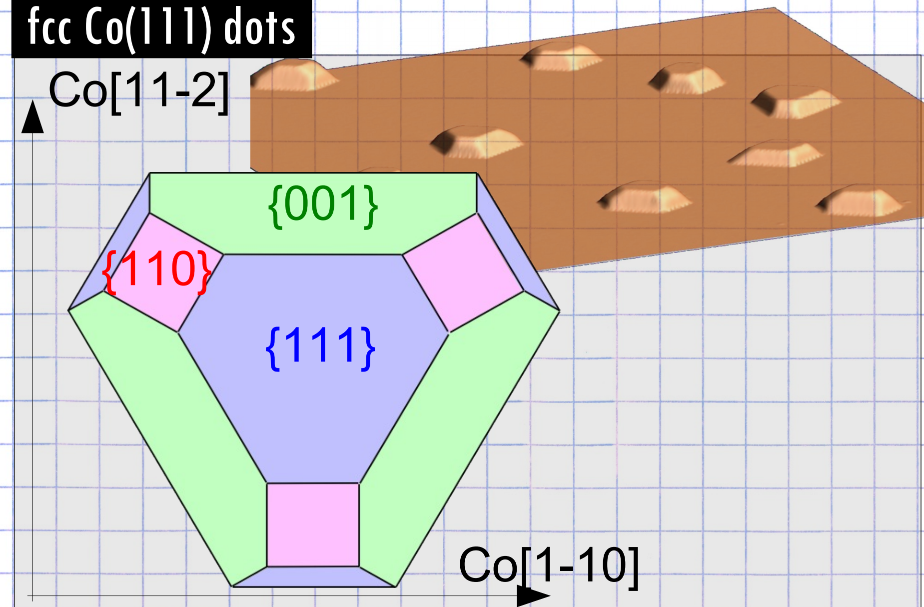


O. Fruchart et al., J. Phys.: Condens. Matter 19, 053001, Topical Review (2007).

Atomically flat facets

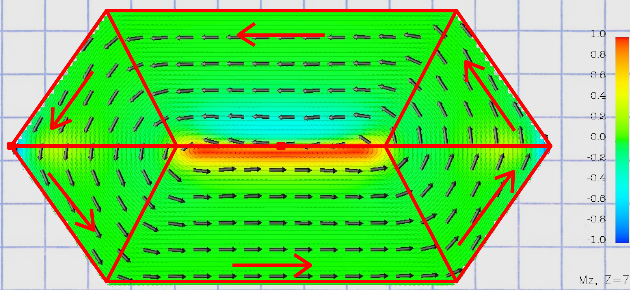


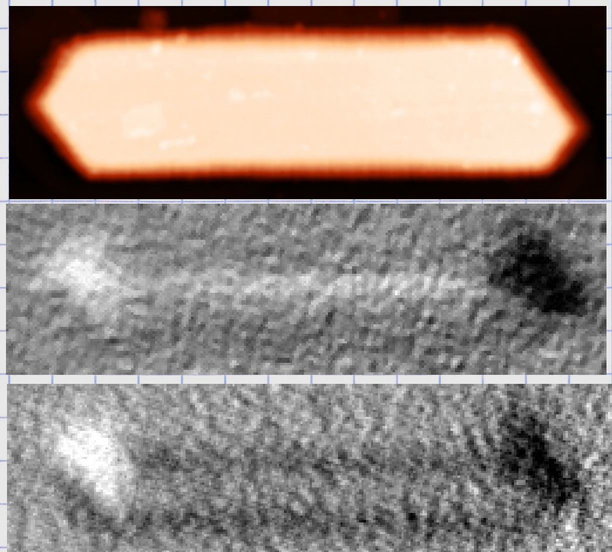
fcc Co(111) dots



Magnetization processes inside domain walls

Landau states: flux closure

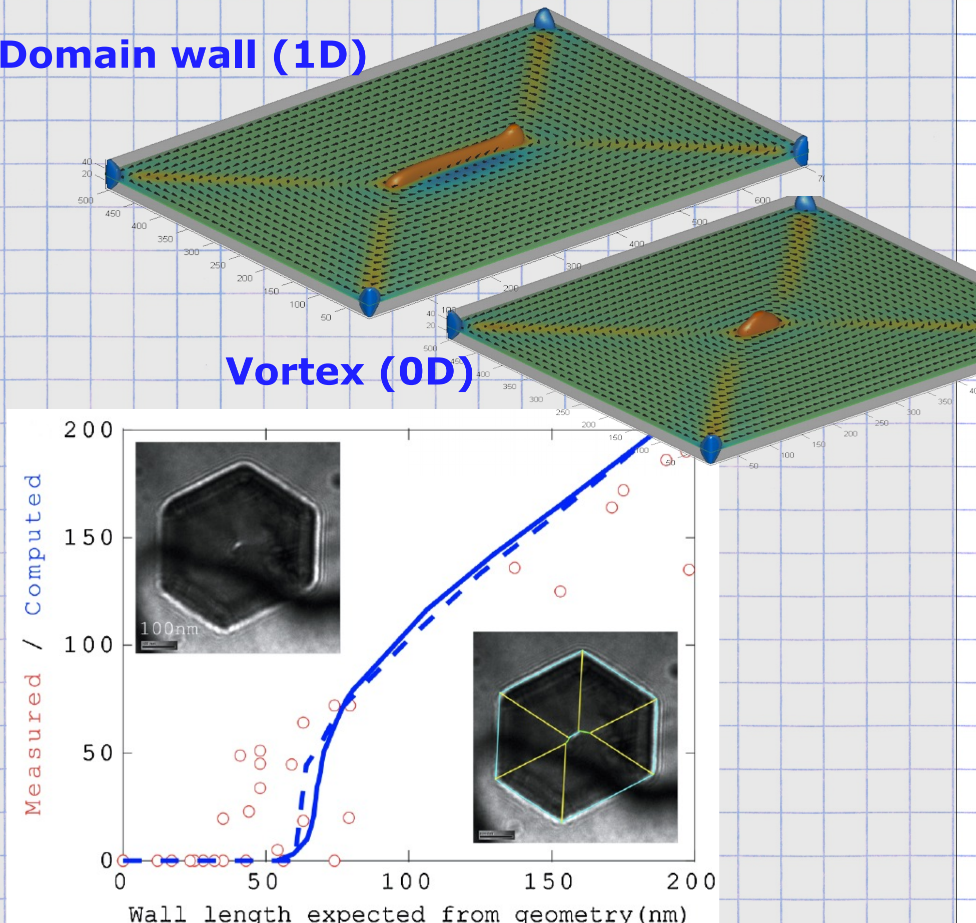




X-ray Magnetic Circular Dichroism
PhotoEmission Electron Microscopy

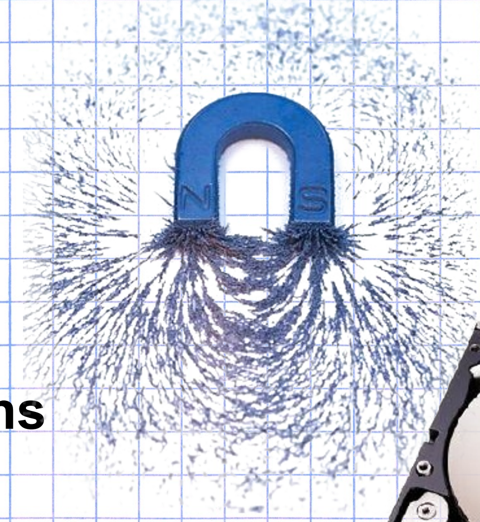
F. Cheynis et al., PRL 102, 107201 (2009)

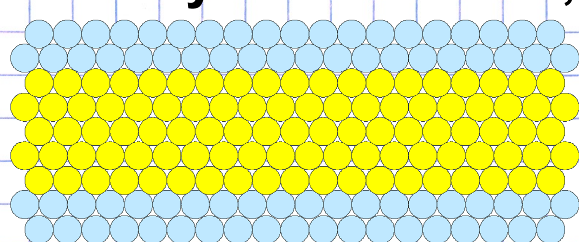
Dimensionality cross-over : from 0D to 1D textures

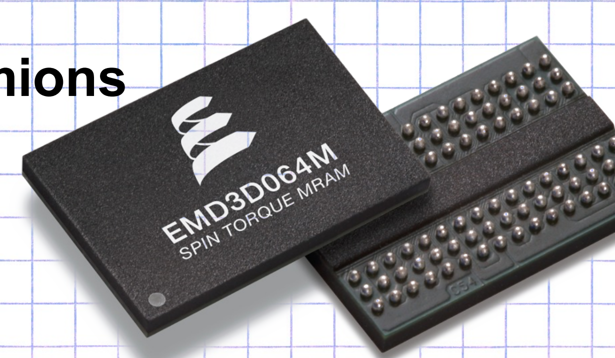


Transition is of second order

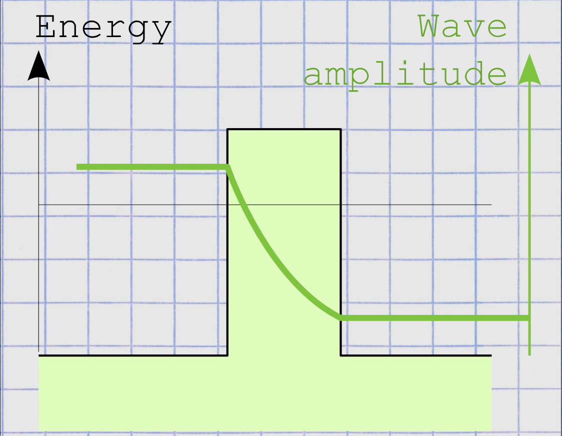
A. Masseboeuf et al., PRL 104, 127204 (2010)


N
S




EMD3D064M
SPIN TORQUE MRAM

Tunneling resistance



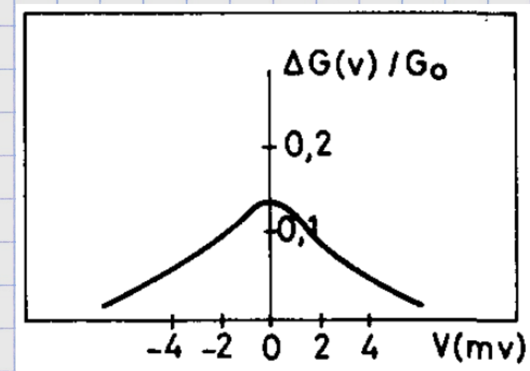
- Exponential decay of wave functions in the barrier

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

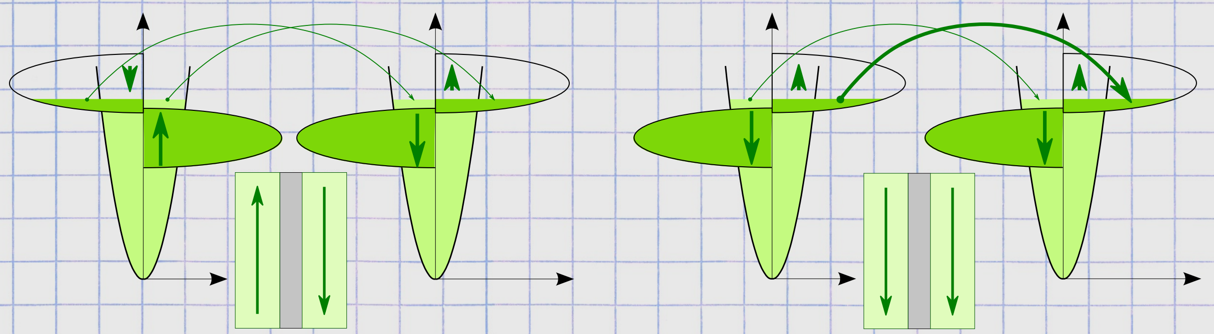
Tunneling magneto-resistance

- Discovery at 4.2K for Fe/Ge/Fe stacks

M. Julliere, Phys. Lett. 54A, 3, 225 (1975)



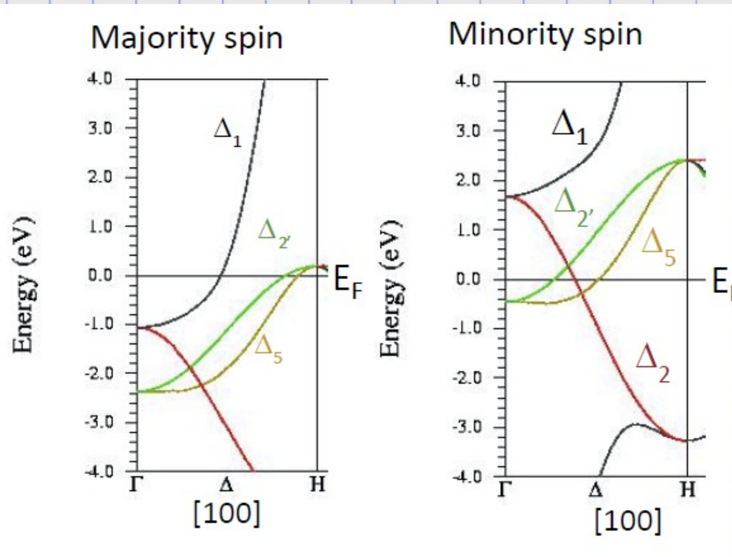
Antiparallel (AP) Parallel (P)

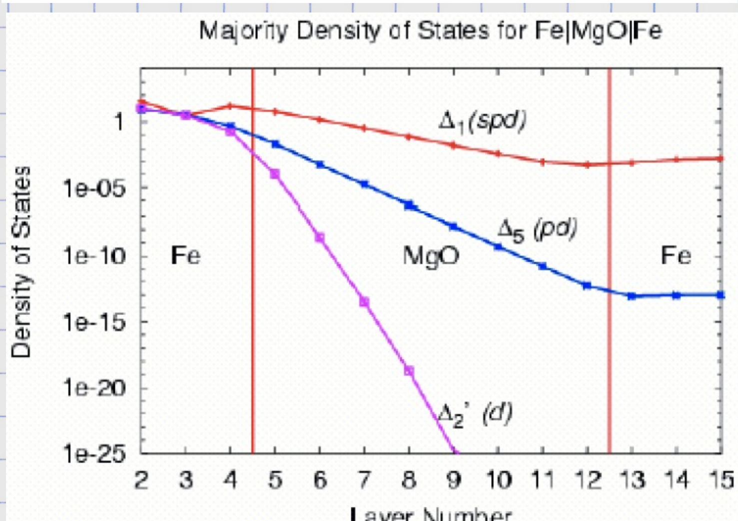


- Define polarization : $P = \frac{D_{Maj} - D_{Min}}{D_{Maj} + D_{Min}}$

- Define and evaluate TMR ratio : $TMR = \frac{\Delta R}{R_p} = \frac{2P^2}{1-P^2}$

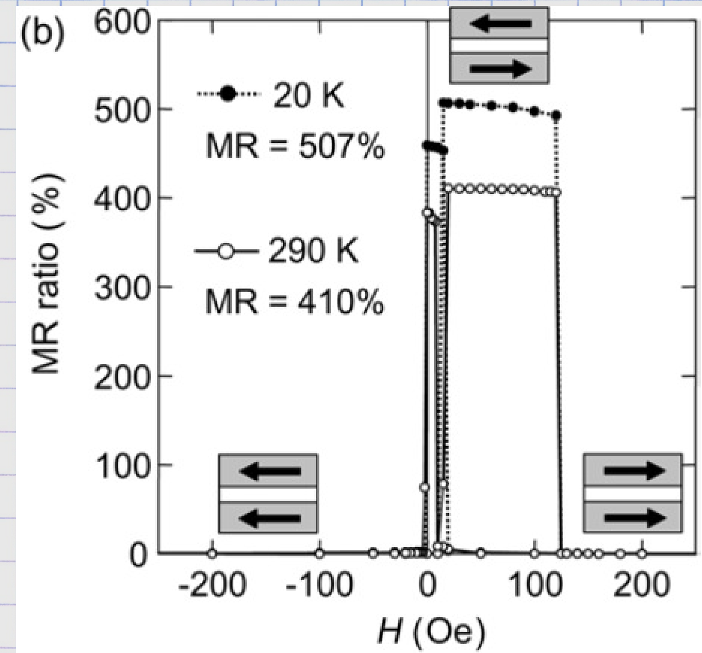
Prediction

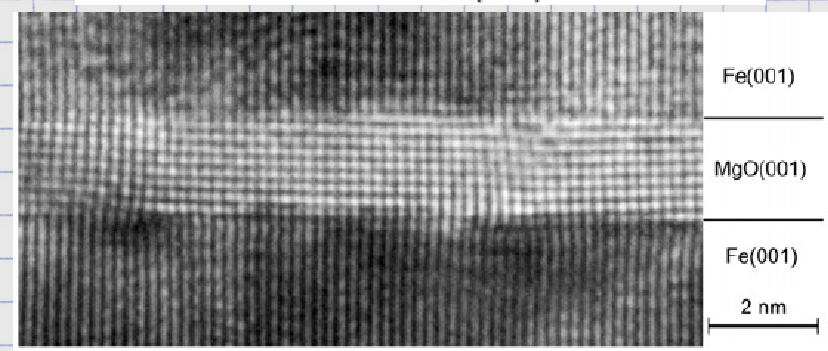




Butler et al., Phys. Rev. B 63, 220403 (R) (2001)

Implementation



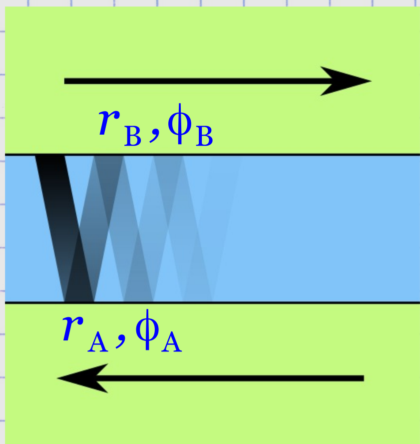


S. Yuasa, J. Phys. D 40, R337 (2007)

⇨ NB : >500 % with CoFeB electrodes

The physics

Spin-dependent quantum confinement in the spacer layer



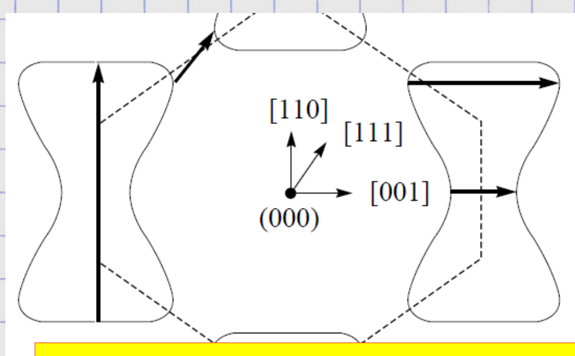
Forth & back phase shift

$$\Delta\phi = qt + \phi_A + \phi_B$$

Spin-dependent

$$r_A, \phi_A, r_B, \phi_B$$

⇨ Constructive or destructive interferences with spacer thickness



Cu Fermi surface

↳ **Depends on crystal direction**

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

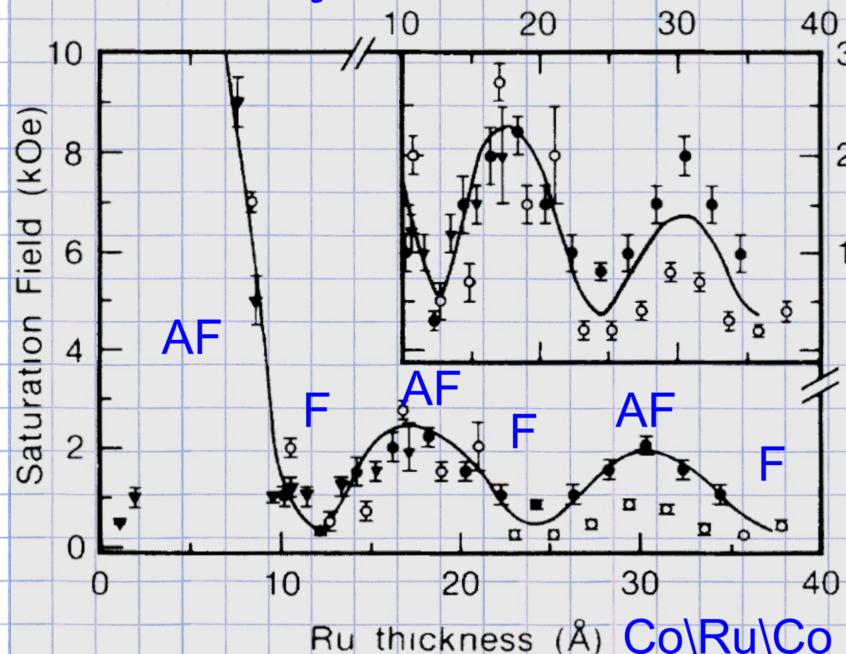
Illustration

Coupling strength:

$$E_S = J(t)\cos\theta \quad \text{in } J/m^2$$

$$\theta = \langle m_1, m_2 \rangle$$

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

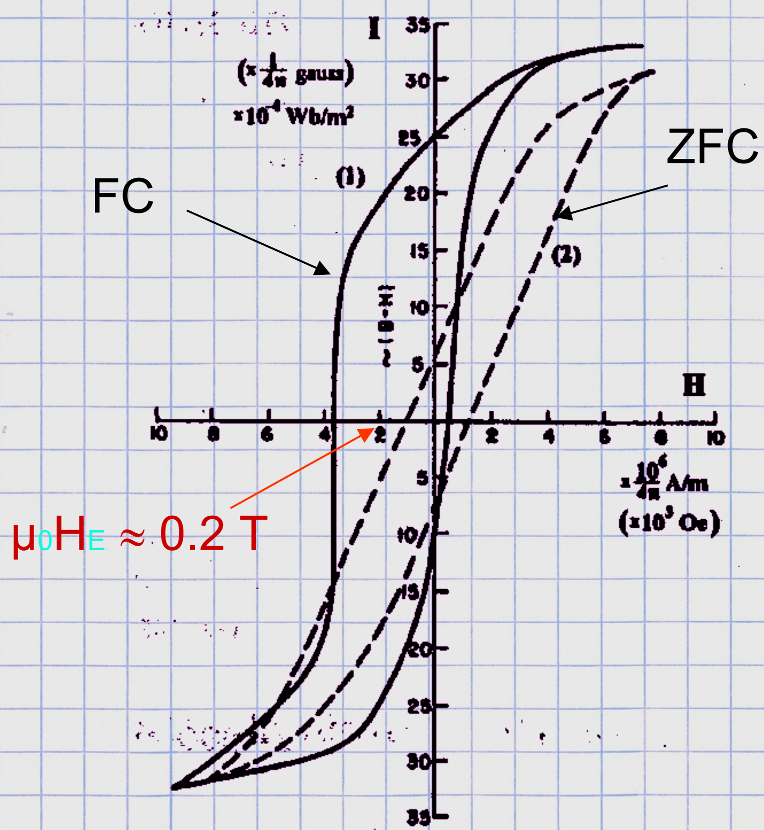


Co\Ru\Co

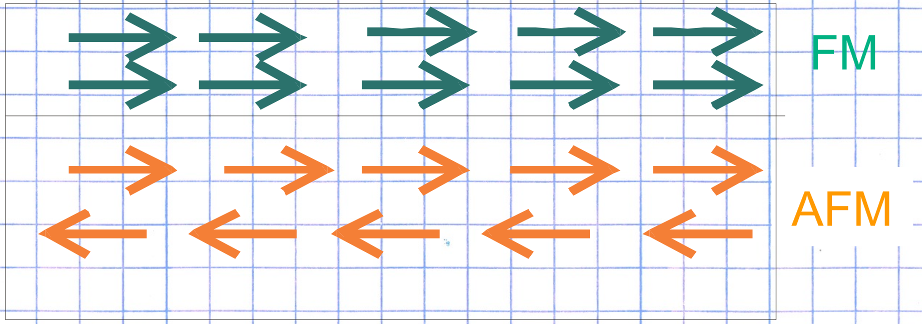
S. S. P. Parkin et al., PRL64, 2304 (1990)

Seminal studies

Oxidized Co nanoparticles



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



Field-cooled hysteresis loops

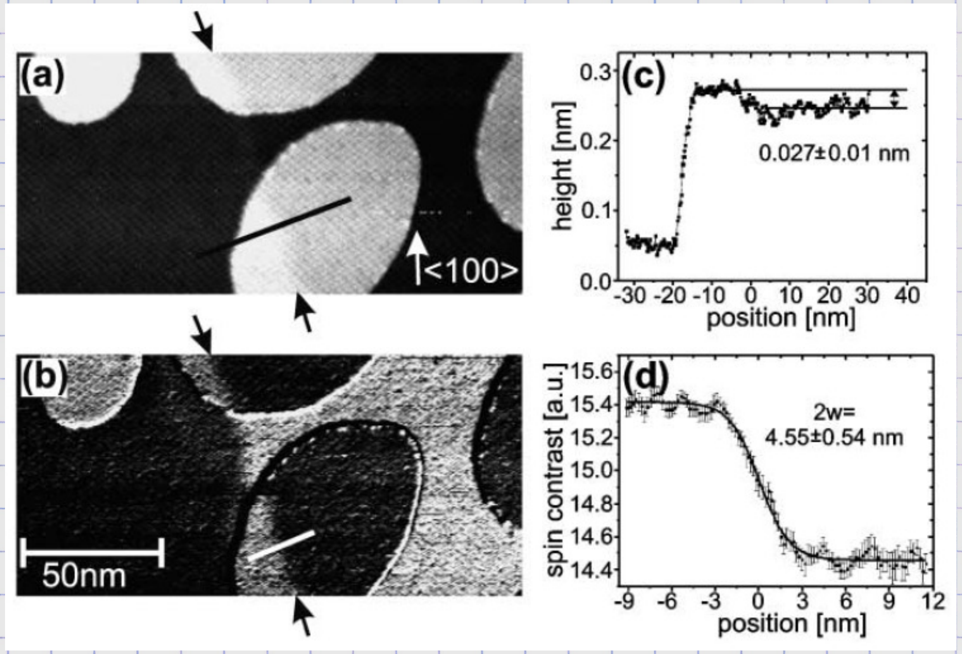
- Shift in field
- Increase coercivity

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)

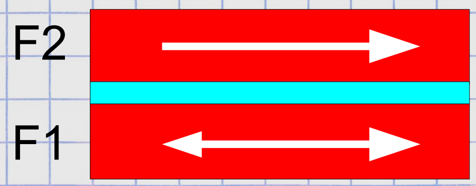
Frustration starting at step edges

Analysis with spin-polarized STM



U. Schlickum, Phys. Rev. Lett. 92, 107203 (2004)

RKKY Synthetic Ferrimagnets (SyF) – Basics



Crude phenomenology:

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

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

⇨ Enhances coercive field

⇨ Reduces cross-talk

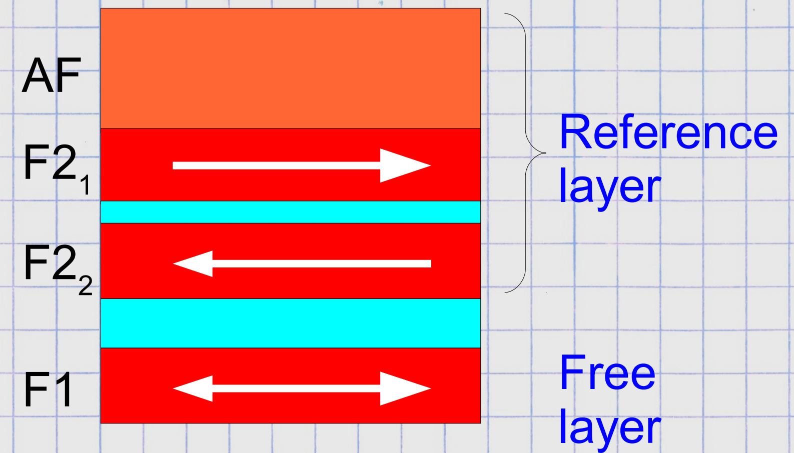
Practical aspects

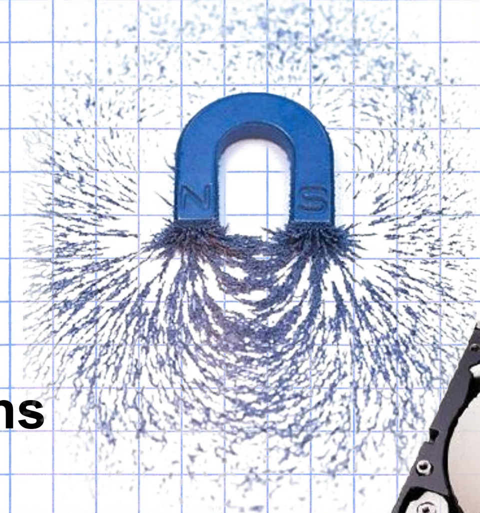
⇨ Ru spacer layer (largest effect)

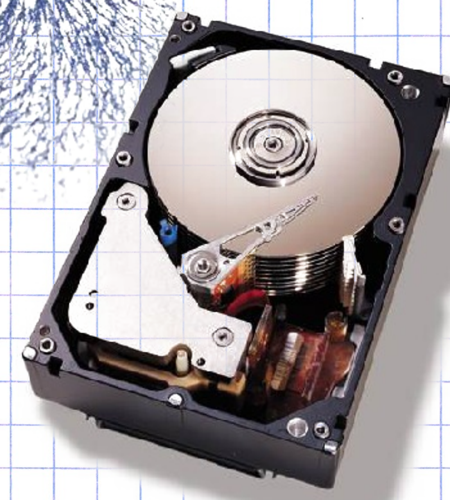
⇨ Control thickness within a few Angströms !

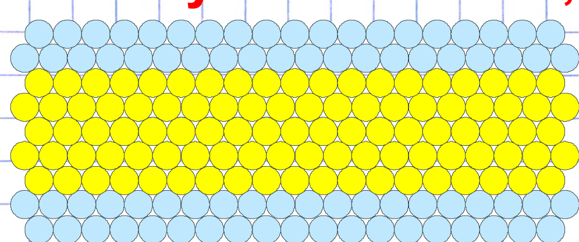
Spin valves

⇨ 'Free' and reference layers





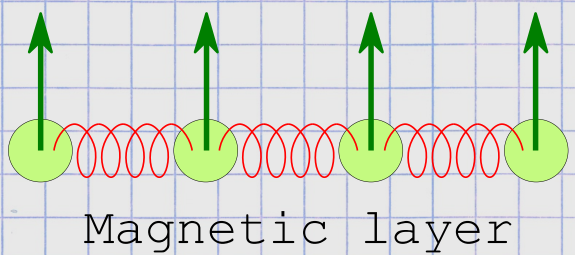





EMD3D064M
SPIN TORQUE MRAM

The usual ferromagnetic exchange interaction

$$E_{1,2} = -J\,\mathbf{S}_1.\mathbf{S}_2$$



⇨ Favors parallel alignment

⇨ Ferromagnetic ordering

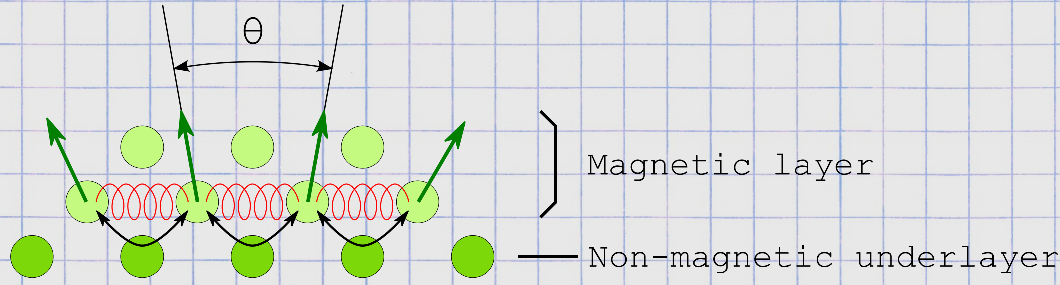
The Dzyaloshinskii-Moriya interaction

$$E_{1,2} = -\mathbf{D}_{1,2}.\left(\mathbf{S}_1 \times \mathbf{S}_2\right)$$

Symmetry considerations

→ Requires absence of inversion symmetry

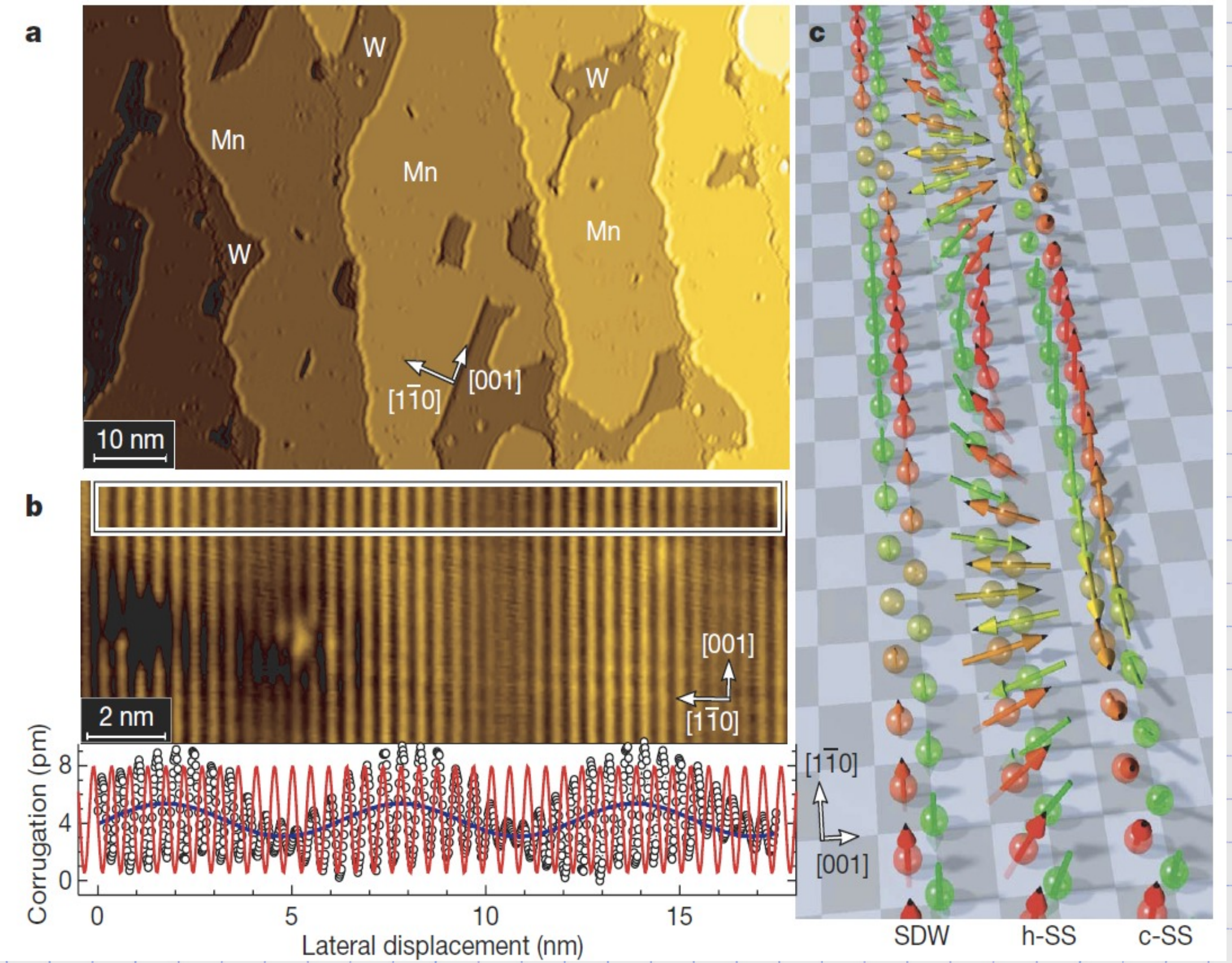
→ May be bulk or interfacial



⇨ Favors spin spirals or cycloids

Chiral spin structures at interfaces

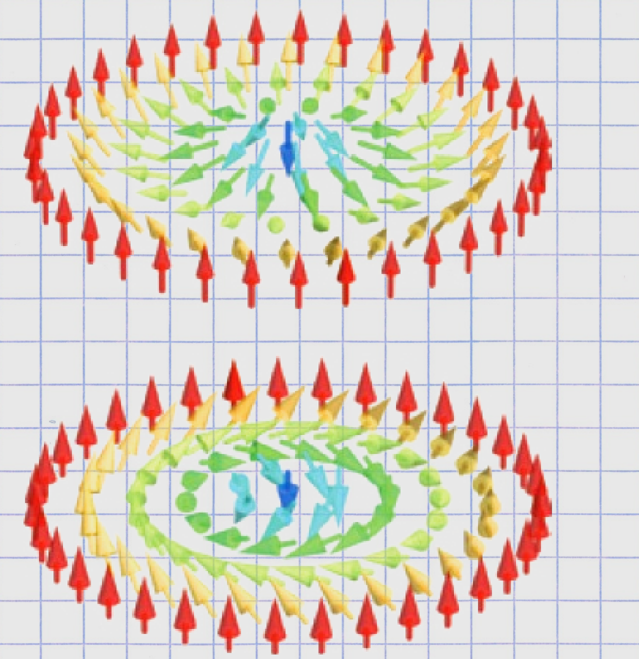
Mn/W(110)



Spin-polarized STM

M. Bode et al., Nature 477, 190 (2007)

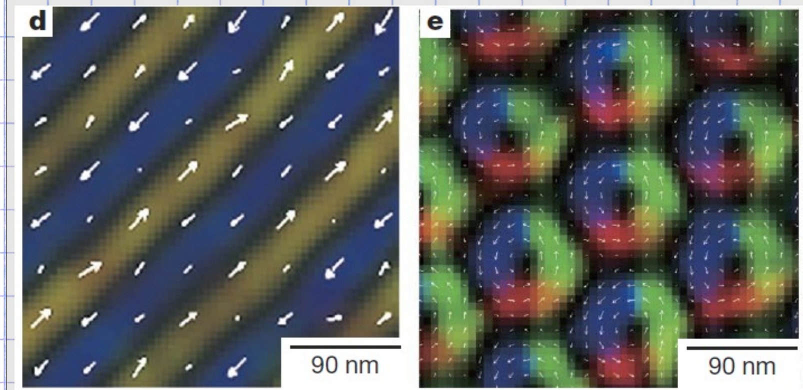
What is a skyrmion ?



- Spiral or chiral 0D texture
- Topological protection
- NB : is NOT a magnetic vortex

First proof (bulk) $Fe_{0.5}Co_{0.5}Si$

Spiral phase under perpendicular field

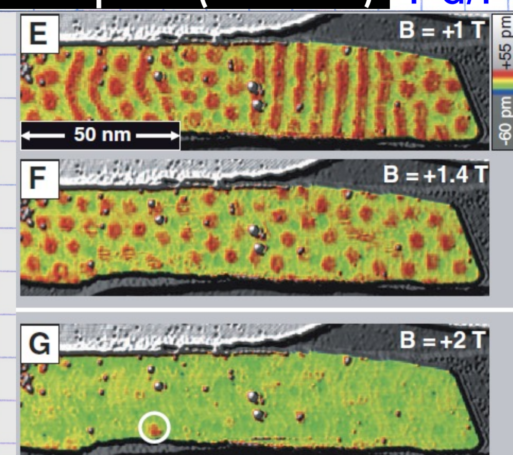


H=0 **H≠0**

- Array of skyrmions

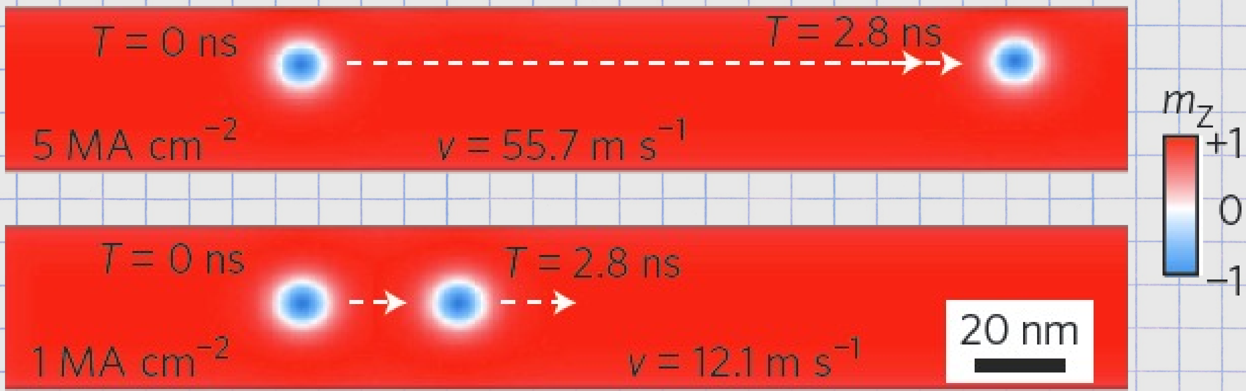
X. Z. Yu et al., Nature 465, 901 (2010)

First proof (interface) Pd/Fe/Ir(111)



N. Romming, Science 341 (2013)

Simulations

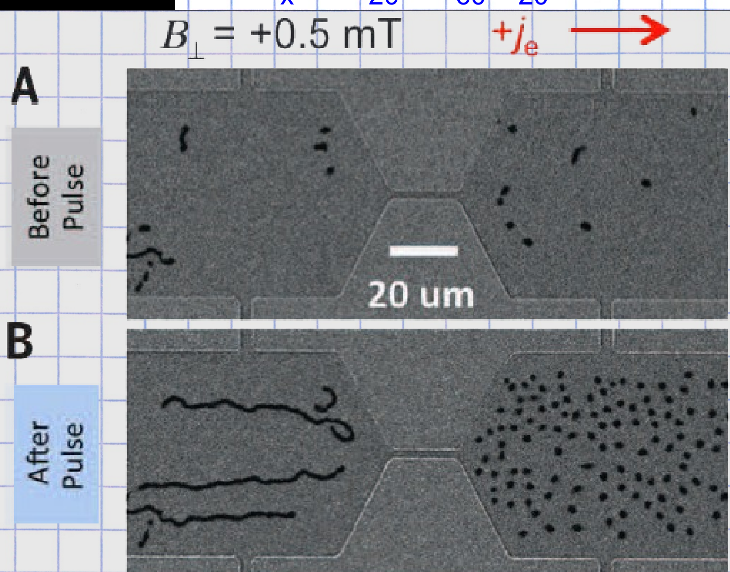


A. Fert etal., Nature Nanotech. 8, 152 (2013)

- Single skyrmions may exist as metastable entities
- Skyrmions may be moved with spin-polarized current (spin transfer effect)

Experiments

$TaO_x/Co_{20}Fe_{60}B_{20}/Ta$



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

- Skyrmions may be nucleated
- Skyrmions may be moved with electric current

Epitaxy and magnetic materials

O. Fruchart

Institut NEEL
CNRS & Univ. Grenoble - Alpes
Grenoble - France