(Quelques) tendances et défis du magnétisme en dimensions réduites

Fondements et applications à l'électronique de spin

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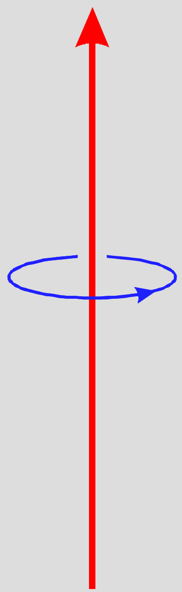
Grenoble

CNRS from mountains

Part of the lab (Summer)

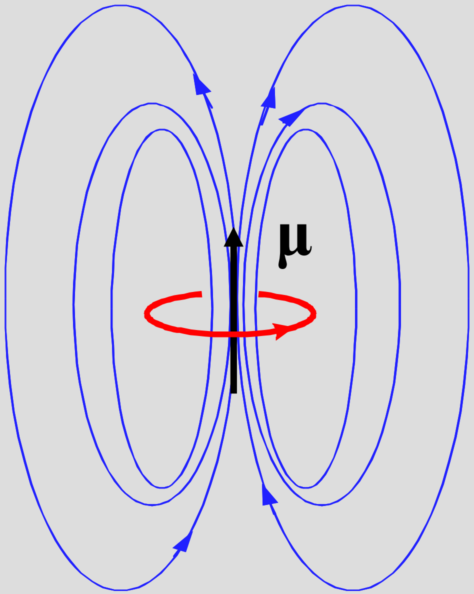
Table of Contents

Oersted field



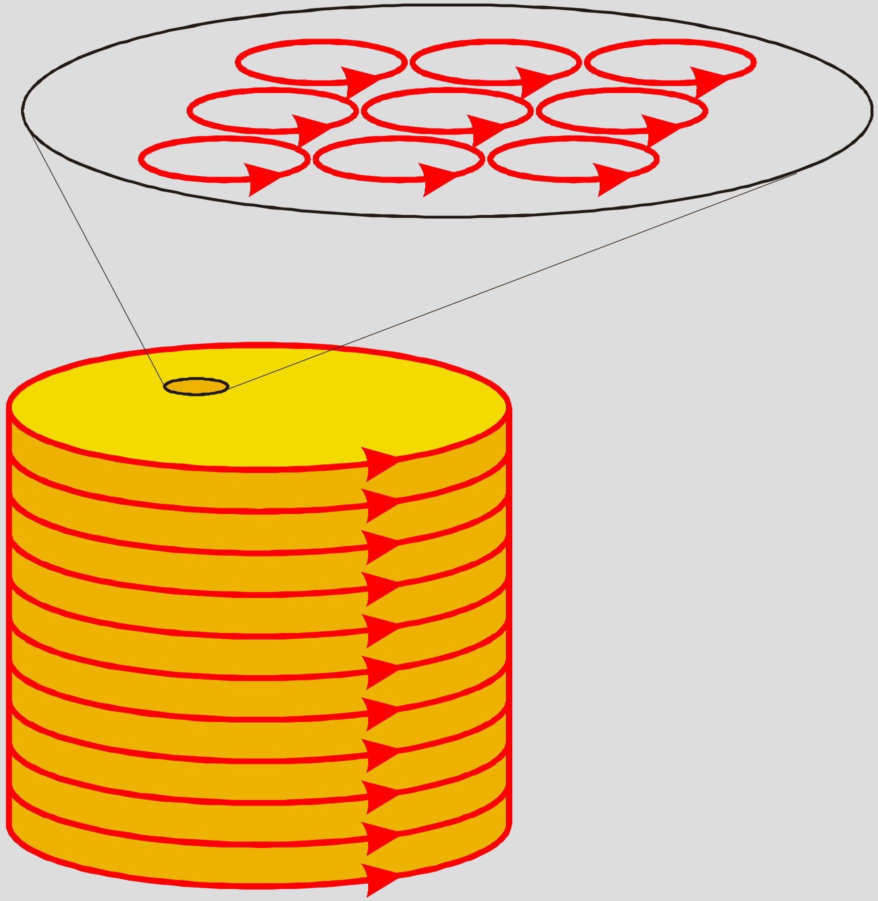
$$B = \frac{\mu_0 I}{2\pi r}$$

Magnetic moment



$$B = \frac{\mu_0}{4\pi r^3} \times \left[\frac{3}{r^2}(\boldsymbol{\mu}.\mathbf{r})\mathbf{r} - \boldsymbol{\mu} \right]$$

Magnetic material

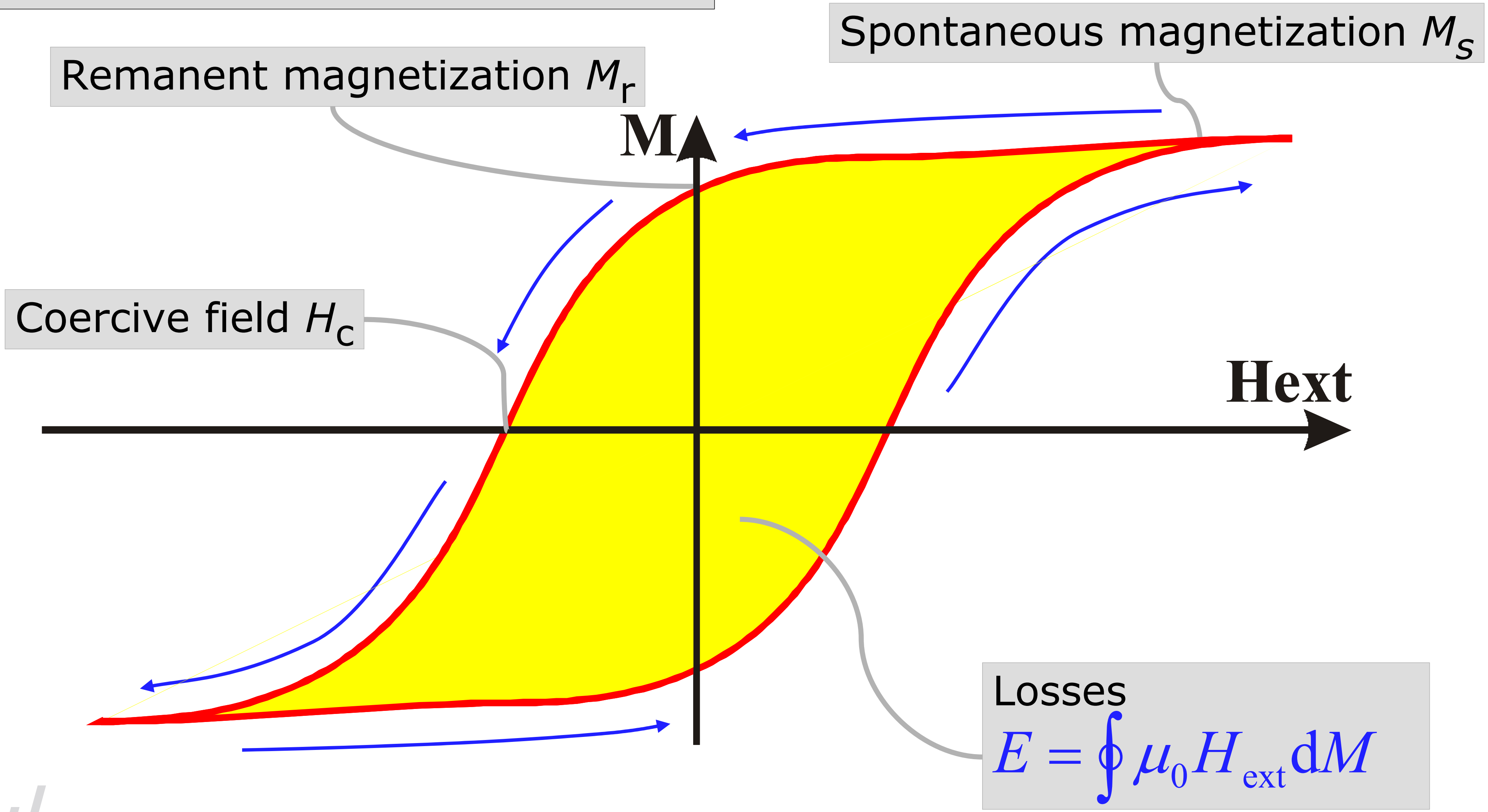


Magnetization: $A.m^{-1}$

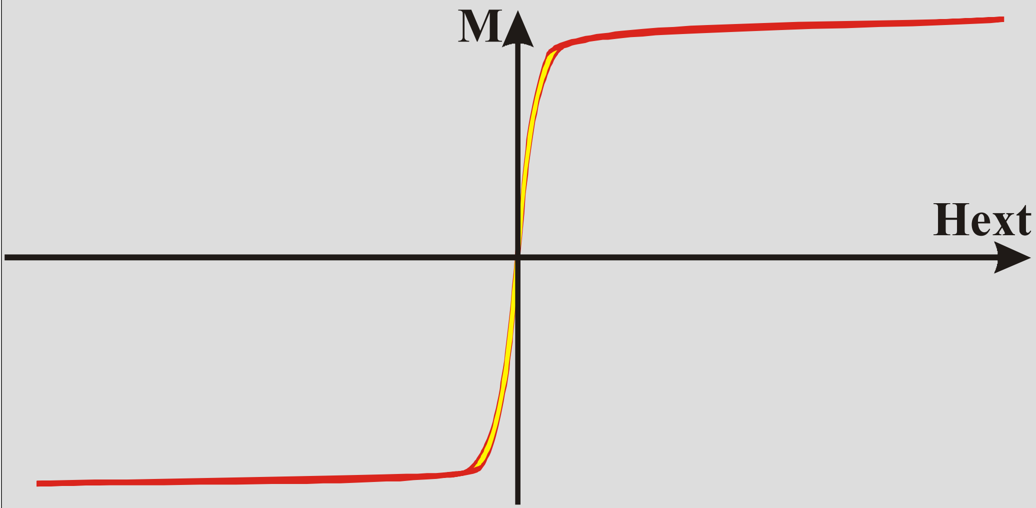
Magnetic moment: $A.m^{2}$

Manipulation of magnetic materials:
↳ Application of a magnetic field

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



Soft materials

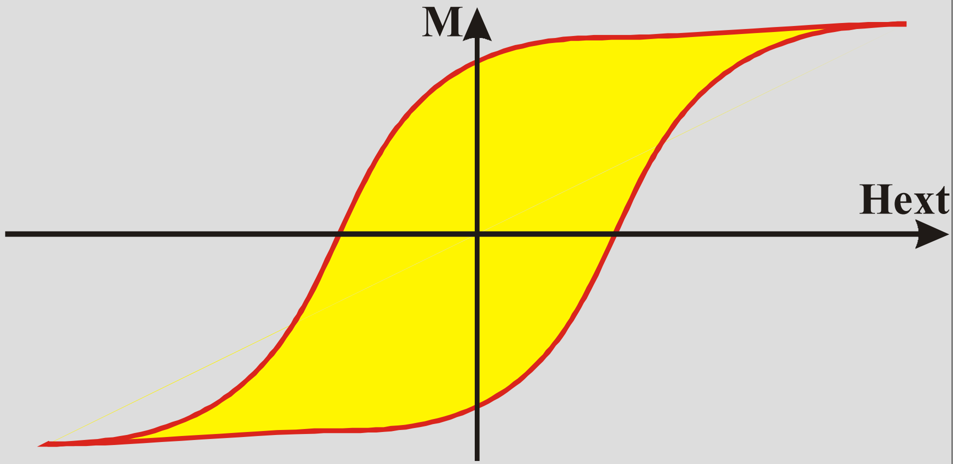


Transformers

Flux guides

Magnetic shielding

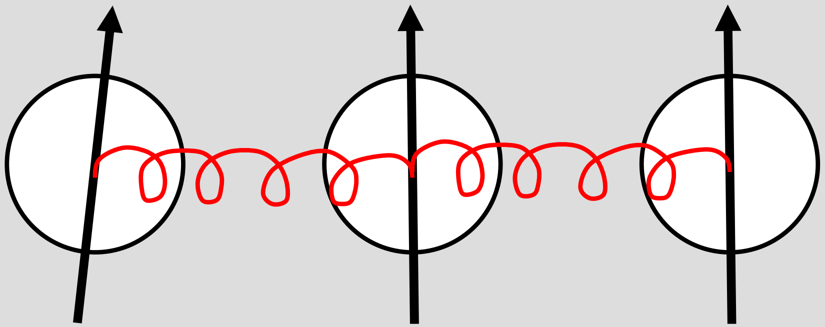
Hard materials



Permanent magnets, motors

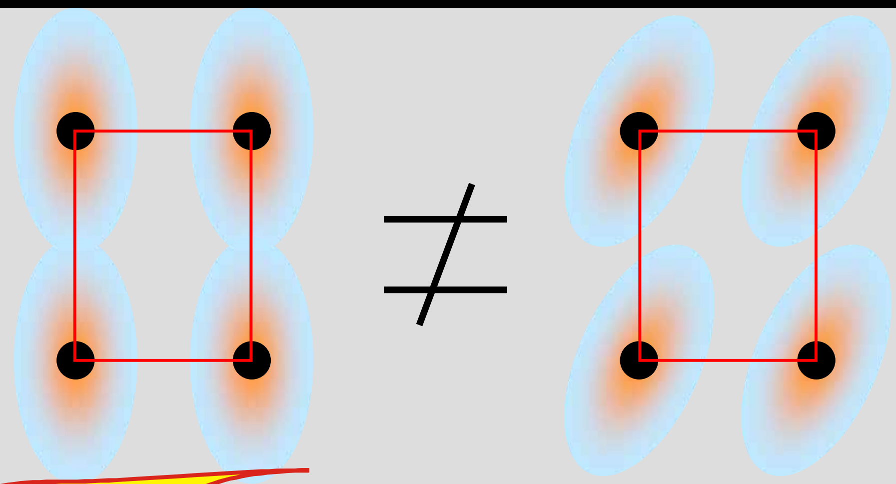
Magnetic recording

Echange energy

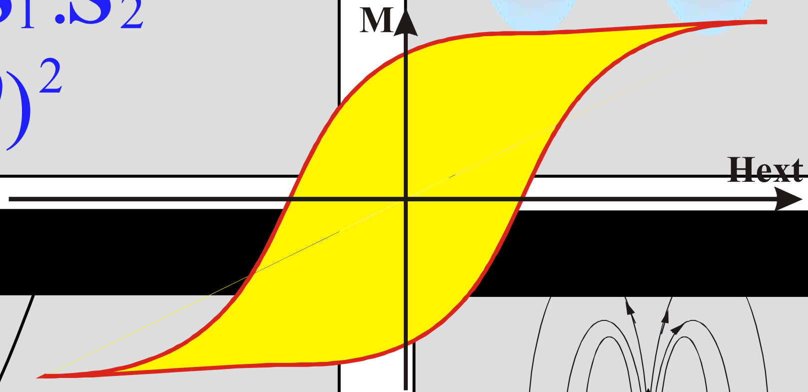


$$E_{\mathrm{Ech}} = -J_{1,2}\,\vec{\mathbf{S}}_1 . \vec{\mathbf{S}}_2 = A(\nabla\theta)^2$$

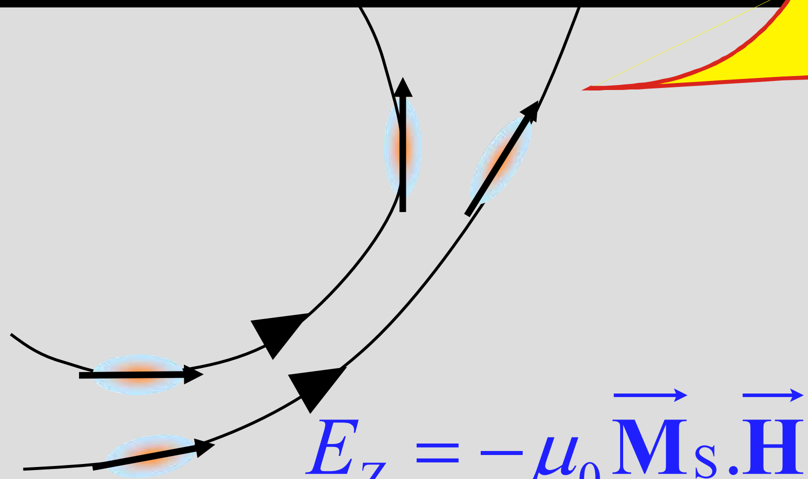
Magnetocrystalline anisotropy energy



$$E_{\mathrm{mc}} = K\sin^2(\theta)$$

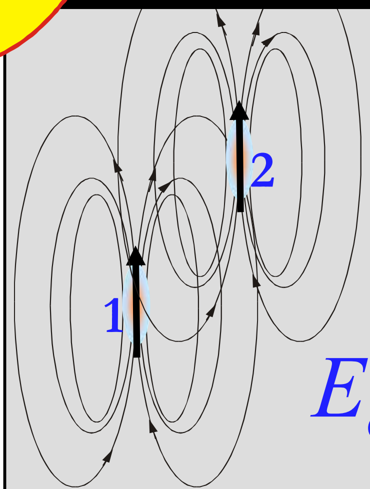


Zeeman energy (enthalpy)



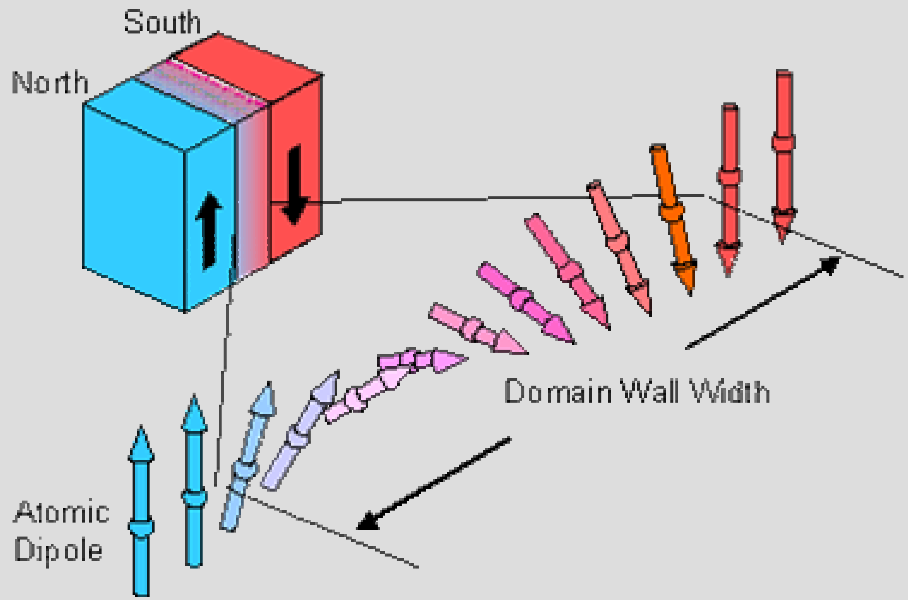
$$E_{\mathrm{Z}} = -\mu_0\,\vec{\mathbf{M}}_{\mathrm{S}} . \vec{\mathbf{H}}$$

Dipolar energy



$$E_{\mathrm{d}} = -\frac{1}{2}\mu_0\,\vec{\mathbf{M}}_{\mathrm{S}} . \vec{\mathbf{H}}_{\mathrm{d}}$$

Typical length scale: Bloch wall width λ_B



$$e = A(d\theta / dx)^2 + K \sin^2 \theta$$

Exchange → J/m

Anisotropy → J/m^3

Numerical values

$$\lambda_B = \pi\sqrt{A/K}$$

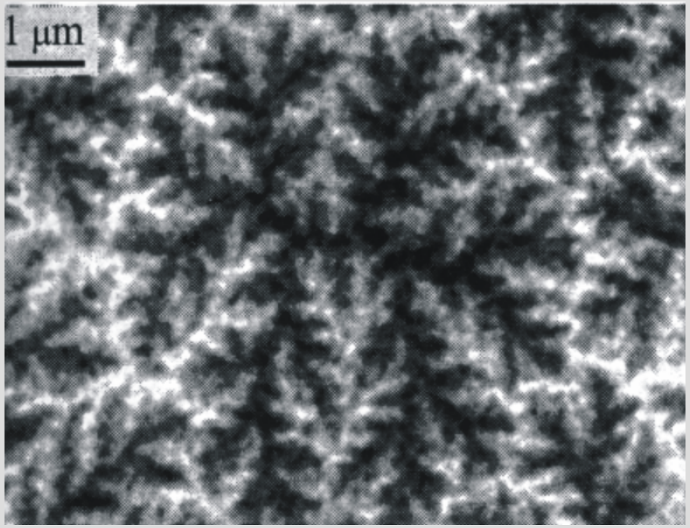
$\lambda_B = 2-3$ nm ⟶ $\lambda_B \geq 100$ nm

Hard   Soft

Nanomagnetism ~ mesoscopic magnetism

Bulk material

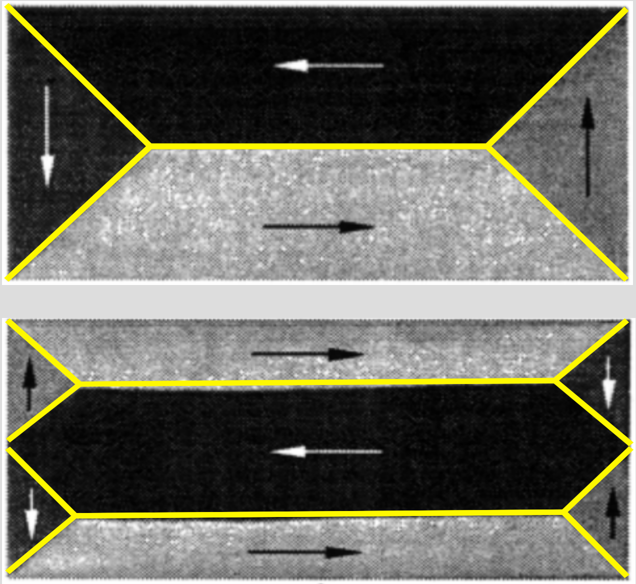
Numerous and complex magnetic domains



Co(1000) crystal - SEMPA
A. Hubert, *Magnetic domains*

Mesoscopic scale

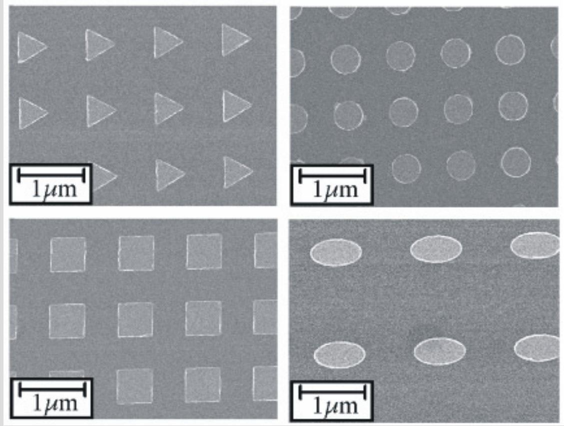
Small number of domains, simple shape

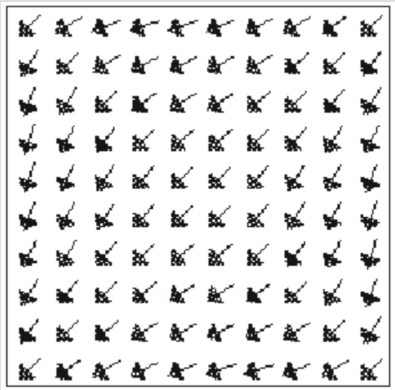


Microfabricated dots
Kerr magnetic imaging
A. Hubert, *Magnetic domains*

Nanometric scale

Magnetic single-domain





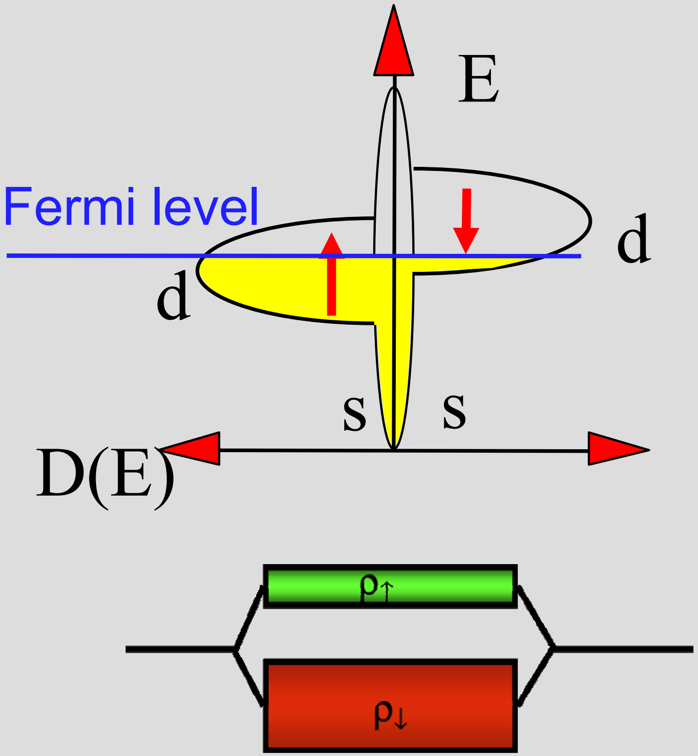
R.P. Cowburn, J.Phys.D:Appl.Phys.33, R1 (2000)

Magnetic recording essentially makes use of single-domain particles

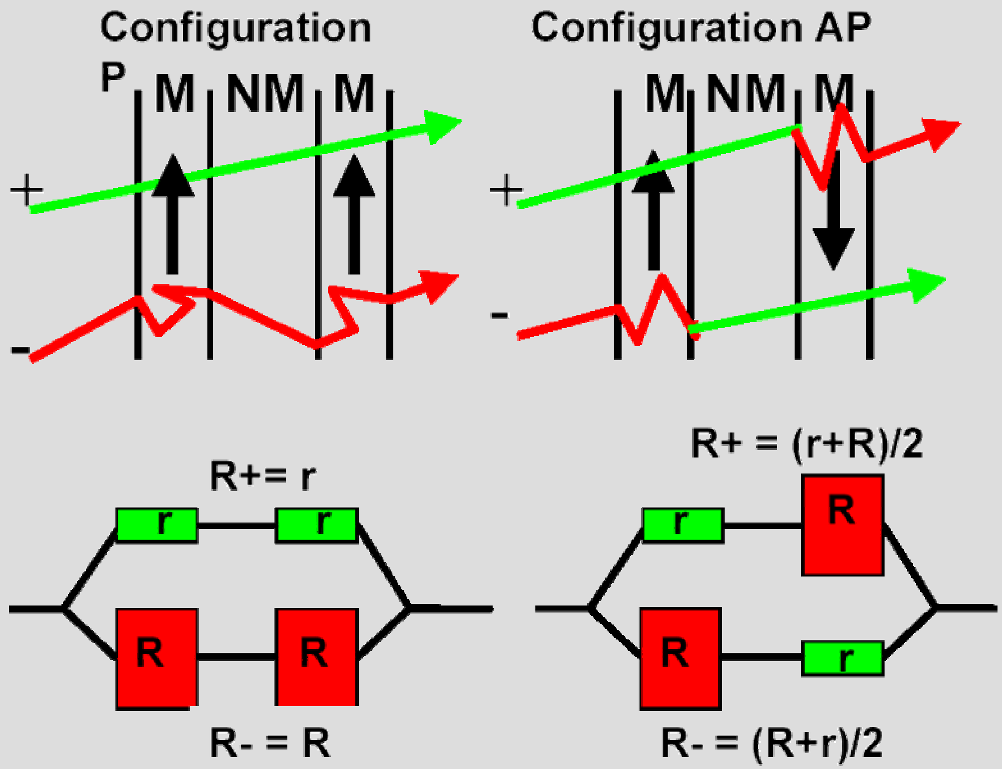
Principle of GMR

Discovery: 1988, A. Fert (CNRS-Thalès) and P. Grünberg (Jülich)

Spin filtering in an heterostructure



Two-current model



Features

$\Delta R \propto \cos(\theta)$

Geometry: multilayers

Magnitude: ≤ 40-50%

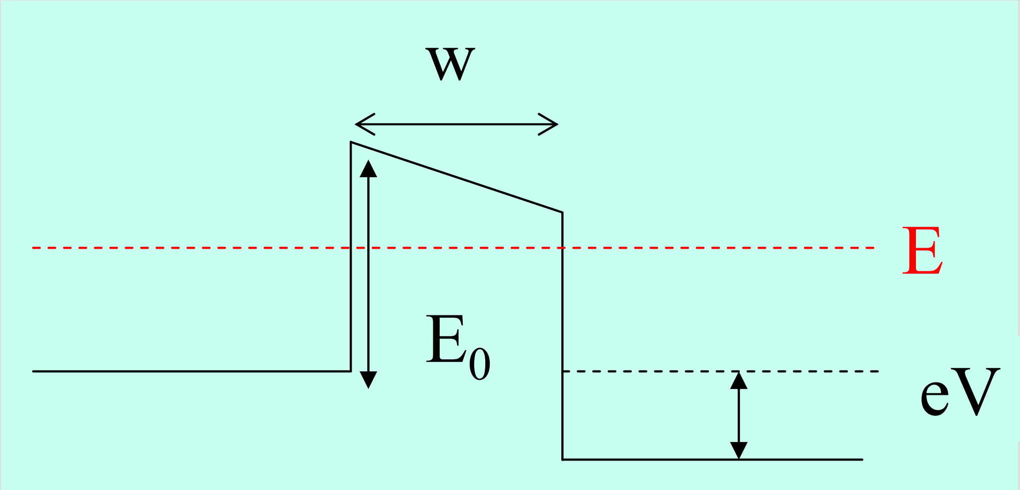
Applications

- Magnetic sensors: compass, read heads
- Magnetic memory direct reading

Principle of TMR

Discovery: 1975 (Jullière); 'rehabilitated' 1995, Moodera et coll.

- Spin filtering in heterostructures
- Electron tunnelling between electrodes



- Mécanique classique: pas de courant
- Mécanique quantique: courant tunnel

Équation de Schrödinger

$$-\frac{\hbar^2}{2m}\frac{d^2}{dx^2}\left|\psi\right\rangle + V(x)\left|\psi\right\rangle = E\left|\psi\right\rangle$$

Features

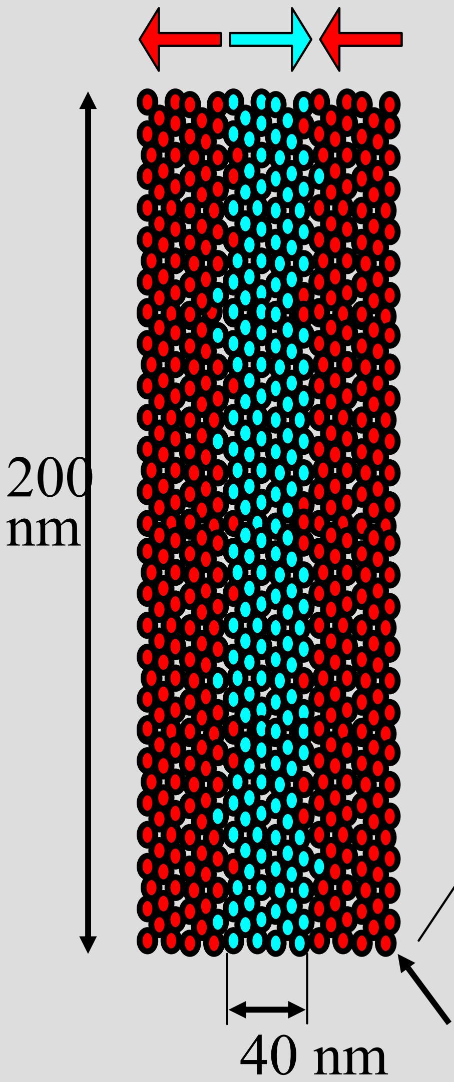
$$\Delta R \propto \cos(\theta)$$

Geometry: multilayers
Magnitude: ≤ 100-150%
High resistance
Ultrathin oxyde layer

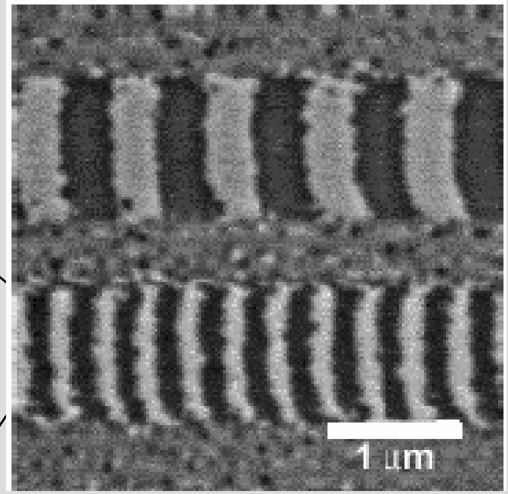
Applications

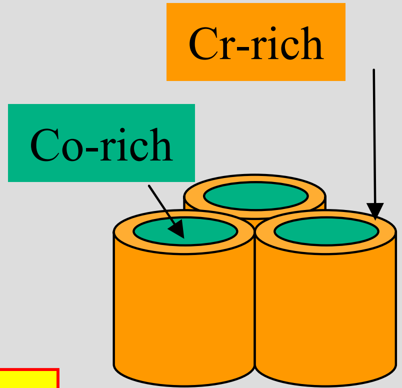
- Magnetic sensors
- Magnetic memory direct reading

Media: granular and columnar

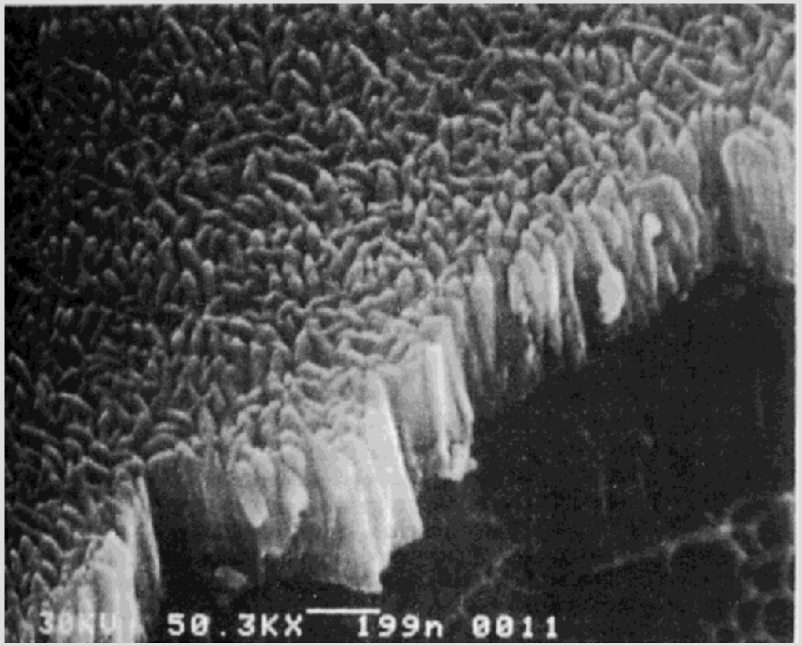


Large number of grains per bit



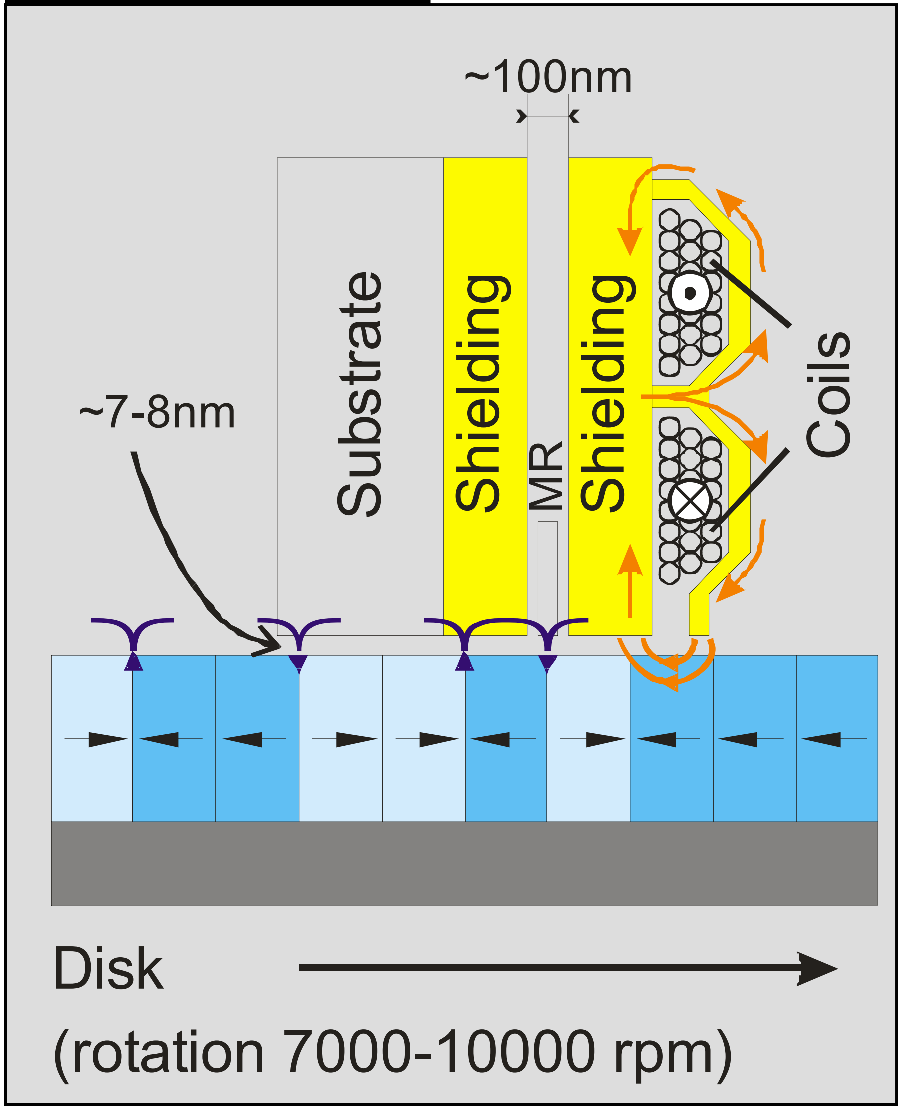


Grain : 10 nm

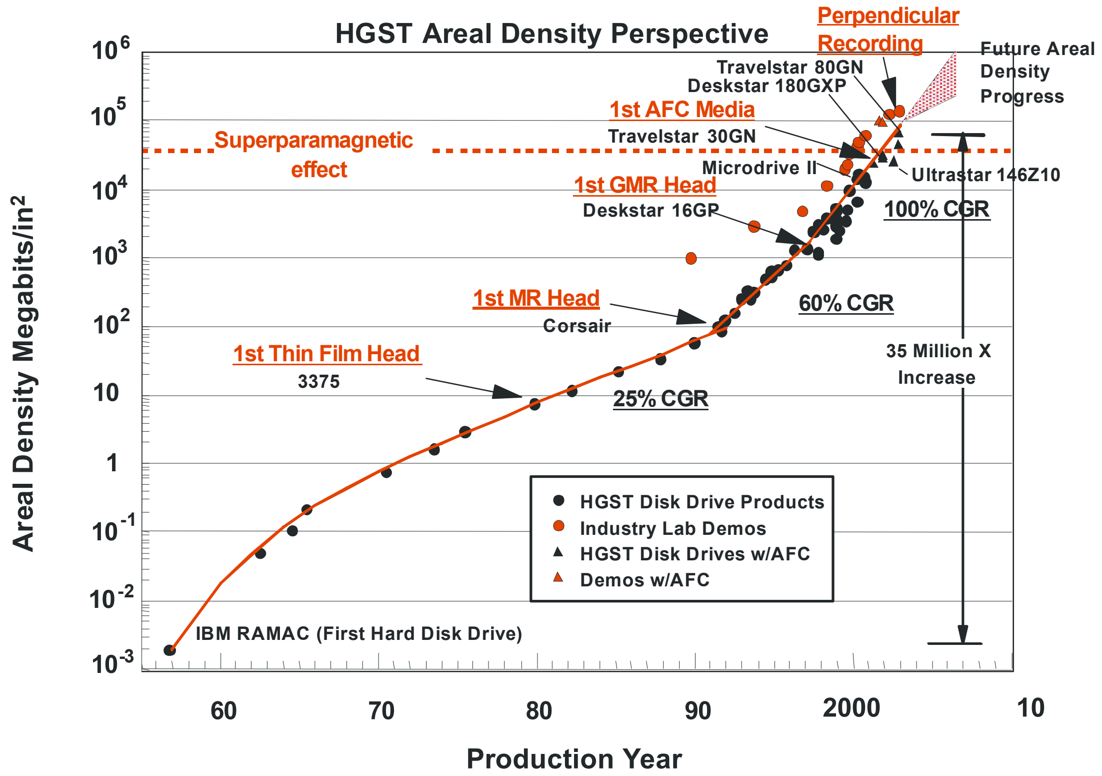


CoPtCrTaB Disk

Read-write heads

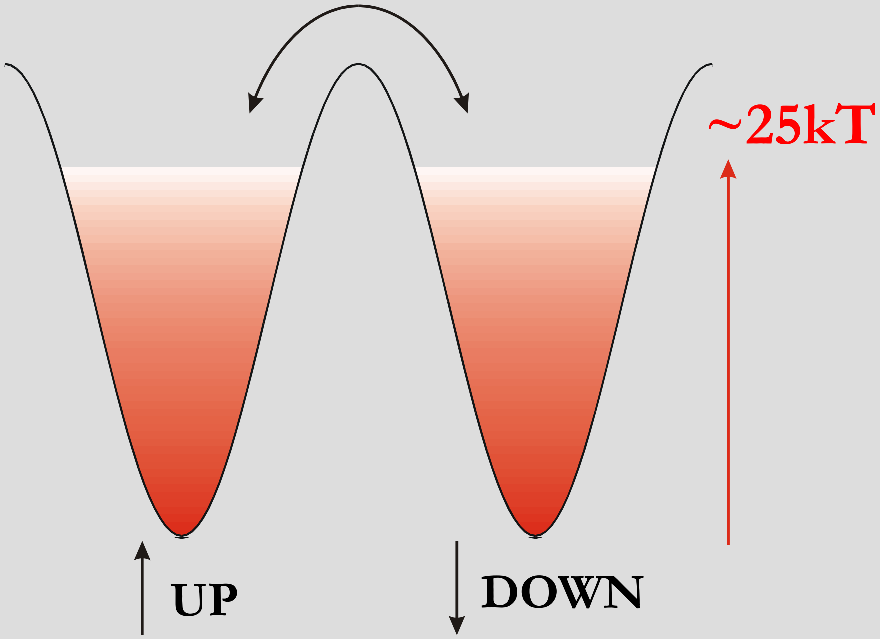


Increase of areal density



The Physics of Ultrahigh-density Magnetic Recording,
M. Plumer, J., van Ek, D. Weller,
Springer (2001)

Anisotropy barrier



Anisotropy barrier $E_B \sim KV$

Formalism for thermal excitations

Phenomenological model

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

- Probability for non-reversal

$$P(t) = e^{-t/\tau}$$

- Mean waiting time for reversal

$$\tau = \tau_0 e^{E_B / k_B T} \qquad \tau_0 \approx 10^{-9}\text{s}$$

Energy barrier required to prevent magnetization reversal during duration *t*

$$E_B = k_B T \ln(t/\tau_0)$$

Orders of magnitude

Laboratory : $t = 1\text{s}$		$V_B \approx 25 k_B T / K$
Recording : $t >> 10^9\text{s}$		$V_B \approx 40 - 60 k_B T / K$

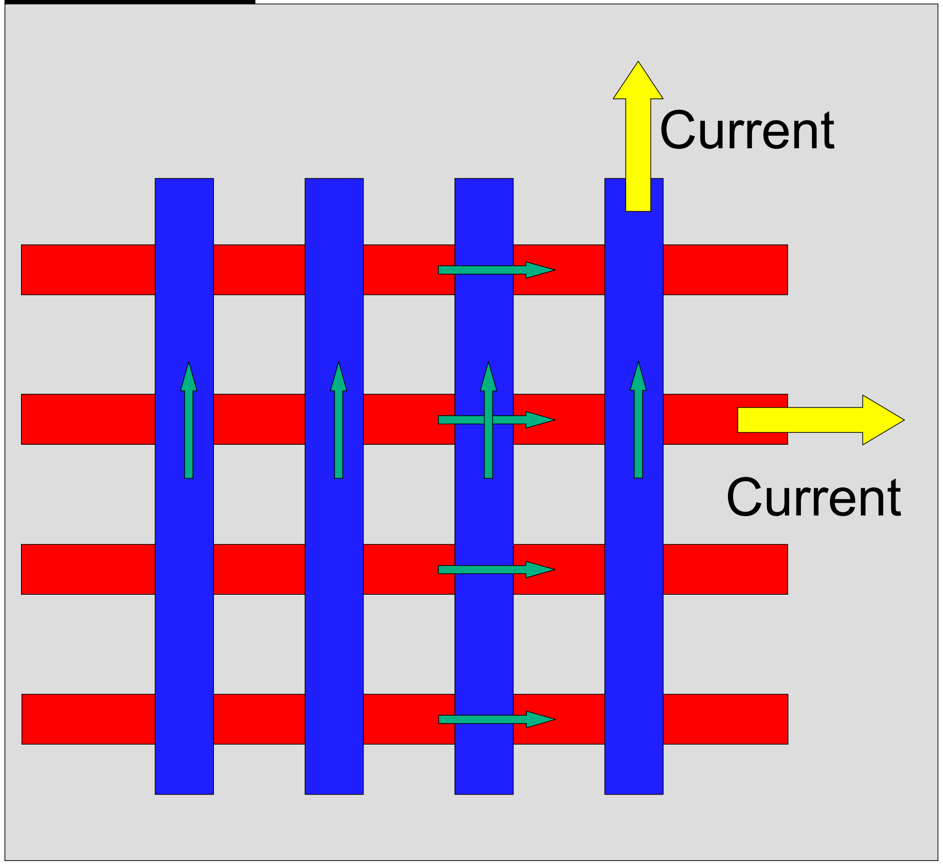
Steady increase of anisotropy K for magnetic recording

> Some drawbacks

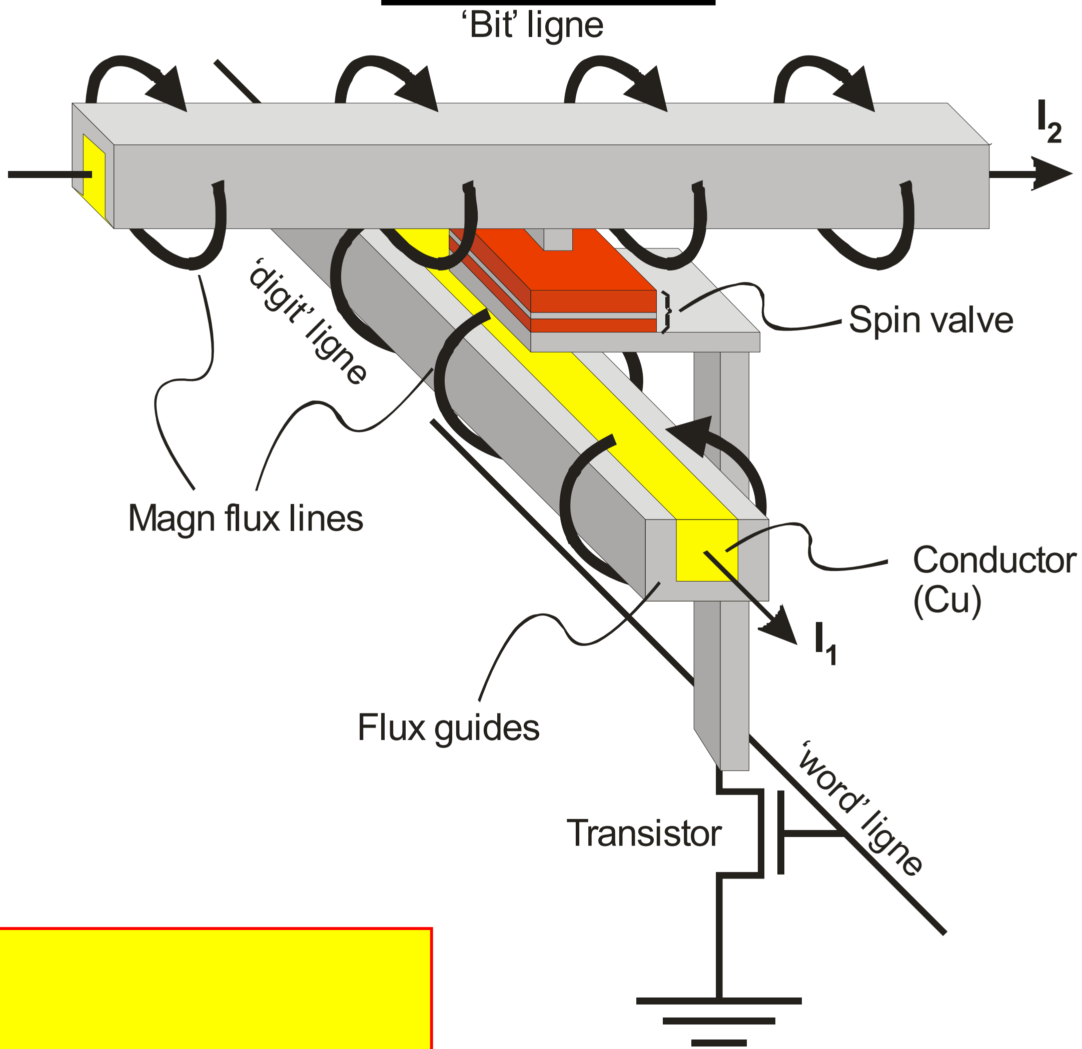
> Physical limits?

MRAM = Magnetic Random Access Memory (Close to commercial products)

Overview



Detail of a cell



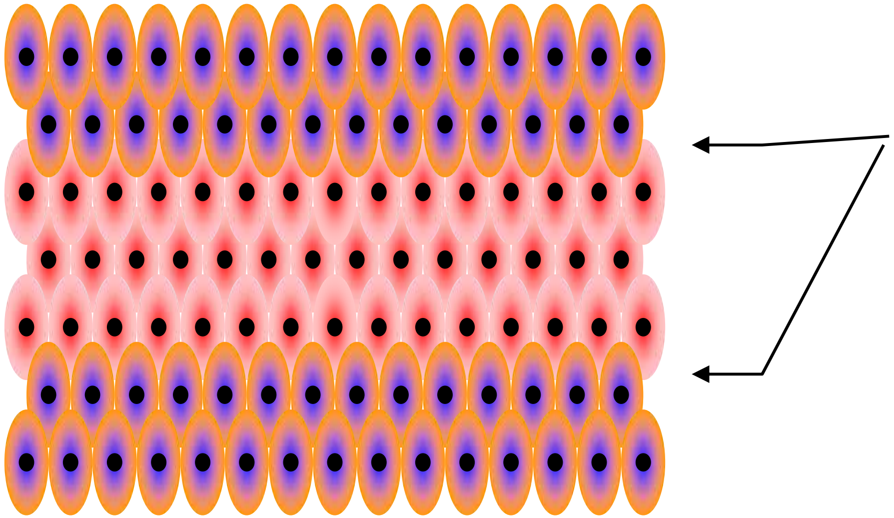
Main features:
Solid state memory
Non-volatile and fast
Complex, expensive, issues of reproductibility

Surface anisotropy

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

« Anisotropie magnétique superficielle et surstructures d'orientation »

« Superficial magnetic anisotropy and orientational superstructures »



Overview

Breaking of symmetry for surface/interface atoms

⇒ Correction to the magneto-crystalline energy

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

« Cette énergie de surface, de l'ordre de 0.1 à 1 erg/cm2, est susceptible de jouer un rôle important dans les propriétés des substances ferromagnétiques dispersées en éléments de dimensions inférieures à 100Å »

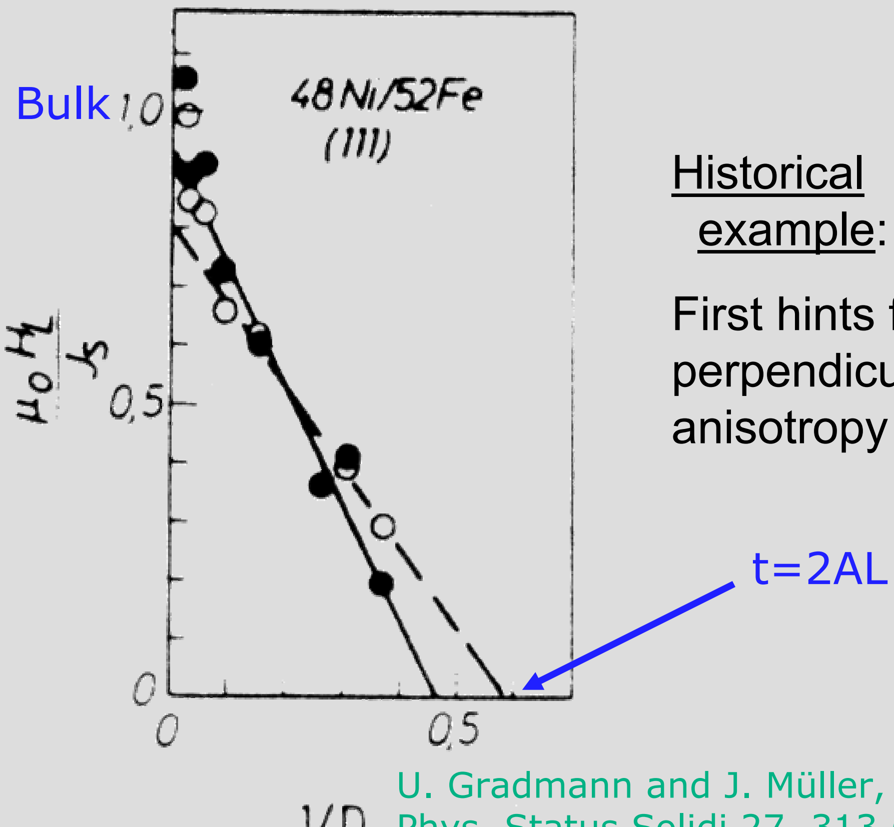
« This surface energy, of the order of 0.1 to 1 erg/cm2, is liable to play a significant role in the properties of ferromagnetic materials spread in elements of dimensions smaller than 100Å »

Pair model of Néel:

- Ks estimated from magneto-elastic constants
- Does not depend on interface material
- Yields order of magnitude only: correct value from experiments or calculations

Experimental approach: 1/t plot

$$E_{tot}(t) = k_V t + 2k_S \;\Rightarrow\; e(t) = k_V + \frac{2k_S}{t}$$



Historical example:

First hints for perpendicular anisotropy

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

Theory

MAE (Magnetic Anisotropy Energy), perturbation theory for 3d metals:

$$\mathrm{MAE} = \alpha \frac{\xi}{4\mu_B} \Delta\mu_L$$

P. Bruno, PRB39, 865 (1989)

μ_L does not rotate in 3d metals
-> MAE reflects cost in ξ

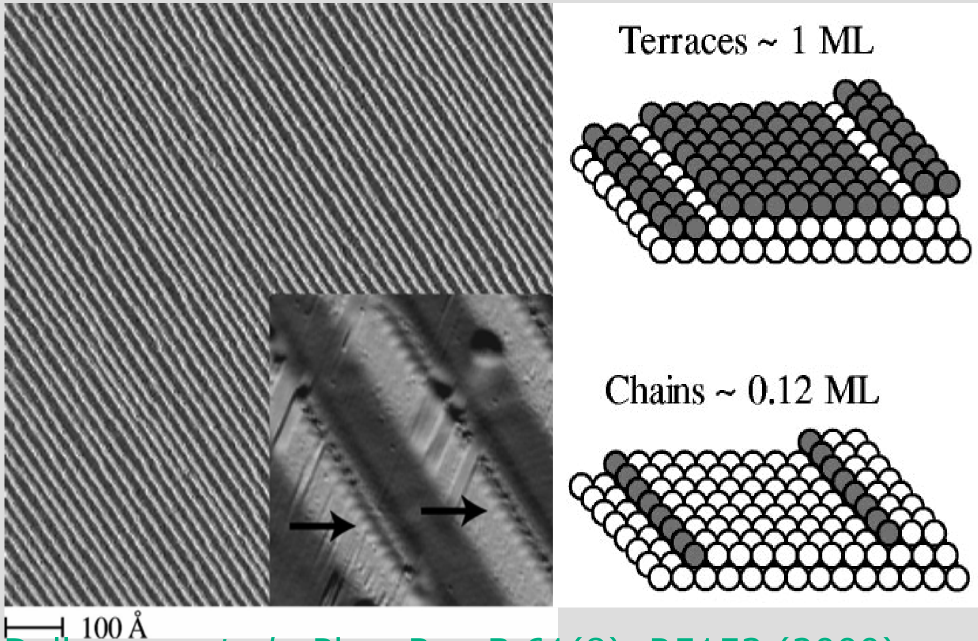
Covers magnetocrystalline, magnetoelastic and surface anisotropy

Important aspect:
In most cases surface and magnetoelastic anisotropies are mixed (1/t plots etc.)

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

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

Co/Pt



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

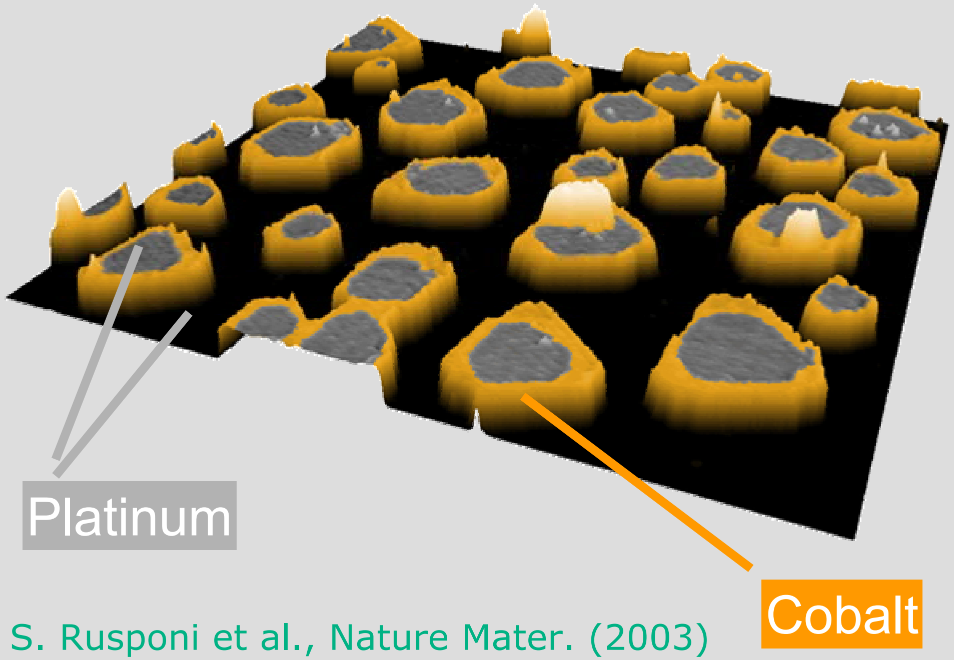
Results

- Bulk: m_L=0.14μ_B/at.
- Surface: m_L=0.31μ_B/at.
- Bi-atomic wire: m_L=0.37μ_B/at.
- Mono-atomic wire: m_L=0.68μ_B/at.
- bi-atom: m_L=0.78μ_B/at.
- atom: m_L=1.13μ_B/at.

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

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

Engineering of anisotropy

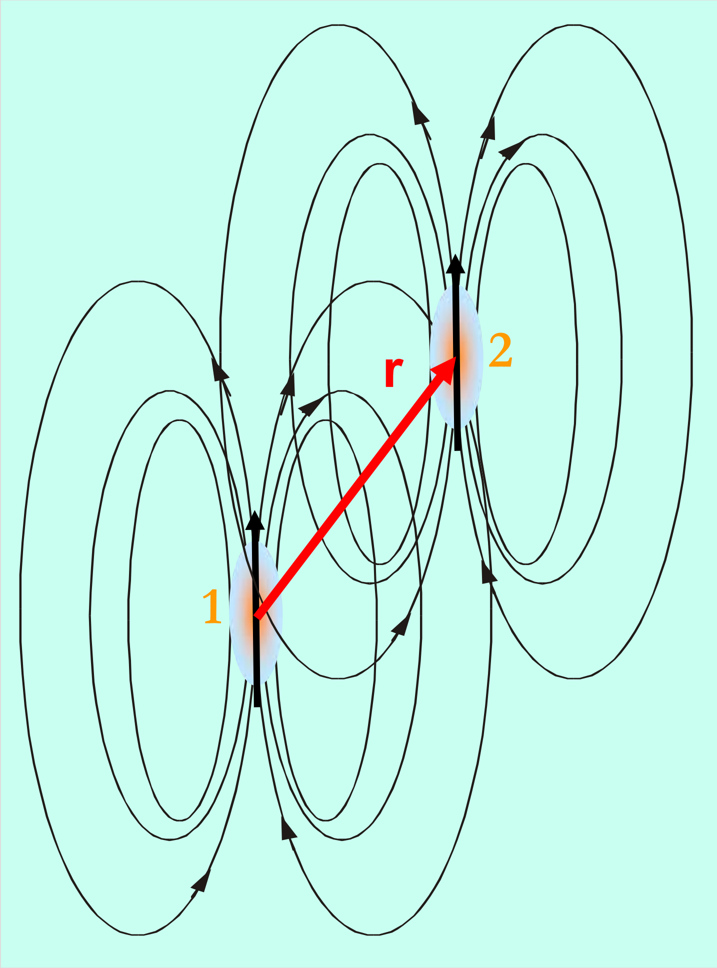


S. Rusponi et al., Nature Mater. (2003)

Basics of dipolar energy

Mutual energy of two magnetic dipoles :

$$E_{1,2} = \frac{\mu_0}{4\pi r^3}\left[\vec{\mu}_1.\vec{\mu}_2 - \frac{3}{r^2}(\vec{\mu}_1.\vec{r}).(\vec{\mu}_2.\vec{r})\right]$$



Notice:

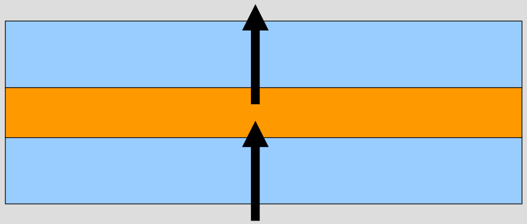
- **Decays like 1/r^3**
- **May favor parallel or antiparallel alignment**
- **Long-ranged in bulk, however short-ranged in 2D:**

$$\iint \frac{1}{r^3} 2\pi r \mathrm{d}r \sim \iint \frac{1}{r^2}\mathrm{d}r \sim \frac{1}{R} + \mathrm{Cte}$$

Stacked dots : dipolar

In-plane magnetization

Out-of-plane magnetization



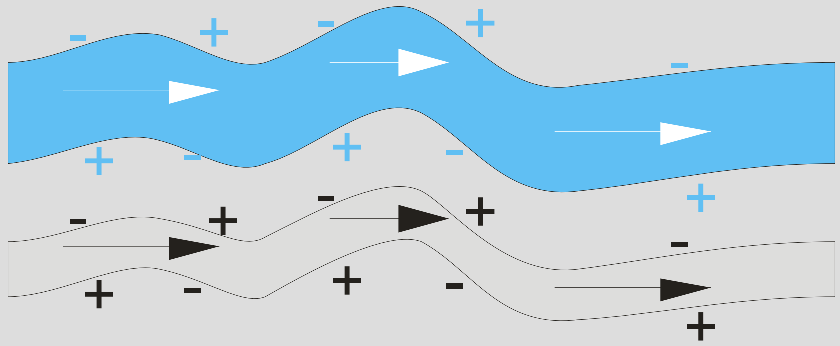
Hint:

An upper bound for the dipolar coupling is the self demagnetizing field

Notice: similar situation as for RKKY coupling

Stacked dots : orange-peel coupling

In-plane magnetization



Always parallel coupling

L. Néel, C. R. Acad. Sci. 255, 1676 (1962)

(valid only for thick films)

J. C. S. Kools et al., J. Appl. Phys. 85, 4466 (1999)

(valid for any films)

Out-of-plane magnetization

May be parallel or antiparallel

J. Moritz et al., Europhys. Lett. 65, 123 (2004)

Probe with reflectivity

Array of dots

Example of perpendicular magnetization

Patterned array of Pt/Co(0.5nm)/Pt dots with perpendicular anisotropy

(50x50 microns, demagnetized state)

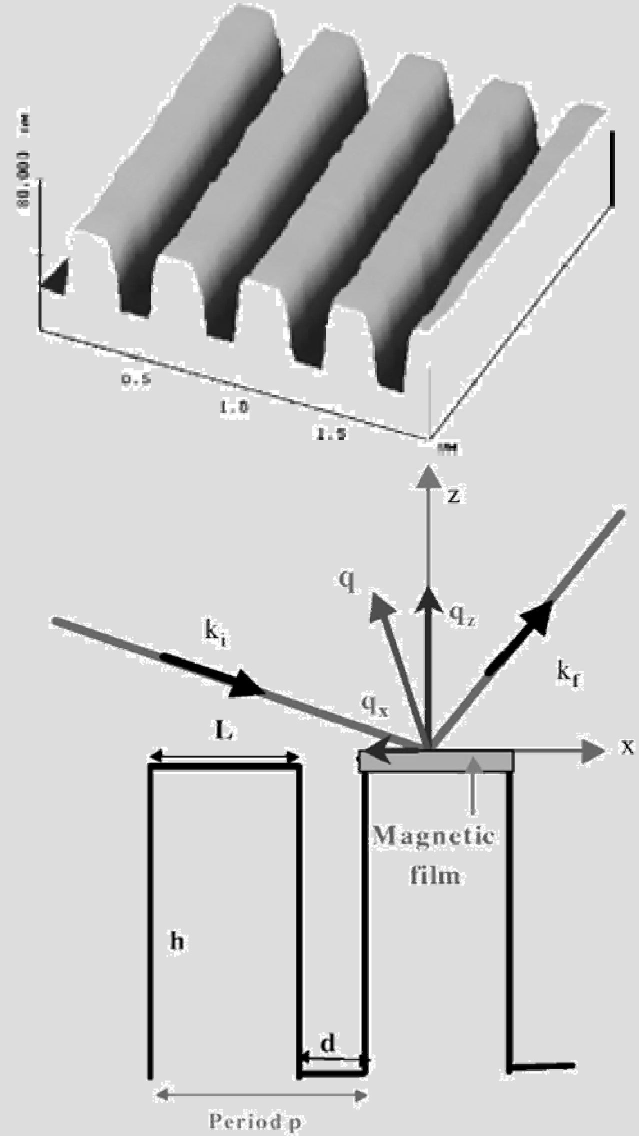
V. Repain et al., J. Appl. Phys. 95, 2614 (2004)

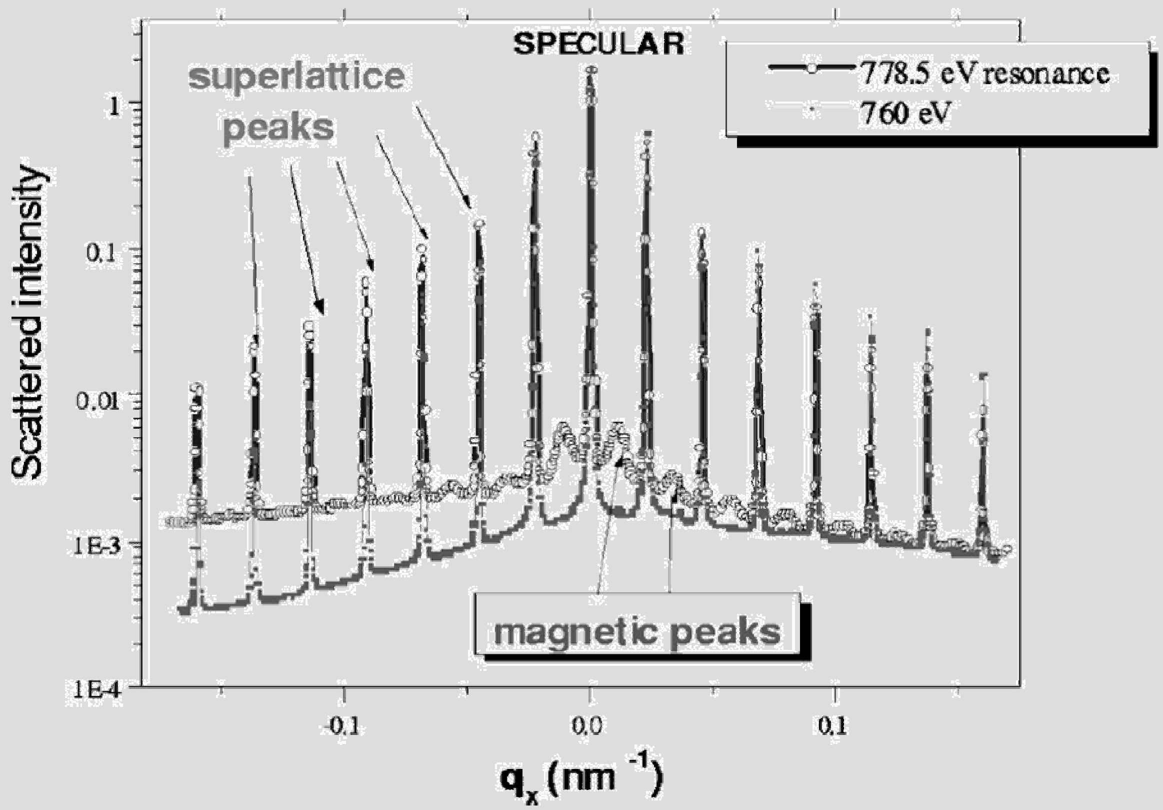
Probe with off-specular or scattering

Magnetic scattering on nanofabricated arrays of lines

Co/Pt(111) multilayers

XMRS: X-ray Magnetic Resonant Scattering



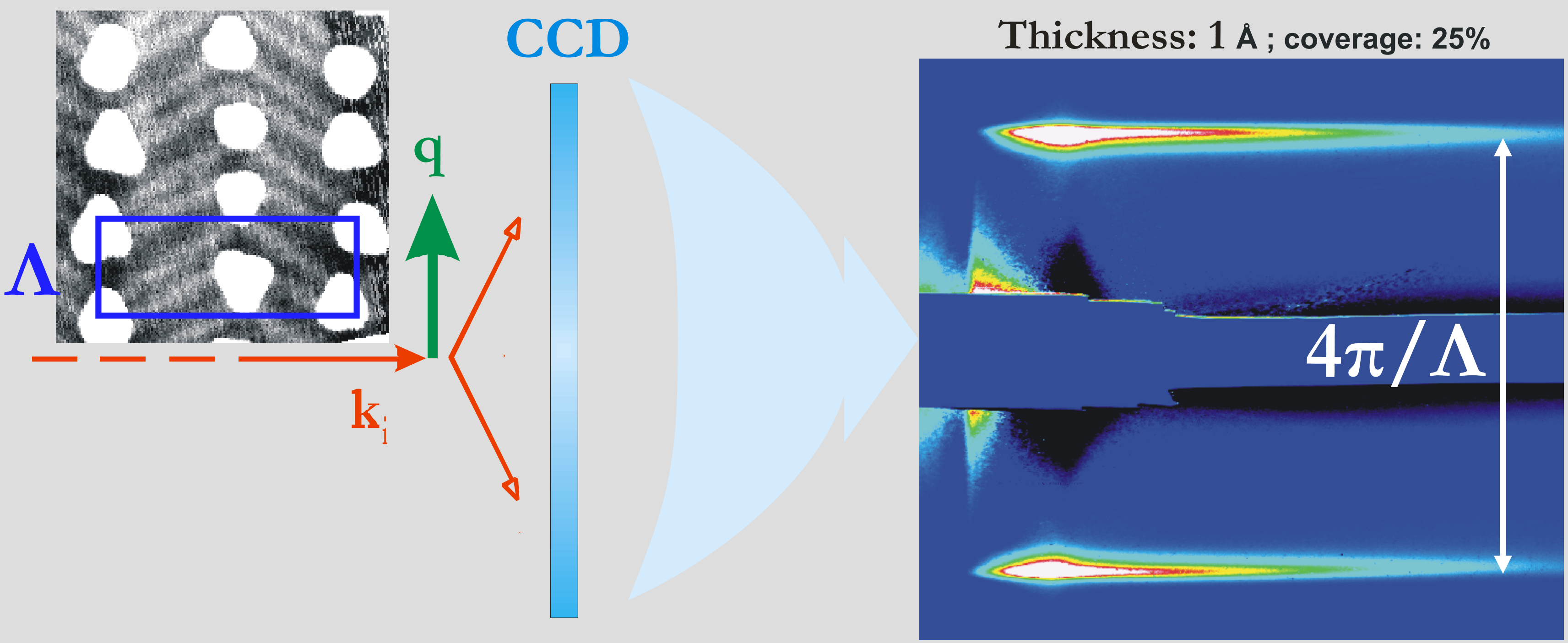


Informations about magnetic correlations are extracted from magnetic satellites

K. Chesnel et al., PRB66, 024435 (2002)

Structural scattering on self-organized systems: GISAXS

Co/Au(111) nanodots



INTRA-ROW ORDER: SUPER-CRYSTAL

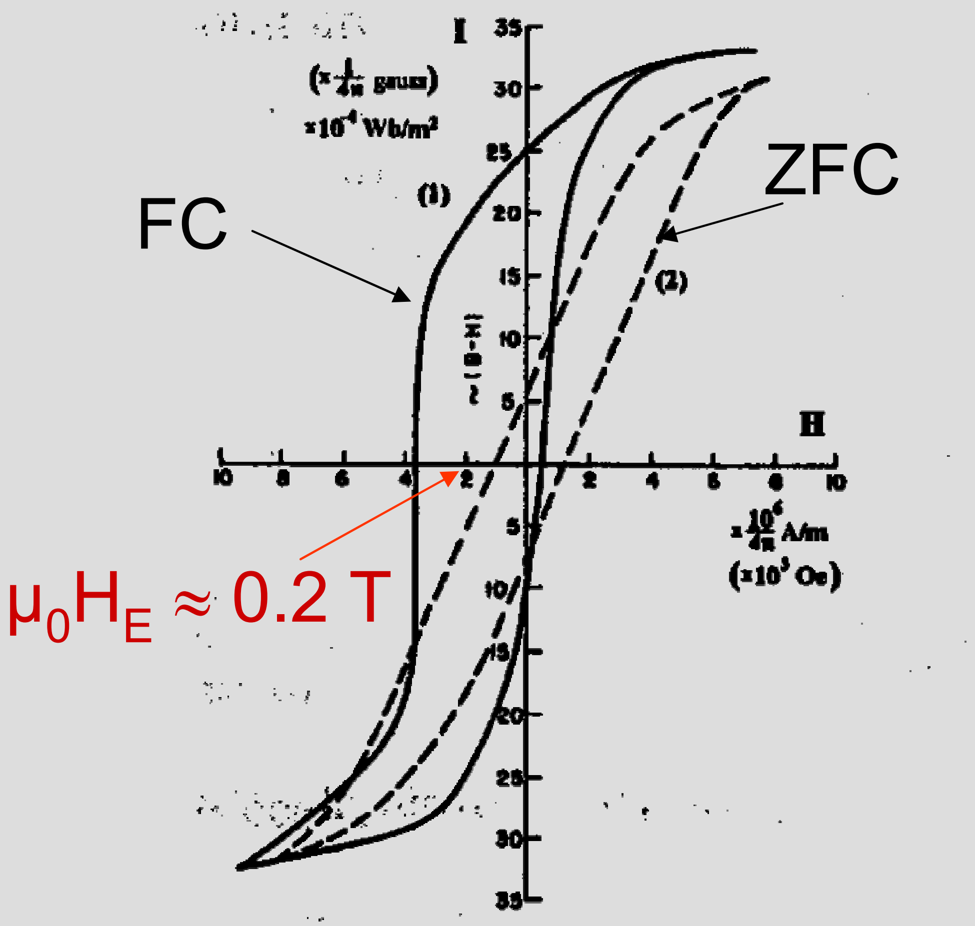
O. Fruchart et al., Europhys. Lett. 63, 275 (2003)

Evidencing magnetic scattering is in principle possible, however:

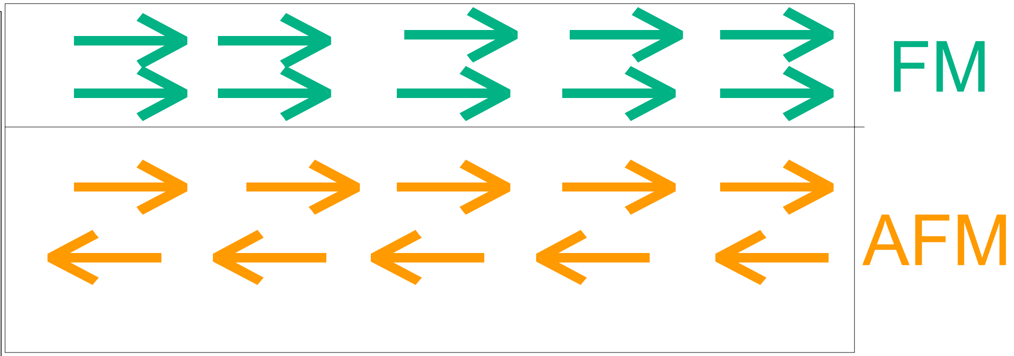
- Low temperature and weak signal
- Distribution of properties may prevent ordering to occur

Seminal studies

Oxidized Co nanoparticles



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



Field-cooled hysteresis loops:

- **Shifted in field**
- **Increased coercivity**
- **Frustration can induce 90° coupling between layers**

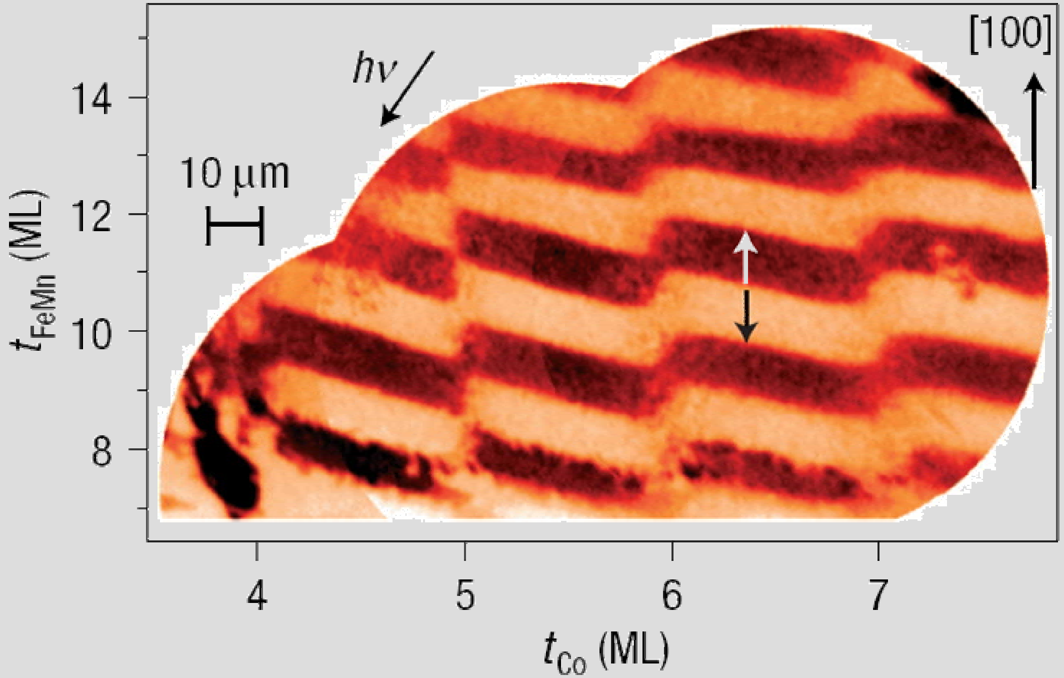
Exchange bias
J. Nogués and Ivan K. Schuller
J. Magn. Magn. Mater. 192 (1999) 203

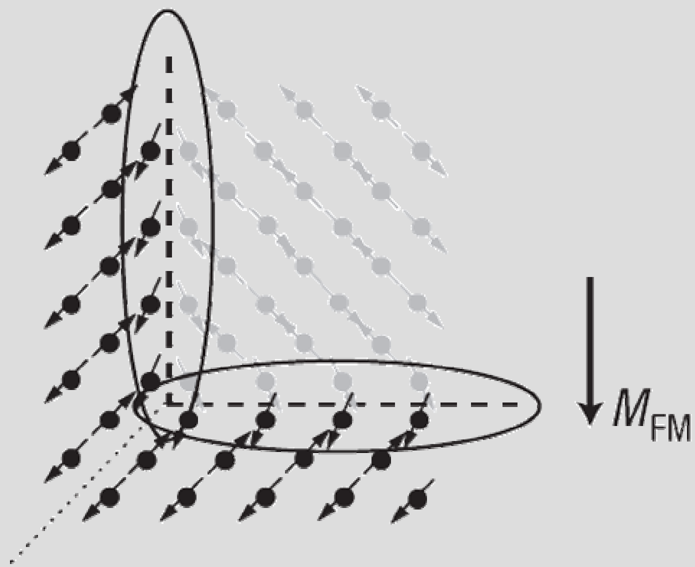
Exchange anisotropy—a review
A E Berkowitz and K Takano
J. Magn. Magn. Mater. 200 (1999)

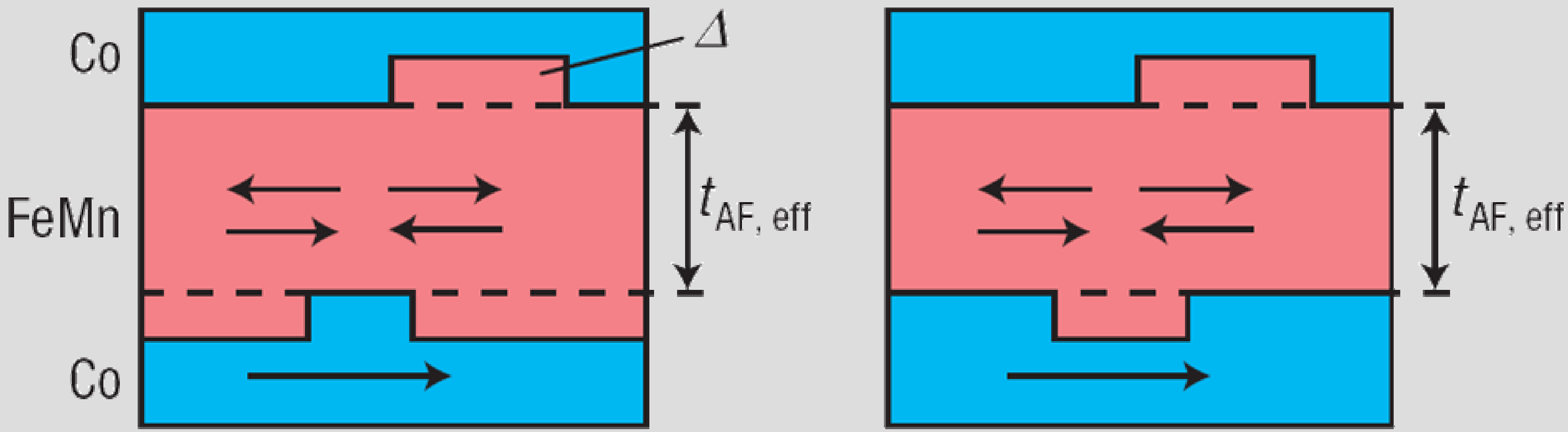
Example of 90° coupling

Co\FeMn(001)\Co

W. Kuch et al., Nature Materials (2006)







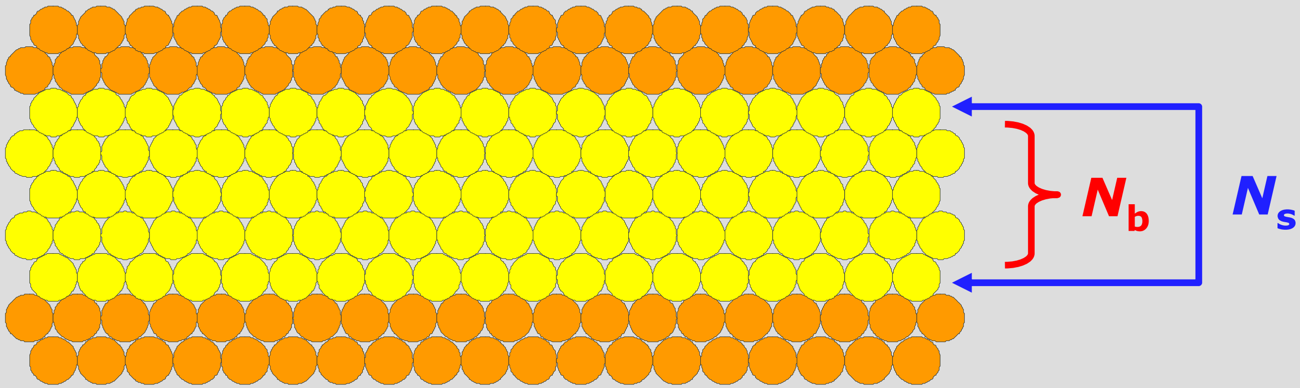
Need both reflectivity (depth information) and imaging (non-averaged)

Naïve model

Molecular field

$$T_c = \mu_0 \cdot \frac{J+1}{3J} \cdot \frac{N w_0 M_0 \, m_0}{k_B}$$

N neighbors



$$\overline{N} = N_b - \frac{2(N_b - N_s)}{t} \Rightarrow \Delta T_c(t) \sim t^{-1}$$

Less naïve

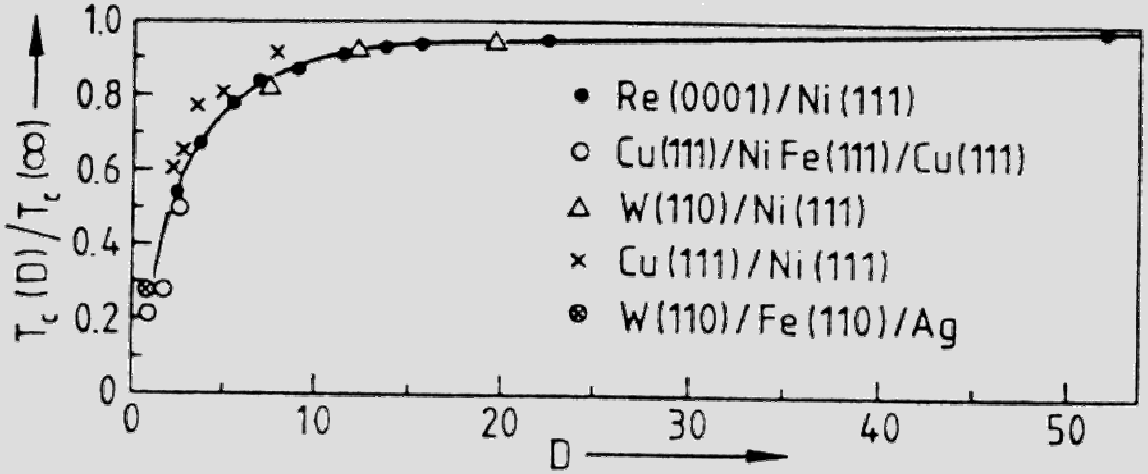
Thickness-dependent molecular field

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

$$\lambda = 1$$

G.A.T. Allan, PRB1, 352 (1970)

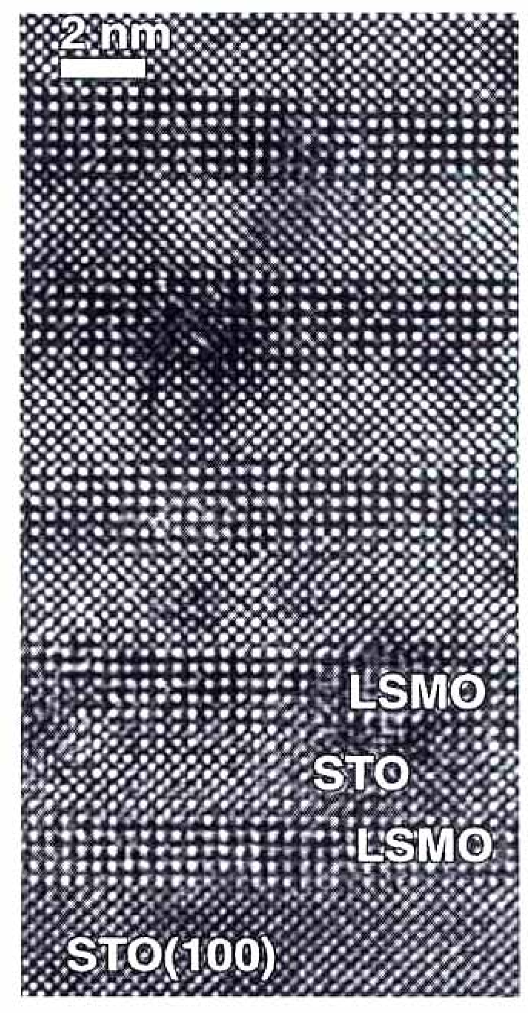
Experiments



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

Probe magnetization profiles in multilayers

$[La_{0.7}Sr_{0.3}MnO_3(46Å)/SrTiO_3(31Å)]x15$

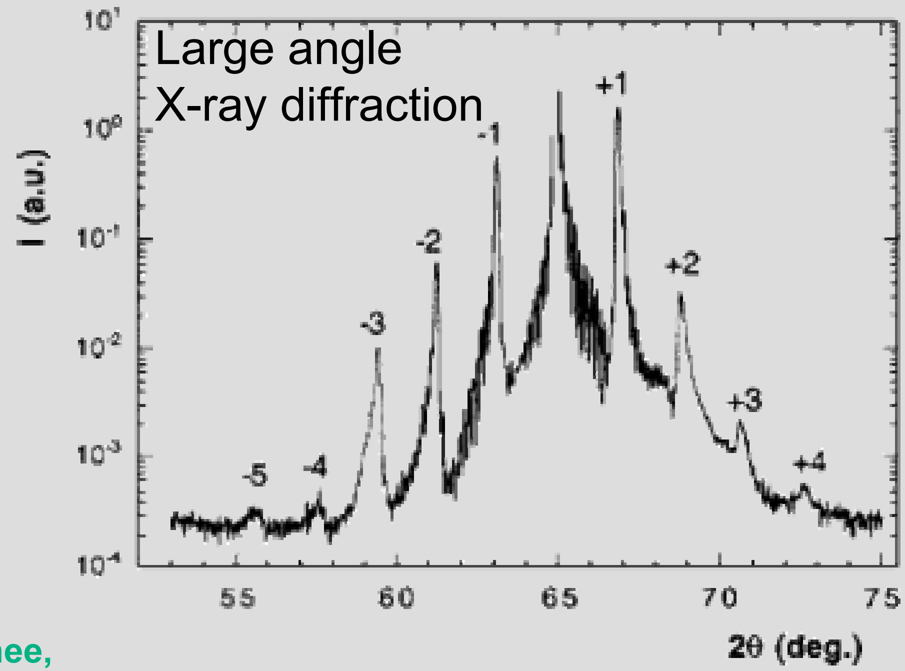


Motivations:

Model system (epitaxial, similar structure)

Tunnelling magnetoresistance (TMR) with high polarization material

TMR depends on polarization at the interface: probe buried interfaces



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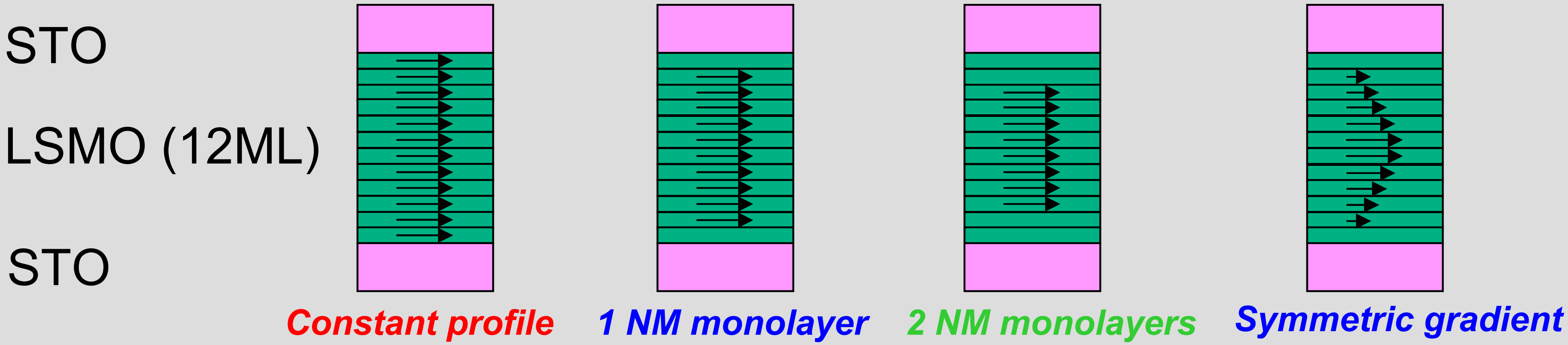
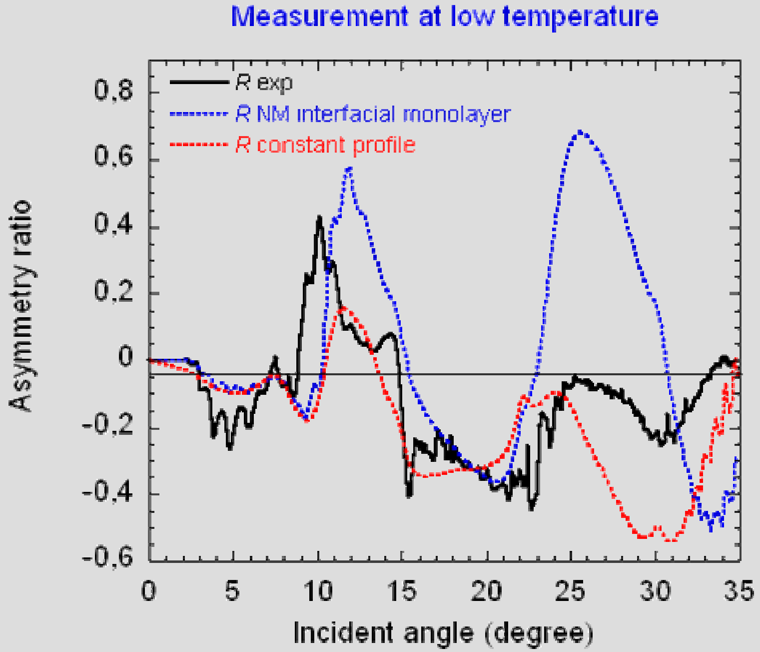
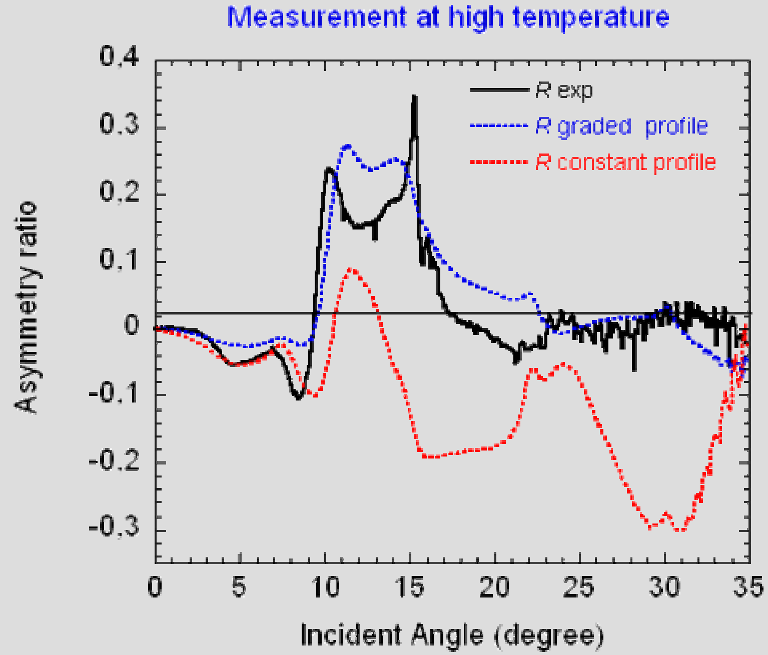
J. L. Hodeau (LdC, Grenoble)
C. Dubourdieu, I. Gelard (LMGP, Grenoble)

Models for magnetization profiles



Experiments



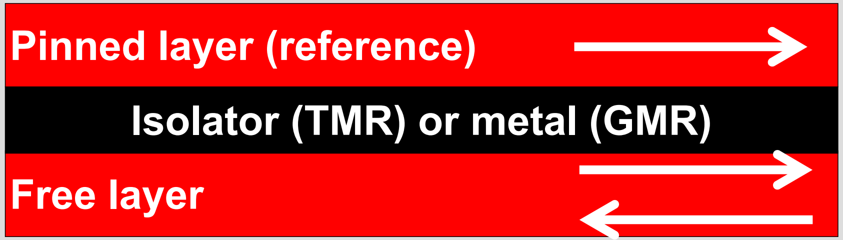


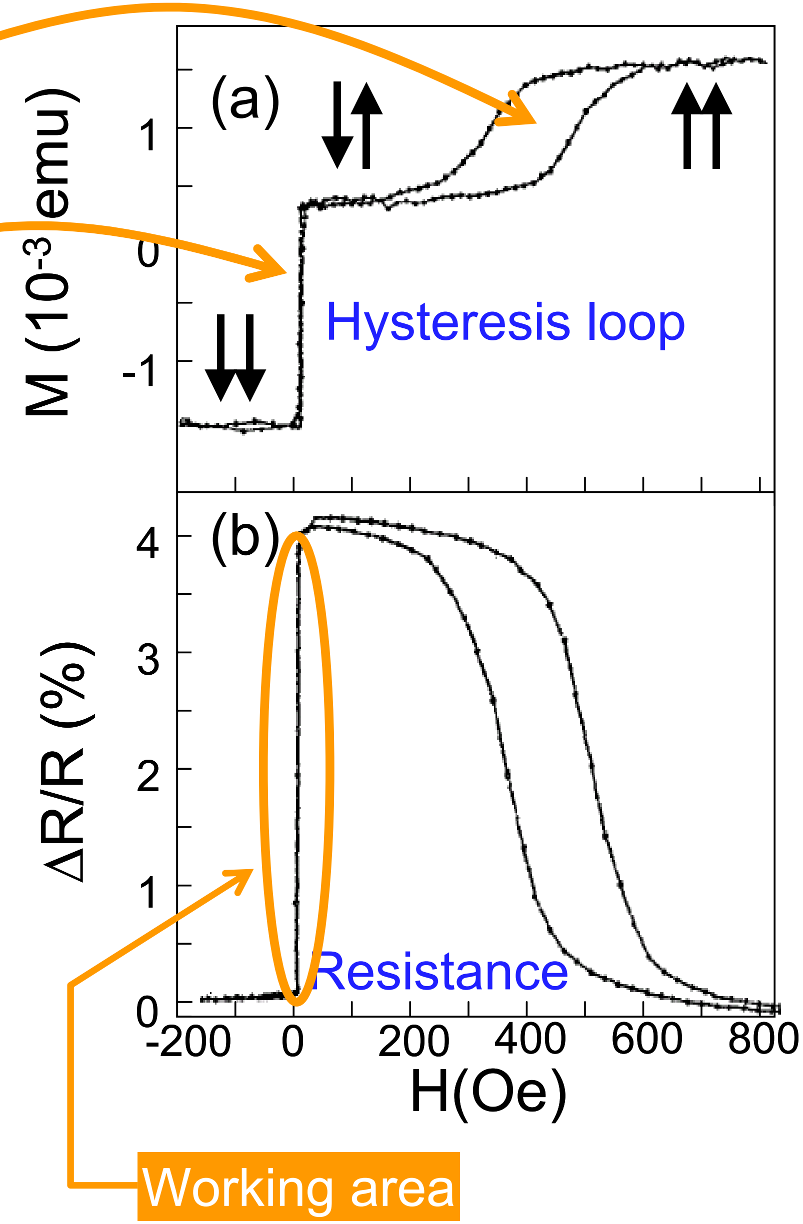
Low temp: constant profile

High temp: gradient profile

Basics of spin valves

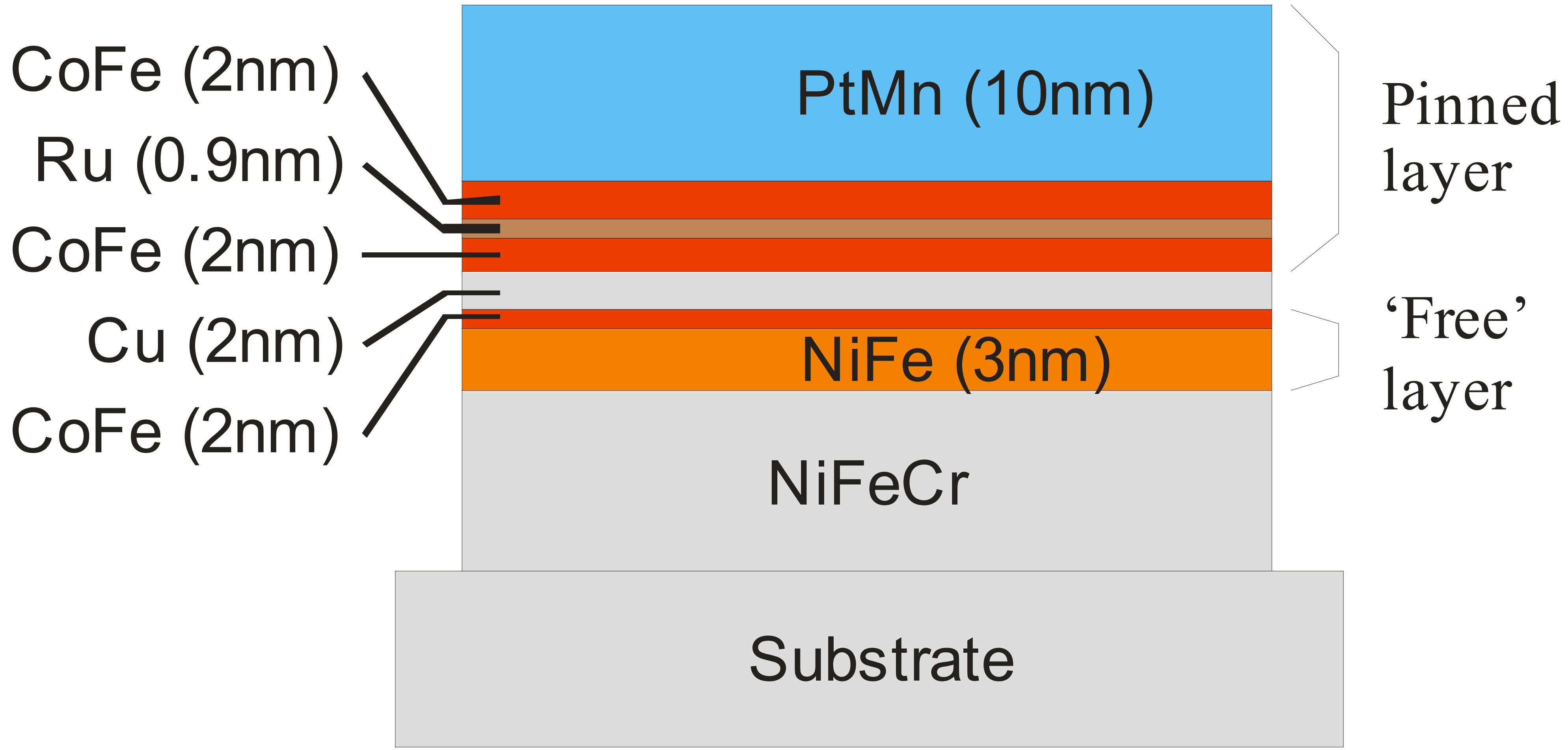
Free and pinned layers





B.Dieny, V.S.Speriosu, et coll.
IBM Almaden (1991)

B. Dieny et al., Phys. Rev. B 43, 1297 (1991).



Need of complementary and accurate local probes (real and reciprocal space) for: layer and/or element selectivity

Basics of precessional switching

Démonstration: 1999

Magnetization dynamics:

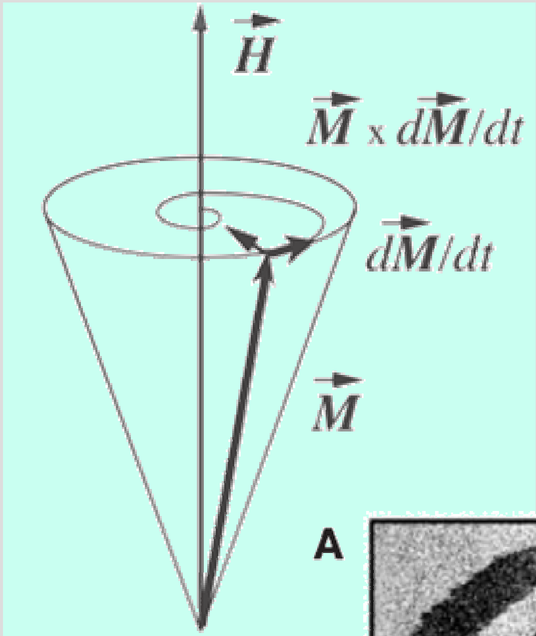
Landau-Lifshitz-Gilbert equation:

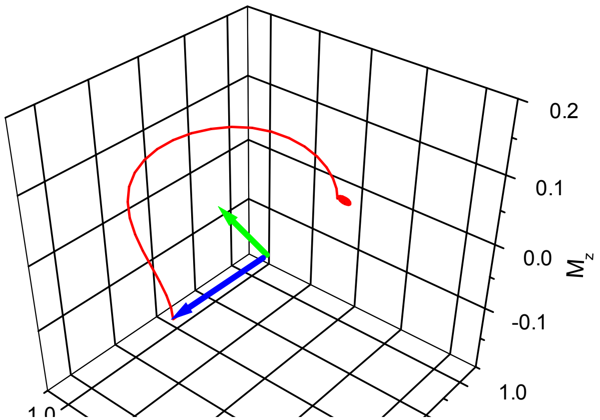
$$\frac{d\mathbf{M}}{dt} = -\gamma_0 \left[\mathbf{M} \times \mathbf{H}_{eff}\right] + \frac{\alpha}{M_s}\left[\mathbf{M} \times \frac{d\mathbf{M}}{dt}\right]$$

γ_0 : gyromagnetic factor

$\mathbf{H}_{eff}$: Effective field (including applied)

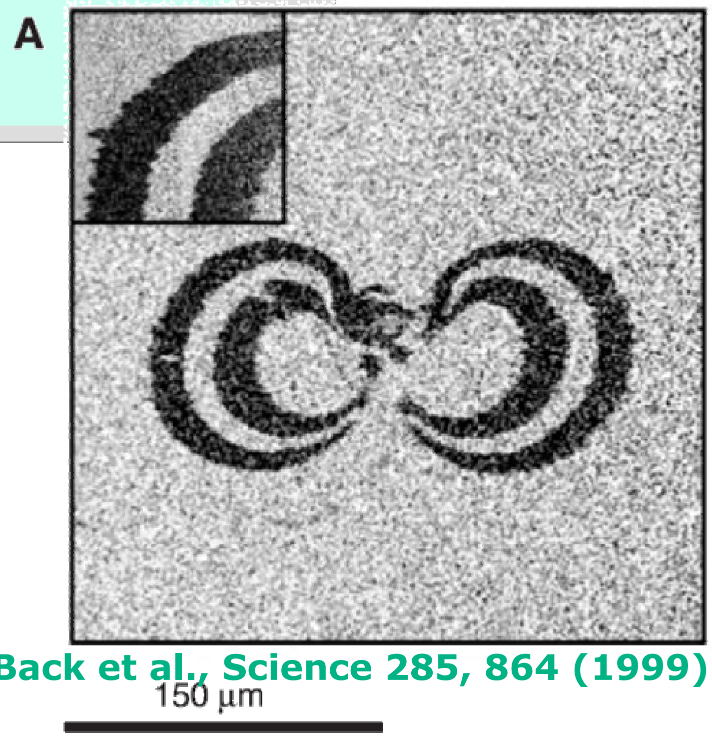
α : Damping coefficient





Magnetization reversal via transverse field > magnetization trajectories

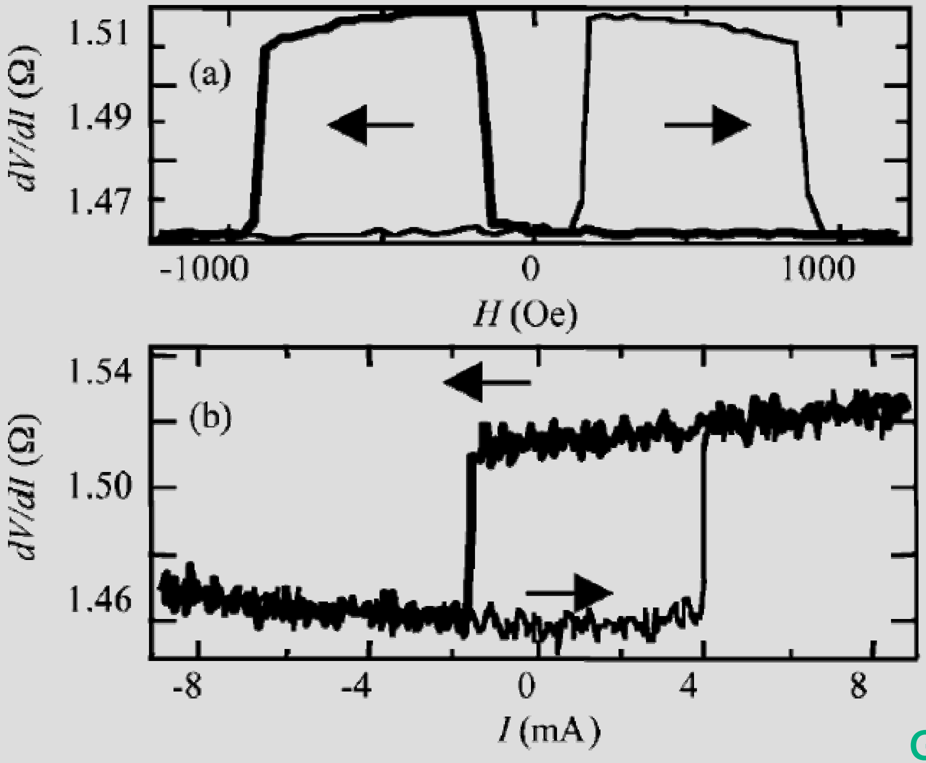
- Typical times: 0.1ns
- Used in MRAMs
- Minimized losses
- Domain wall motion



C. Back et al., Science 285, 864 (1999)

Basics

Can be viewed as the GMR-reversed effect



Conventionnal hysteresis loop

Current-induced magnetization reversal

Group Myers et Ralph, Cornell University (2000)

Motivations

- Simplified architectures (MRAMs etc.)
- Fully electronic read/write
- Devices making use of domain wall motion (memory, logic)
- Unexpected: stationnary GHz oscillators

- III-V: achieved. GaMnAs, Tc>=150K when optimized. Clustering of MnAs above 6-8%. Mn convey both spins and doping
- II-VI: achieved. Ex: CdMnTe. Tc<10K. No clustering. Mn conveys spin, not doping (better for fundamental science).
- IV: under way. Ex: GeMn.
- High band gap. Ex: ZnCoO. Issues of clustering. p-doped: paramagnetic or antiferromagnetic. Prospects: p-doped, field-effect doping (ZnMgO\ZnCoO\ZnMgO), ZnMnO etc.

Motivations

- Direct integration of magnetism in electronics
- « Spin-photo-electronics »
- Electrical control (field effect control of Tc, anisotropy etc.)
- Current-induced domain wall motion demonstrated (GaMnAs)

EXTRA READING

[1] O. Fruchart, A. Thiaville, *Magnetism in reduced dimensions*, C. R. Physique **6**, 921 (2005) [Topical issue, Spintronics].

[2] O. Fruchart, *Couches minces et nanostructures magnétiques*, Techniques de l'Ingénieur, à paraître.

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[4] Lecture notes from undergraduate lectures, plus various slides: http://lab-neel.grenoble.cnrs.fr/themes/couches/ext/slides/

[5] G. Chaboussant, Nanostructures magnétiques, Techniques de l'Ingénieur, revue 10-9 (RE51) (2005)

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[7] Magnetoelectronics, Ed. M. Johnson, Elsevier Academic Press (2004).

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[10] J.P. Bucher, F. Scheurer, *Self-organized clusters and nanosize islands on metal surfaces*, in: J.S. Miller, M. Drillon (Eds.), Magnetism: Molecules to Materials III, Wiley–VCH, Weinheim, Germany, pp. 211–251 (2002).

[11] J.I. Martin et coll., *Ordered magnetic nanostructures: fabrication and properties*, J. Magn. Magn. Mater. **256**, 449-501 (2003).

[12] R. Skomski, *Nanomagnetics*, J. Phys.: Cond. Mat. **15,** R841–896 (2003).

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