A flavor of Nanomagnetism and Spintronics

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http://neel.cnrs.fr

Local environment

Grenoble : 500 000 inhabitants with surroundings

Universities : Université Joseph Fourier (UJF) / Grenoble Institute of Technology (INP)

National Institutes : CNRS (broad topic), CEA (energy), INSERM (health) etc.

Large scale facilities : ILL (neutrons) and ESRF (synchrotron)

Fundamental research and technology (ex : Minatec, LETI, STMicroelectronics etc.)

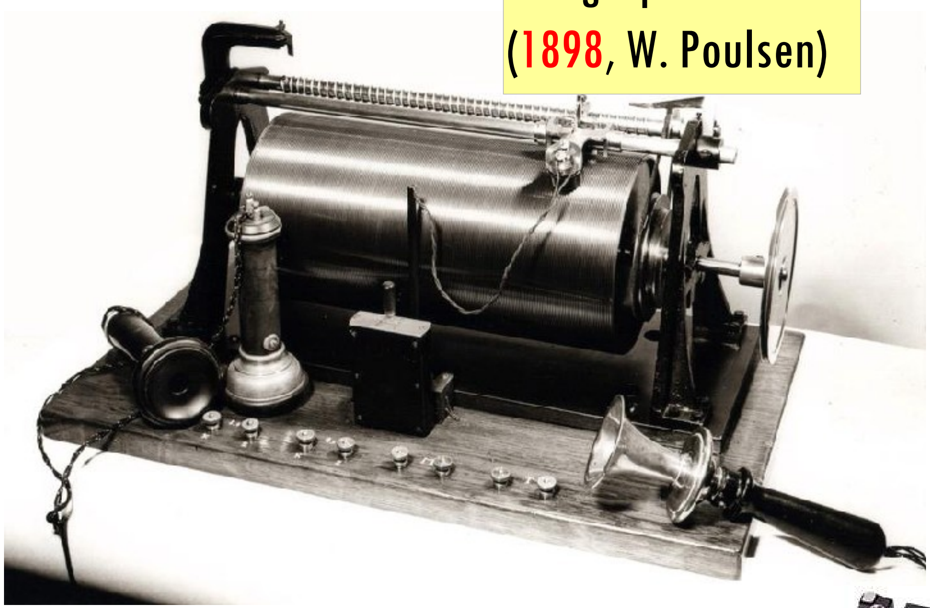
Institut Néel

Staff : 170 scientists ; 125 technical staff ; 140 students & post-docs

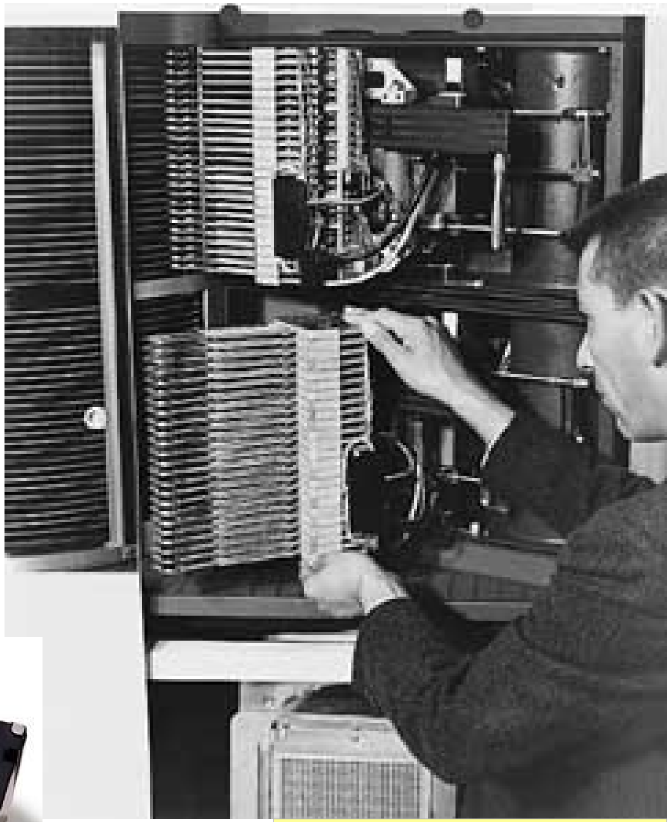
3 departments : Nanosciences, low temperatures, materials & functions

Nanosciences : 7 research teams

Micro- and NanoMagnetism team : 35 staff, including 15 full-staff scientists.



Telegraphone
(1898, W. Poulsen)

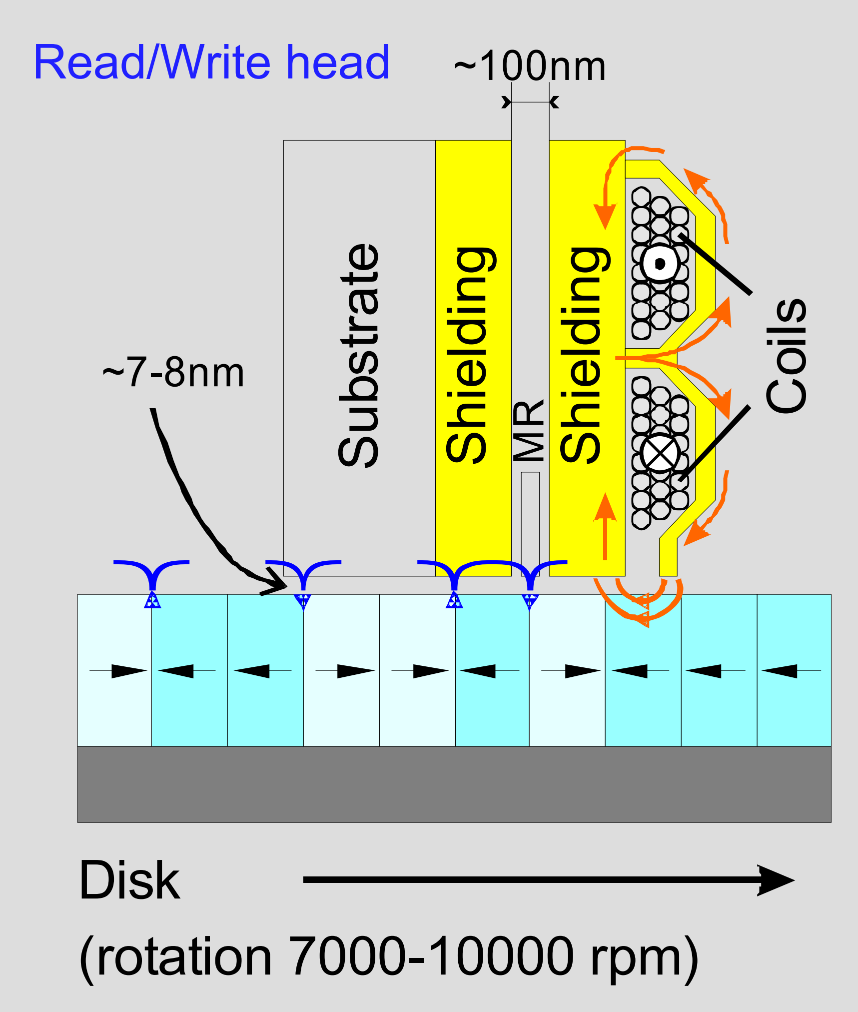


RAMAC (IBM, 1956)
2 kbit/in^2
50 disks Ø 60 cm
Total 5Mbytes

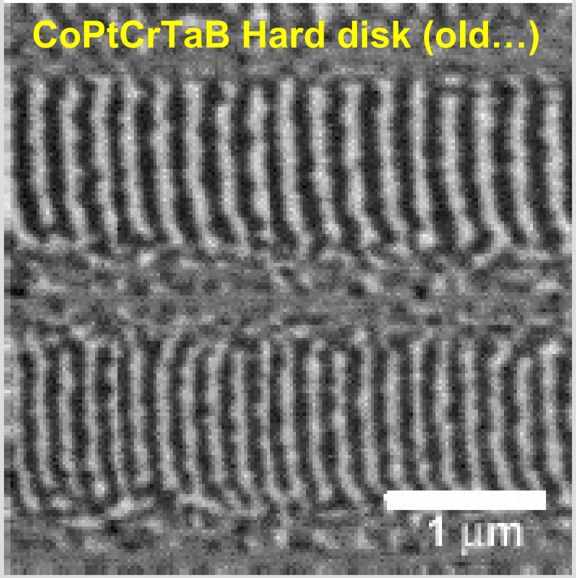
- Same concept over 100 years
- Technological innovation?
- New science?

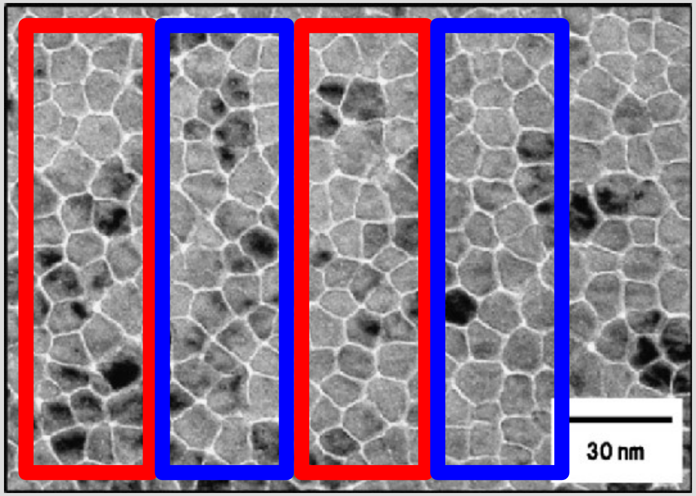
Modern hard disk drive (>1 To)

Principle of hard-disks

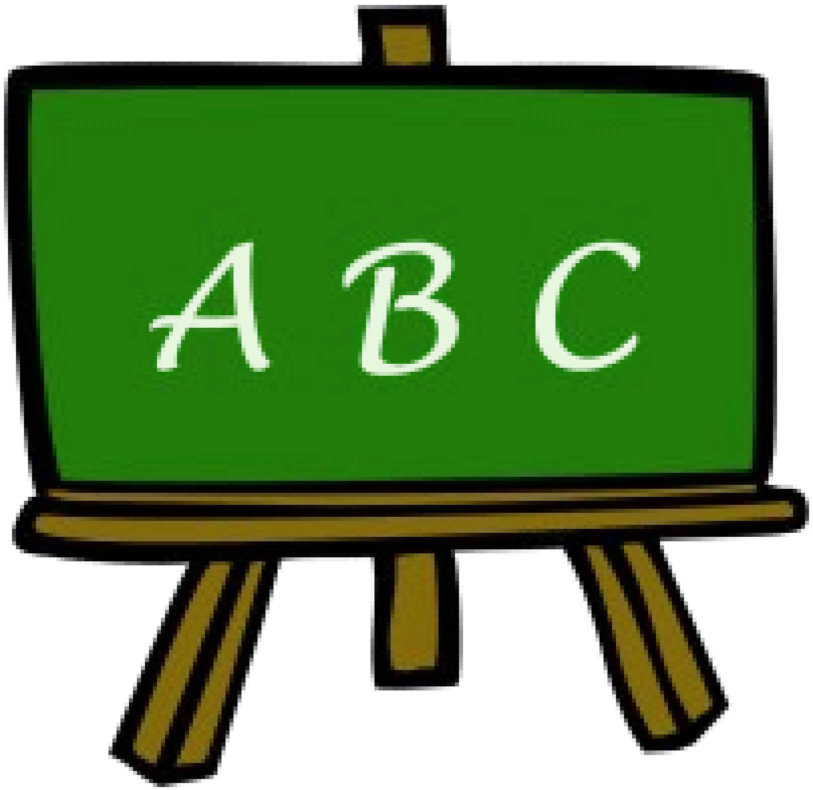


Magnetic bits





S. Takenoiri, J. Magn. Magn. Mater. 321, 562 (2009)


A B C

Fundamental issues for nanomagnetism

- Is a small grain stable against thermal fluctuations?

$$k_B T(300\ \mathrm{K}) \approx 4\times10^{-21}\ \mathrm{J} \approx 25\ \mathrm{meV}$$

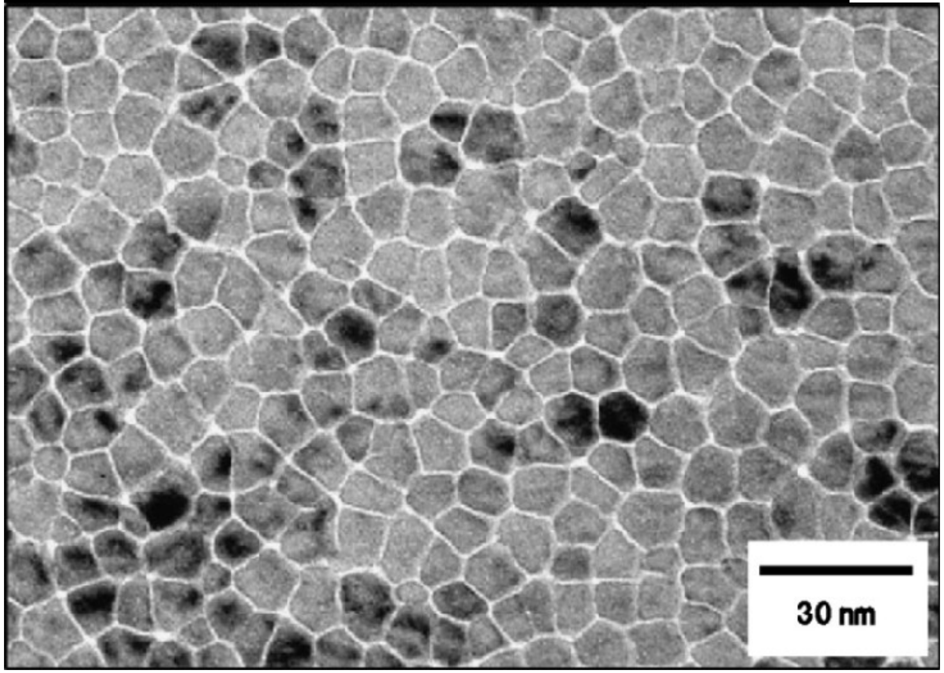
$$100\, k_B T(300\ \mathrm{K}) \approx 2.5\ \mathrm{eV}$$

Derive from macroscopic arguments

- Is a small grain (ferro)magnetic?

Count number of surface atoms

Magnetic grain media of current hard disks

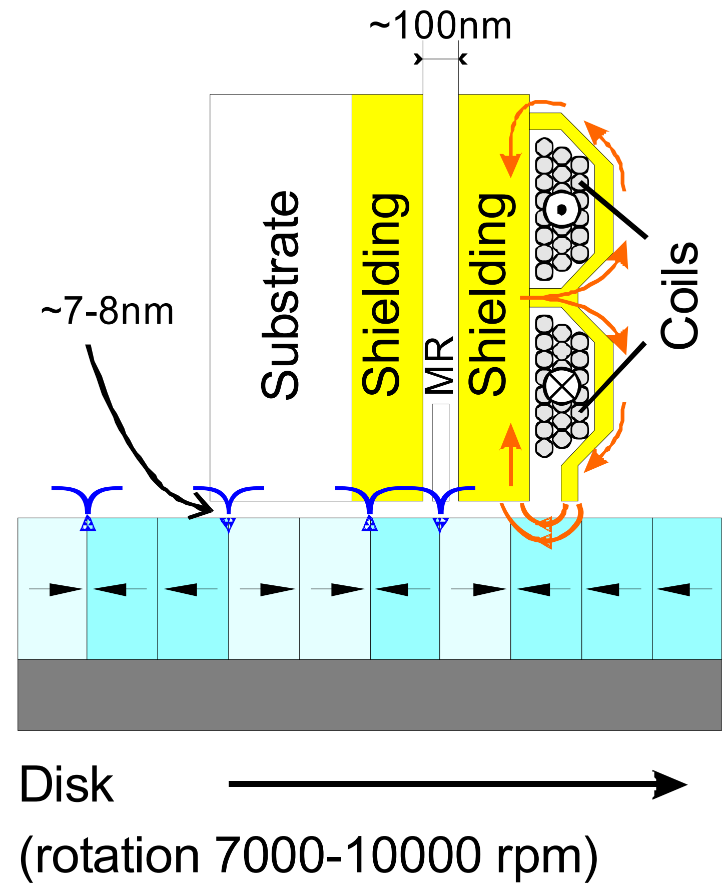


S. Takenoiri, J. Magn. Magn. Mater. 321, 562 (2009)

Decades-old (yet still modern) topic

The technological need for spin electronics

- How to read information?
  → Convert magnetic information to electric signal
- Field of spin electronics
  - Magneto-transport.
  - Requires nanometer length scales

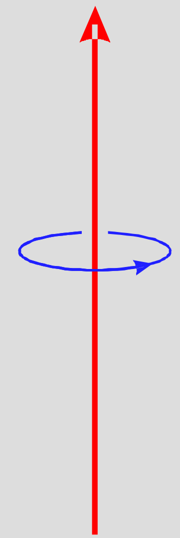


Official birth: discovery of magneto-resistance

N. M. Baibich, Phys. Rev. Lett. 61, 2472 (1988)
G. Binach, Phys. Rev. B 39, 4828 (1989)

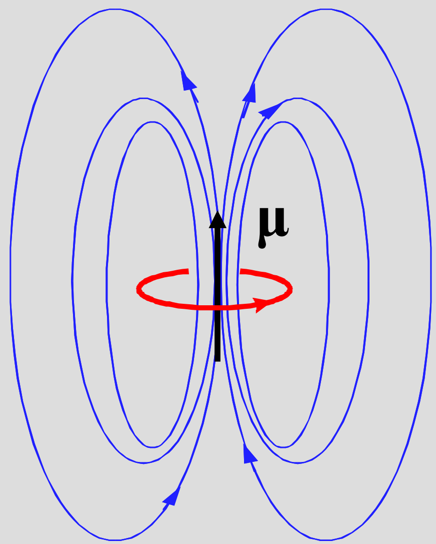
Novel prize 2007: A. Fert & P. Grünberg

Oersted field



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

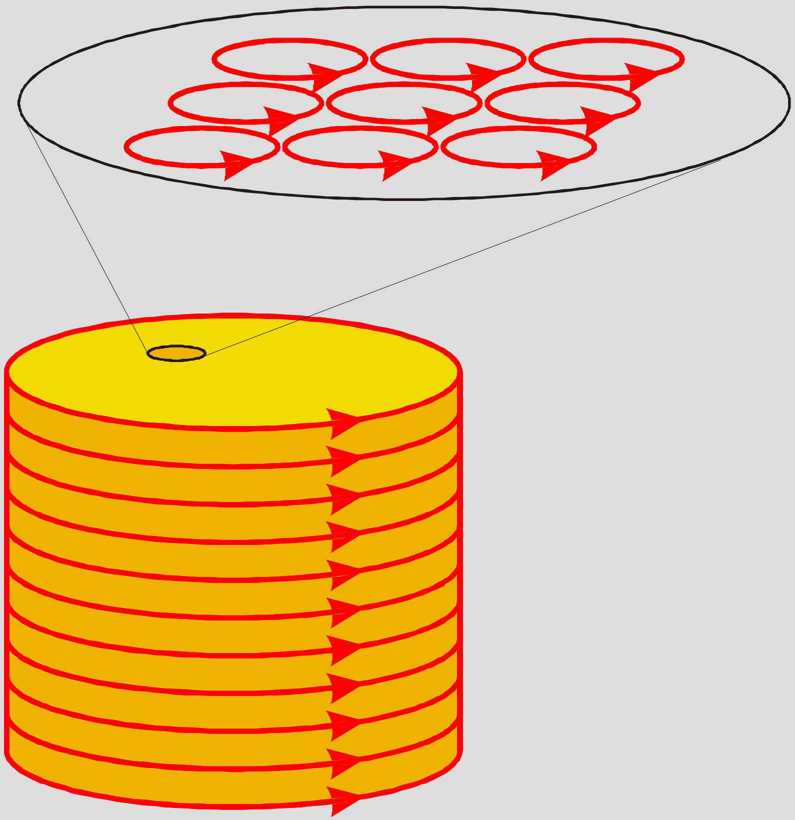
Magnetic dipole



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

Magnetic dipole: $A.m^2$

Magnetic material



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

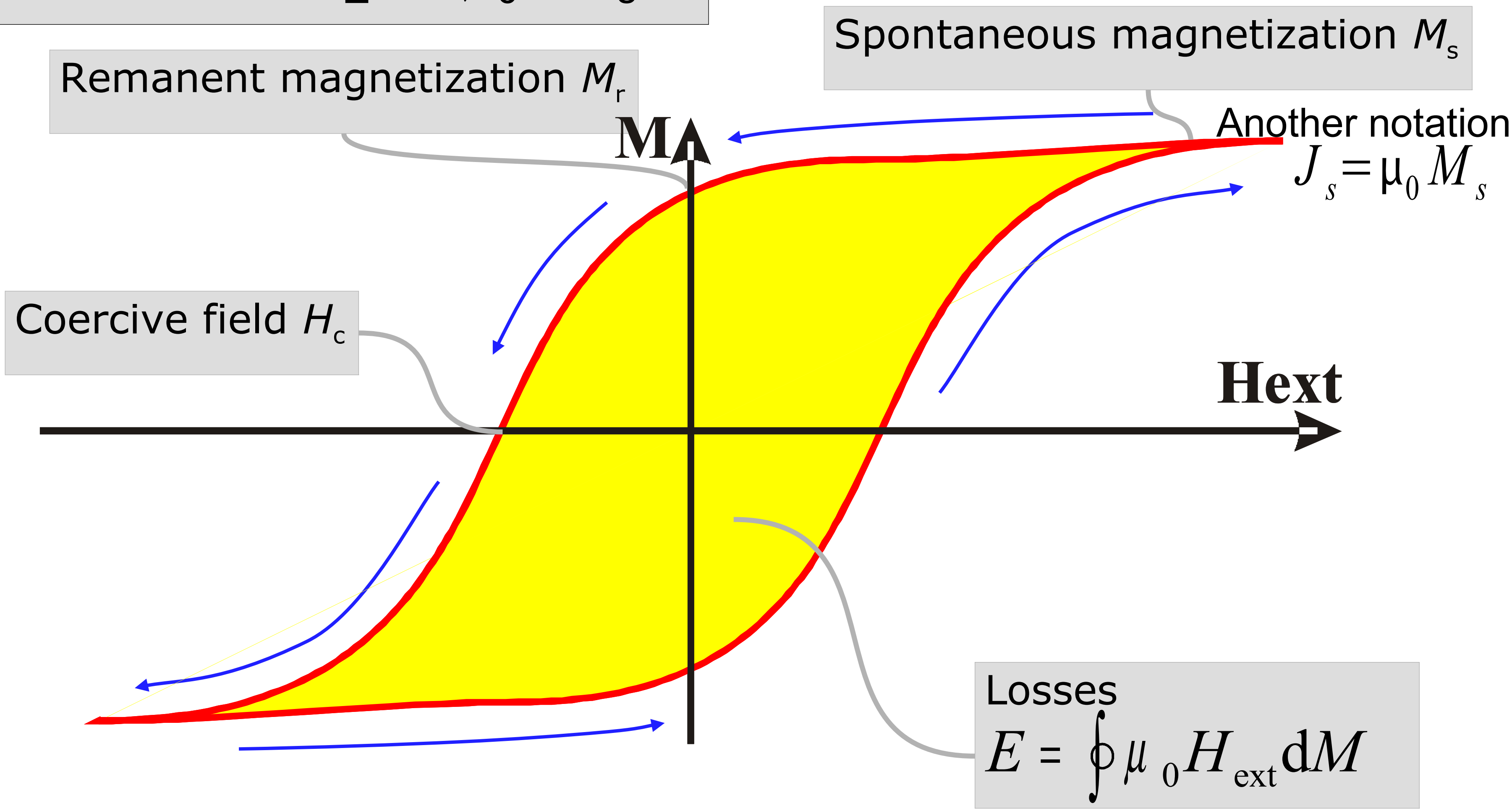
Magnetic moment: $A.m^2$

Manipulation of magnetic materials:

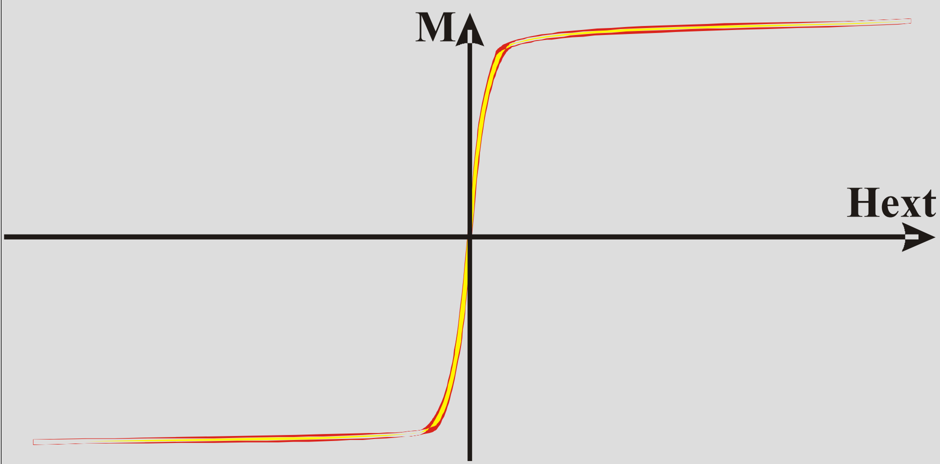
Application of a magnetic field

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

Spontaneous ≠ **S**aturation



Soft materials

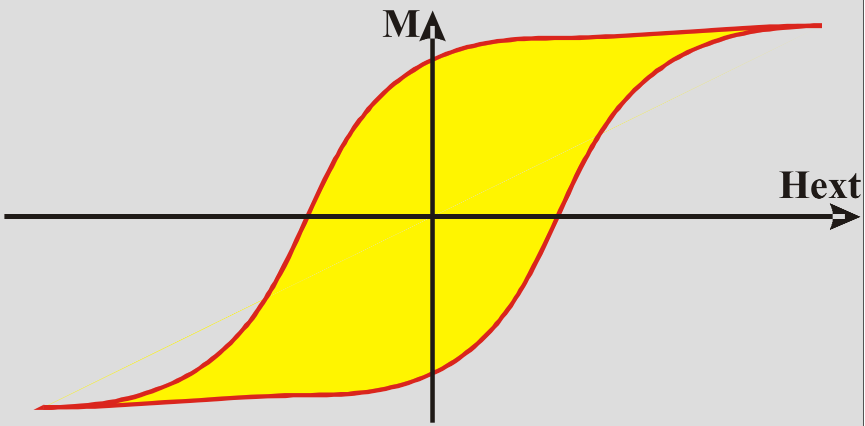


Transformers

Flux guides, sensors

Magnetic shielding

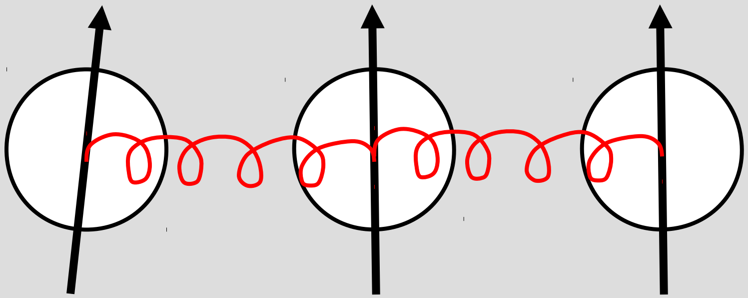
Hard materials



Permanent magnets, motors

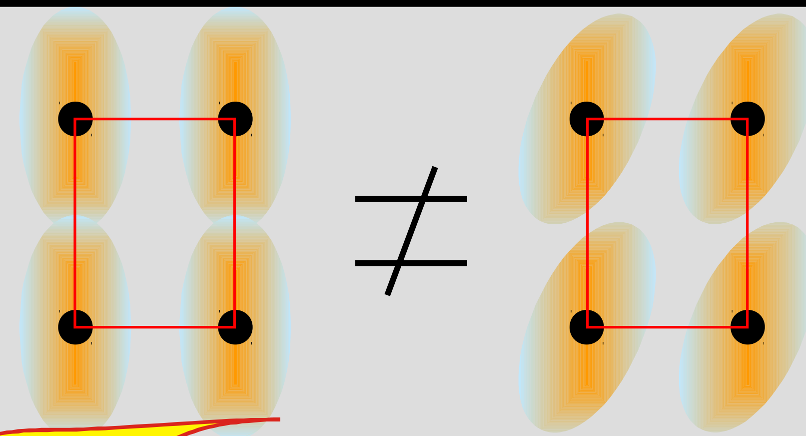
Magnetic recording

Echange energy

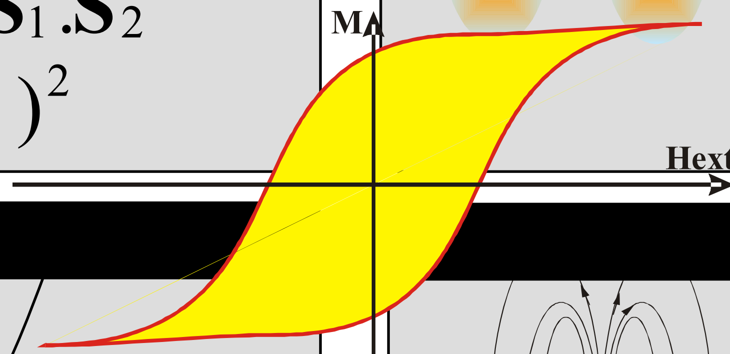


$$E_{\mathrm{Ech}} = -J_{1,2}\,\vec{\mathbf{S}}_1 . \vec{\mathbf{S}}_2$$
$$= A(\nabla\theta)^2$$

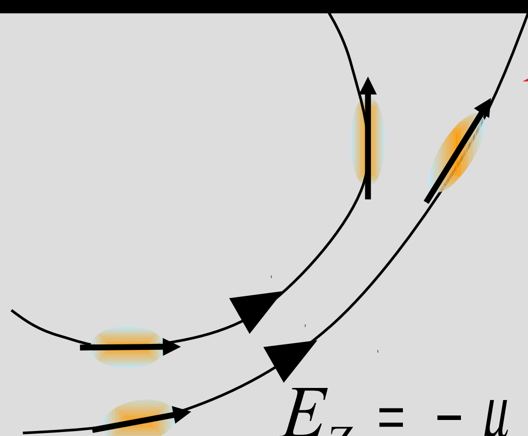
Magnetocrystalline anisotropy energy



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

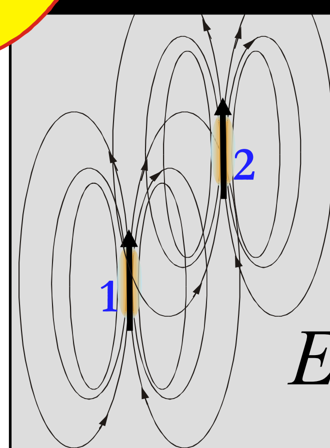


Zeeman energy (enthalpy)



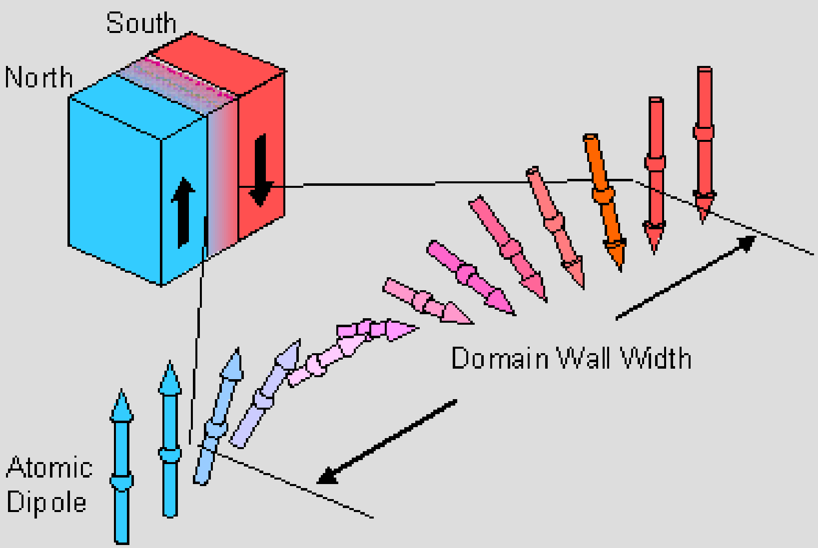
$$E_{\mathrm{Z}} = -\mu_0\,\vec{\mathbf{M}}_{\mathrm{S}} . \vec{\mathbf{H}}$$

Dipolar energy



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

Bloch parameter



$$E = A\left(\partial_x \theta\right)^2 + K \sin^2\theta$$

Exchange → J/m

Anisotropy → J/m^3

Bloch parameter: $\Delta = \sqrt{A/K}$

$\Delta \approx 1$ nm $\rightarrow$ $\Delta \geq 100$ nm

Hard Soft

Exchange length

$$E = A\left(\partial_x \theta\right)^2 + K_\mathrm{d} \sin^2\theta$$

Exchange → J/m

Dipolar energy → J/m^3

$$\Lambda = \sqrt{A/K_\mathrm{d}}$$
$$= \sqrt{2A/\mu_0 M_\mathrm{s}^2}$$

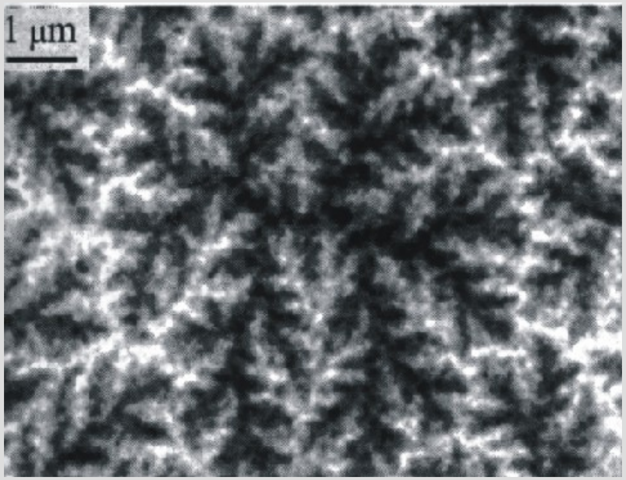
$\Lambda \approx 3-10$ nm

Single-domain critical size relevant for nanoparticules made of soft magnetic material

Notice:
Other length scales: with field etc.

Bulk material

Numerous and complex magnetic domains

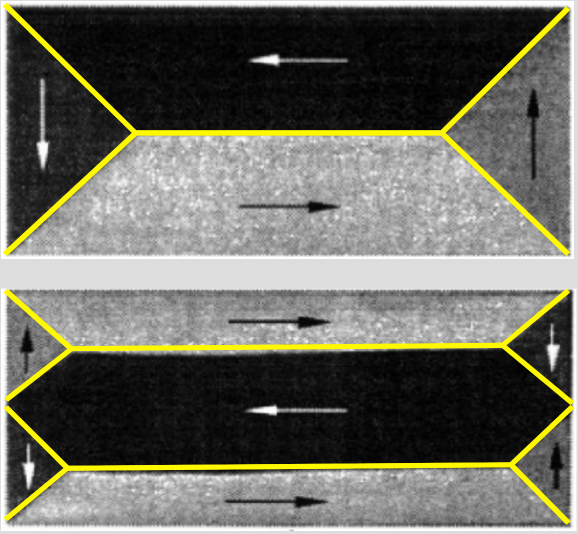


Co(1000) crystal – SEMPA

A. Hubert, *Magnetic domains*

Mesoscopic scale

Small number of domains, simple shape

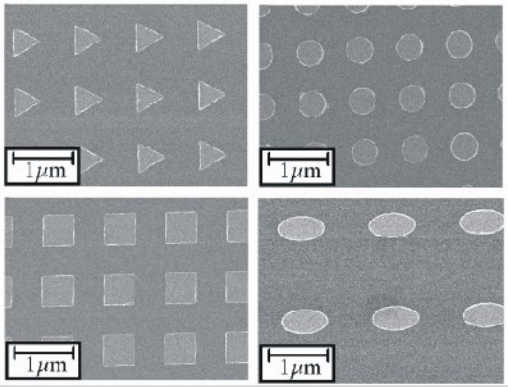


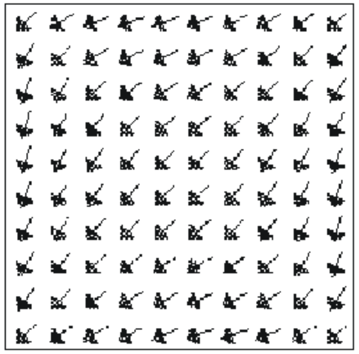
Microfabricated dots
Kerr magnetic imaging

A. Hubert, *Magnetic domains*

Nanometric scale

Magnetic single-domain





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

Nanomagnetism ~ mesoscopic magnetism

Framework

Approximation: $\partial_{\mathbf{r}}\mathbf{m}=\mathbf{0}$ (uniform magnetization)
(strong!)

$$\mathcal{E}=EV=V\left[K_{\mathrm{eff}}\sin^2\theta-\mu_0 M_S H\cos(\theta-\theta_H)\right]$$

$$K_{\mathrm{eff}}=K_{\mathrm{mc}}+K_{\mathrm{d}}$$

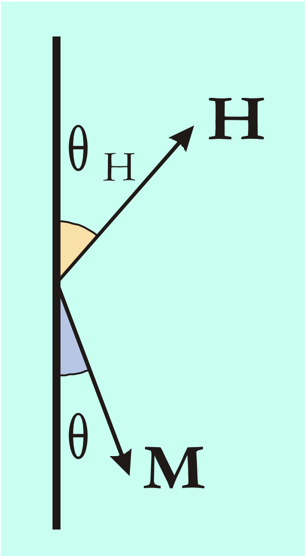
Dimensionless units:

$$e=\mathcal{E}/KV$$

$$h=H/H_a$$

$$H_a=2K/\mu_0 M_S$$

$$e=\sin^2\theta-2h\cos(\theta-\theta_H)$$

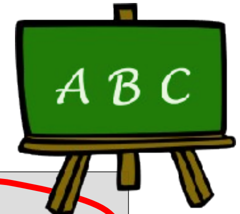


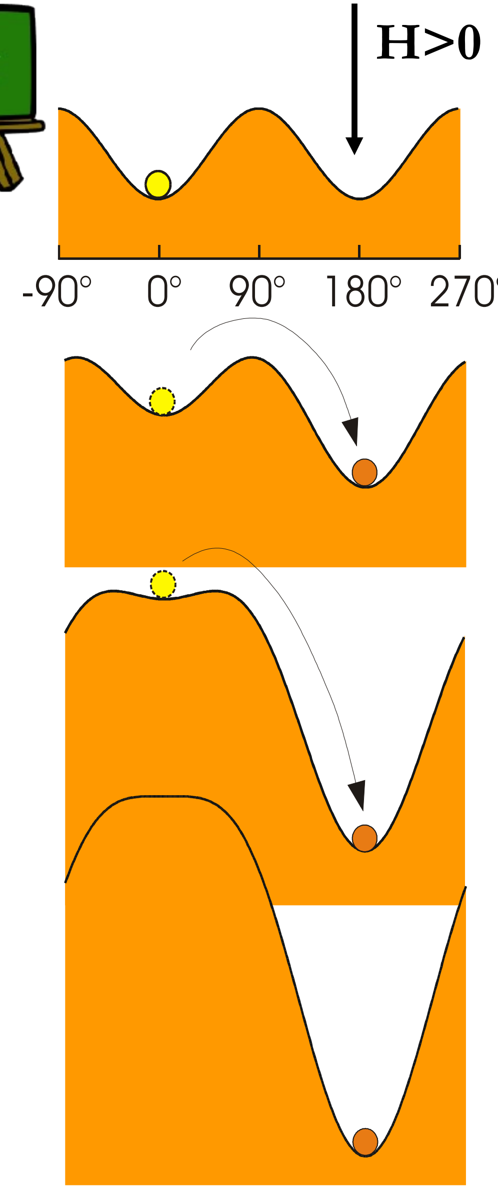
L. Néel, Compte rendu Acad. Sciences 224, 1550 (1947)
E. C. Stoner and E. P. Wohlfarth, *Phil. Trans. Royal. Soc. London* A240, 599 (1948)
IEEE Trans. Magn. 27(4), 3469 (1991) : reprint

Names used

- Uniform rotation / magnetization reversal
- Coherent rotation / magnetization reversal
- Macrospin etc.

Example for $\theta_H = 180°$ $\longrightarrow$ $e = \sin^2\theta + 2h\cos\theta$





Equilibrium states

$\partial_\theta e = 2\sin\theta(\cos\theta - h)$ $\quad$ $\partial_\theta e = 0$ $\Longrightarrow$ $\left| \begin{array}{l} \cos\theta_m = h \\ \theta \equiv 0[\pi] \end{array} \right.$

Stability

$$\partial_{\theta\theta} e = 2\cos 2\theta - 2h\cos\theta = 4\cos^2\theta - 2 - 2h\cos\theta$$

$$\partial_{\theta\theta} e(0) = 2(1-h)$$
$$\partial_{\theta\theta} e(\theta_m) = 2(h^2-1)$$
$$\partial_{\theta\theta} e(\pi) = 2(1+h)$$

Energy barrier

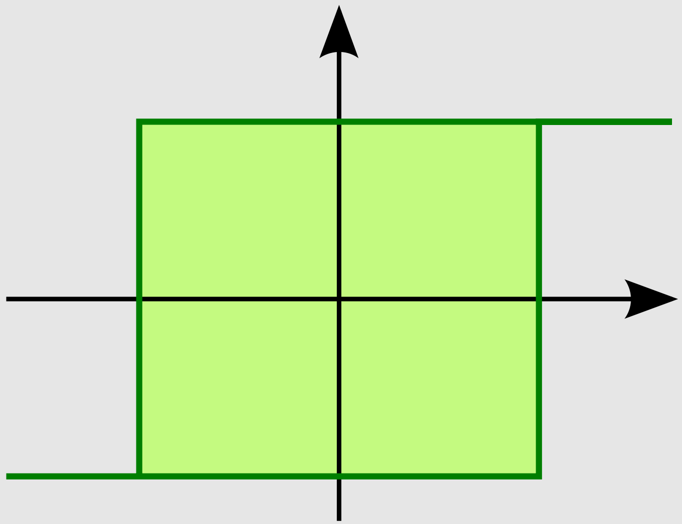
$$\Delta e = e(\theta_{max}) - e(0) = 1 - h^2 + 2h^2 - 2h = (1-h)^2$$

Switching

$$h = 1$$
$$H = H_a = 2K/\mu_0 M_s$$

$(1-h)^\alpha$ with exponent 1.5 in general

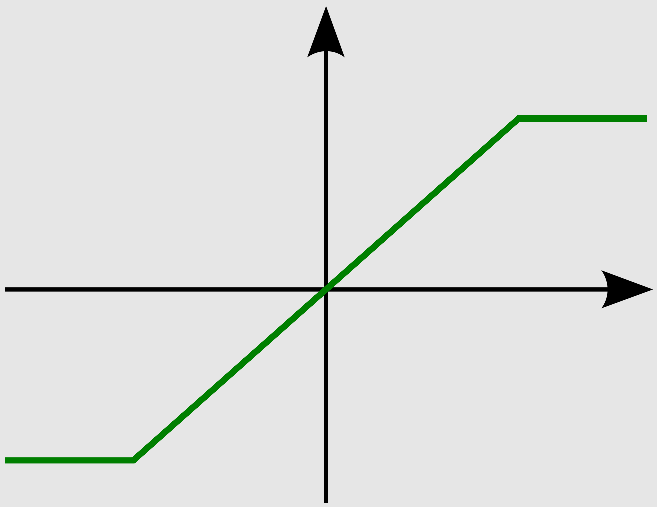
Easy axis



- ⇨ High +/- remanence
- ⇨ Coercivity

Memory, permanent magnet etc.

Hard axis



- ⇨ Reversibility
- ⇨ Linearity

Sensor, shielding etc.

Hitachi to Buy IBM's Hard Drive Business

By: Ken Popovich

06.05.2002 0 comments

IBM has agreed to sell its more than 45-year-old hard-drive business to Tokyo-based electronics giant Hitachi Ltd. for $2.05 billion, the two companies announced Tuesday.

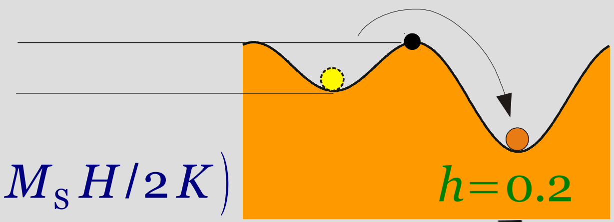
http://www.pcmag.com/article2/0,2817,5915,00.asp

You see things and say « Why ?»,
but I dream things that never were and I say « Why not »

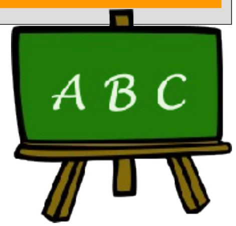
G. B. Shaw

Barrier height

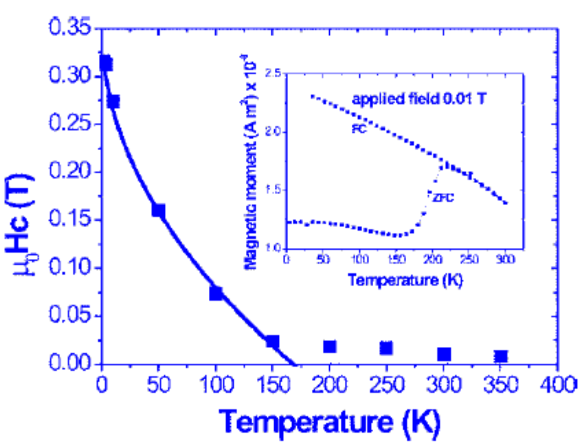
$$\Delta e = e(\theta_{max}) - e(0) = (1-h)^2$$



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



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



Thermal activation

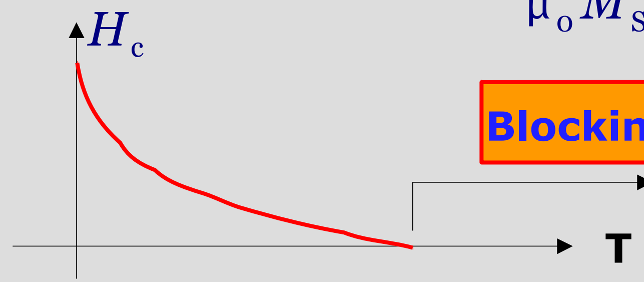
Brown, Phys.Rev.130, 1677 (1963)

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

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

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

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



Blocking temperature

$$T_b \approx KV / 25 k_B$$

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

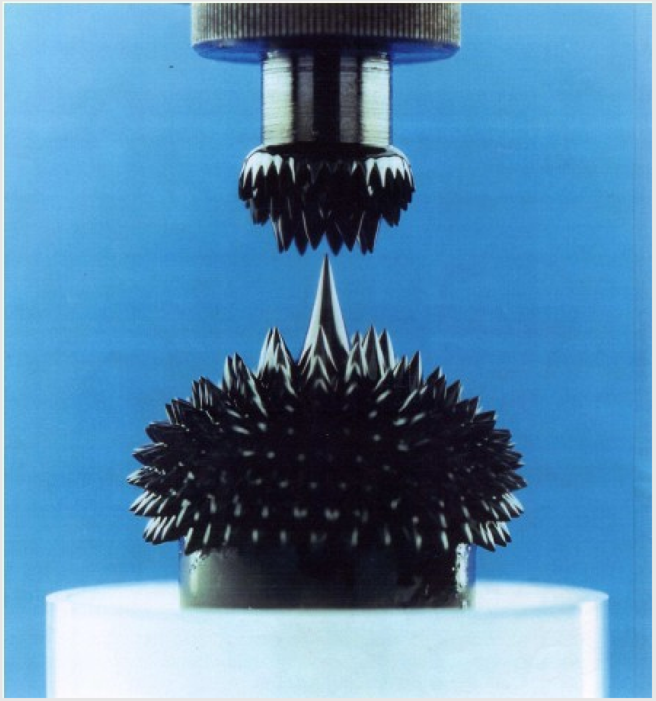
M. P. Sharrock, J. Appl. Phys. 76, 6413-6418 (1994)

Notice, for magnetic recording : $\tau \approx 10^9\ \mathrm{s}$ $\quad KV_b \approx 40-60 k_B T$

Ferrofluids

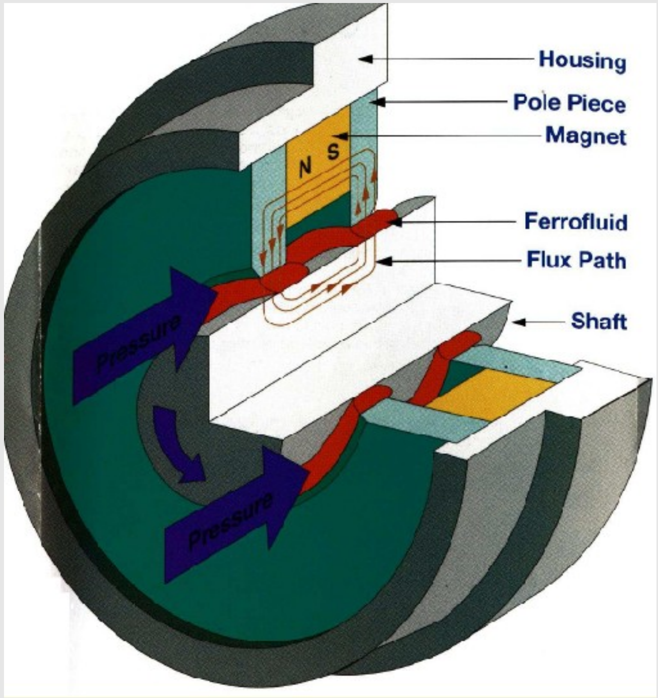
Principle

Surfactant-coated nanoparticles, preferably superparamagnetic
→ Avoid agglomeration of the particles
→ Fluid and polarizable



Example of use

Seals for rotating parts



R. E. Rosensweig, Magnetic fluid seals, US patent 3,260,584 (1971)

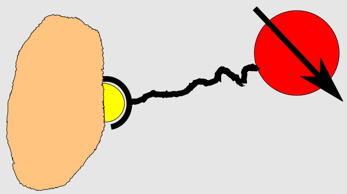
http://esm.neel.cnrs.fr/2007-cluj/slides/vekas-slides.pdf

Health and biology

Beads = coated nanoparticles, preferably superparamagnetic
→ Avoid agglomeration of the particles

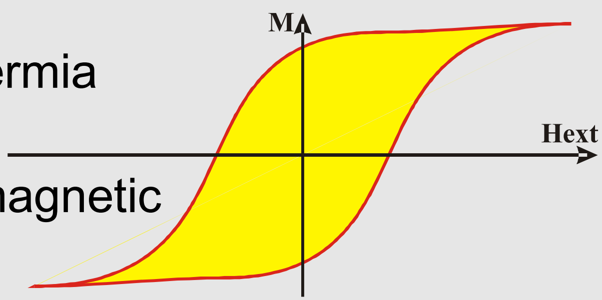
⇨ Cell sorting

$$\mathbf{F}=\nabla\mu.\mathbf{B}$$



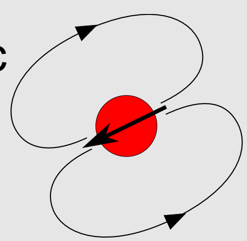
⇨ Hyperthermia

Use ac magnetic field



$$H_c=H_{c,0}\left(1-\sqrt{\frac{\ln(\tau/\tau_0)k_B T}{KV}}\right)$$

⇨ Contrast agent in Magnetic Resonance Imaging (MRI)



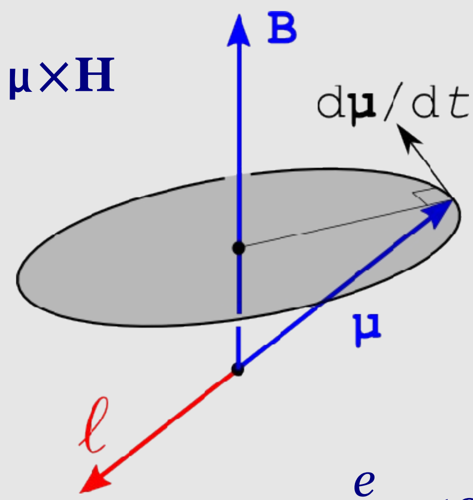
RAM (radar absorbing materials)

⇨ Principle

Absorbs energy at a well-defined frequency (ferromagnetic resonance)

$$\frac{d\boldsymbol{\ell}}{dt}=\boldsymbol{\Gamma}=\mu_0\boldsymbol{\mu}\times\mathbf{H}=\mu_0\gamma\boldsymbol{\ell}\times\mathbf{H}$$

$$\frac{d\boldsymbol{\mu}}{dt}=\mu_0\gamma\boldsymbol{\mu}\times\mathbf{H}$$



$$\gamma=-g_J\frac{e}{2m_e}<0$$

$$\gamma_s/2\pi\approx 28\ \mathrm{GHz/T}$$

Density of dipolar energy

$$E_d(\mathbf{r}) = -\frac{1}{2}\mu_0 \mathbf{M}(\mathbf{r}).\mathbf{H}_d(\mathbf{r})$$

By definition $\mathrm{div}(\mathbf{H}_d) = -\mathrm{div}(\mathbf{M})$. As $\mathbf{curl}(\mathbf{H}_d) = \mathbf{0}$ we have (analogy with electrostatics):

Notation

$$\mathbf{M}(\mathbf{r}) = M_s m_i(\mathbf{r})\mathbf{u_i}$$

$$\mathbf{H}_d(\mathbf{r}) = -M_s \iiint_{\text{space}} \frac{\mathrm{div}[\mathbf{m}(\mathbf{r}')].(\mathbf{r}'-\mathbf{r})}{4\pi \left\|\mathbf{r}-\mathbf{r}'\right\|^3} \mathrm{d}^3 r'$$

$$\rho(\mathbf{r}) = -M_s \mathrm{div}[\mathbf{m}(\mathbf{r})]$$ volume density of magnetic charges

To lift the divergence arising at sample boundaries:

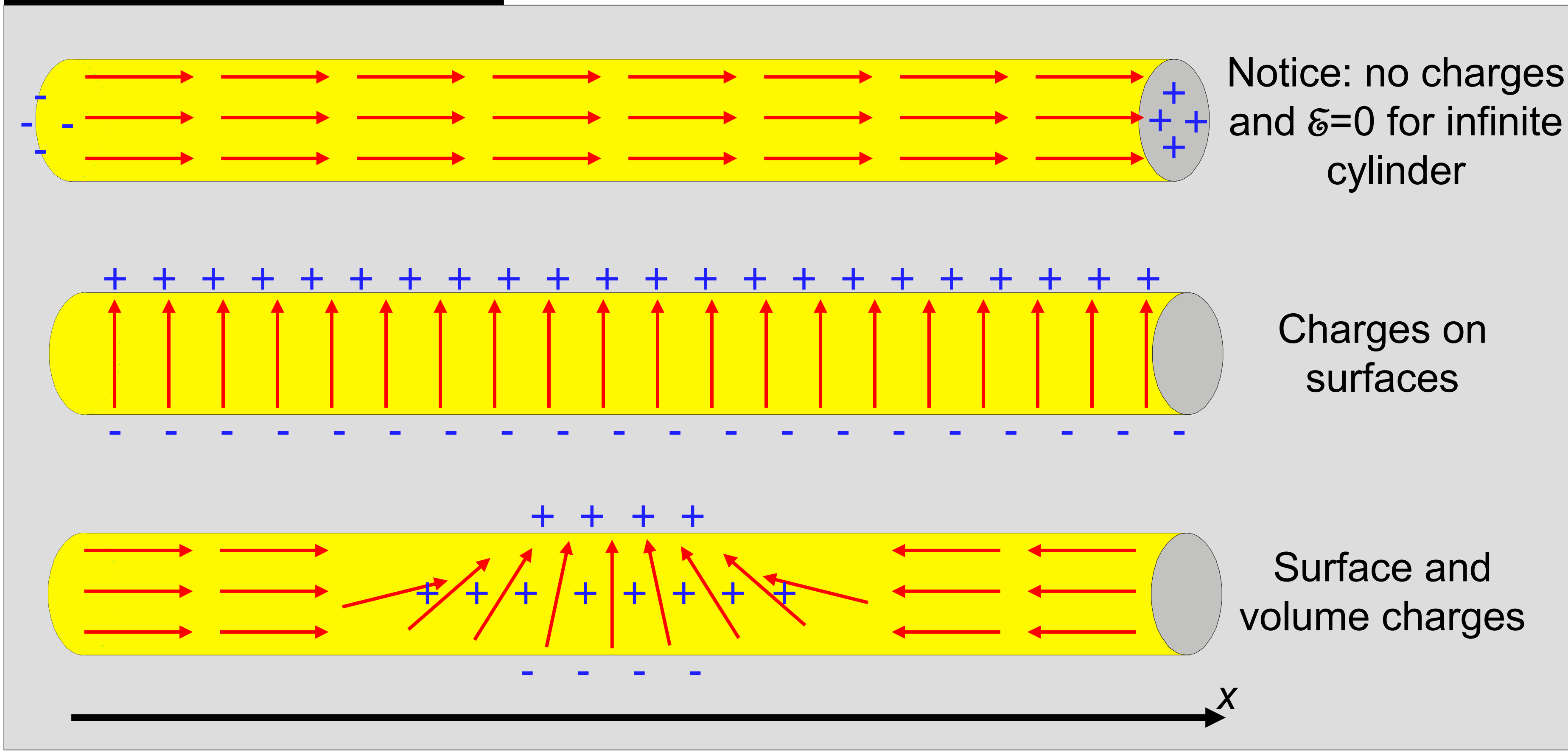
$$\mathbf{H}_d(\mathbf{r}) = M_s\left(-\iiint_{\text{space}} \frac{\mathrm{div}[\mathbf{m}(\mathbf{r}')].(\mathbf{r}'-\mathbf{r})}{4\pi \left\|\mathbf{r}-\mathbf{r}'\right\|^3} \mathrm{d}^3 r' + \iint_{\text{sample}} \frac{[\mathbf{m}(\mathbf{r}').\mathbf{n}(\mathbf{r}')].(\mathbf{r}'-\mathbf{r})}{4\pi \left\|\mathbf{r}-\mathbf{r}'\right\|^3} \mathrm{d}^2 r'\right)$$

$$\sigma(\mathbf{r}) = M_s \mathbf{m}(\mathbf{r}).\mathbf{n}(\mathbf{r})$$ surface density of magnetic charges, where n(r) is the outgoing unit vector at boundaries

$$\mathcal{E} = -\frac{1}{2}\mu_0 \iiint_{\mathrm{sample}} \mathbf{M}.\mathbf{H}_\mathrm{d}.\mathrm{d}V = \frac{1}{2}\mu_0 \iiint_{\mathrm{space}} \mathbf{H}_\mathrm{d}^2.\mathrm{d}V$$

⇨ $\mathcal{E}$ is always positive

Examples of magnetic charges



Magnetization will tend to align parallel to long axis of samples

Hypothesis

Uniform magnetization $\mathbf{M}(\mathbf{r}) = M_s m_i \mathbf{u_i}$ (strong assumption!)

Demagnetizing coefficients

$$< \mathbf{H}_\mathrm{d}(\mathbf{r}) > = -M_\mathrm{s}\bar{\bar{\mathbf{N}}}.\mathbf{m}$$

$$\mathcal{E}_\mathrm{d} = K_\mathrm{d} N_{ij} m_i m_j = K_\mathrm{d}\, {}^t\mathbf{m}.\bar{\bar{\mathbf{N}}}.\mathbf{m}$$

N is a positive second-order tensor

...and can be defined and diagonalized for any sample shape

$$N = \begin{pmatrix} N_x & 0 & 0 \\ 0 & N_y & 0 \\ 0 & 0 & N_z \end{pmatrix}$$

$$\mathcal{E}_\mathrm{d} = K_\mathrm{d}(N_x m_x^2 + N_y m_y^2 + N_z m_z^2)$$

$$< H_{\mathrm{d},i}(\mathbf{r}) > = -M_\mathrm{s} N_i$$ ← Valid along main axes only!

$$N_x + N_y + N_z = 1$$

What with ellipsoids???

Requires $\mathbf{H}_\mathrm{d}(\mathbf{r})$ is uniform. Satisfied only in volumes limited by polynomial surfaces of order 2 or less:slabs, cylinders, ellisoids etc.

J. C. Maxwell, Clarendon 2, 66-73 (1872)

Ellipsoids

$$N_x = \tfrac{1}{2}abc\int_0^\infty \left[(a^2+\eta)\sqrt{(a^2+\eta)(b^2+\eta)(c^2+\eta)}\right]^{-1}\mathrm{d}\eta$$

General ellipsoid: main axes (a,c,c)

$$N_x = \frac{\alpha^2}{1-\alpha^2}\left[\frac{1}{\sqrt{1-\alpha^2}}\,\mathrm{Asinh}\left(\frac{\sqrt{1-\alpha^2}}{\alpha}\right)-1\right]$$

For prolate revolution ellipsoid: (a,c,c) with α=c/a<1

$$N_y = N_z = \tfrac{1}{2}(1-N_x)$$

$$N_x = \frac{\alpha^2}{\alpha^2-1}\left[1-\frac{1}{\sqrt{\alpha^2-1}}\,\mathrm{Asin}\left(\frac{\sqrt{\alpha^2-1}}{\alpha}\right)\right]$$

For oblate revolution ellipsoid: (a,c,c) with α=c/a>1

Cylinders

$$N_x = 0;\quad N_y = c/(b+c);\quad N_z = b/(b+c)$$

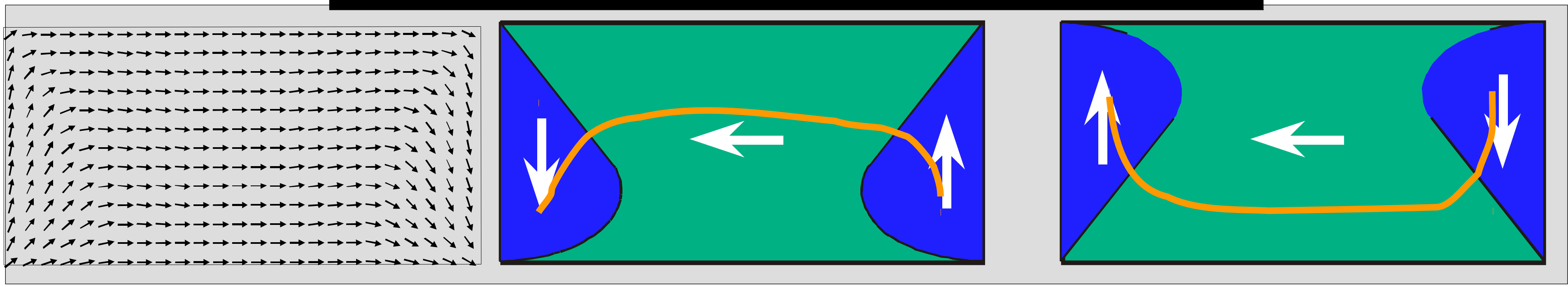
For a cylinder along x

J. A. Osborn, Phys. Rev. 67, 351 (1945).

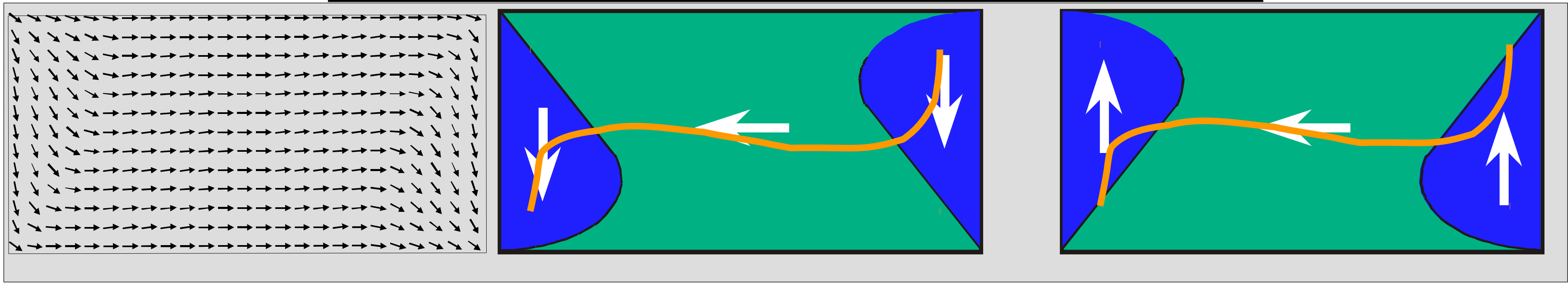
For prisms, see: **A. Aharoni, J. Appl. Phys. 83, 3432 (1998)**

More general forms, FFT approach: **M. Beleggia et al., J. Magn. Magn. Mater. 263, L1-9 (2003)**

'C' state

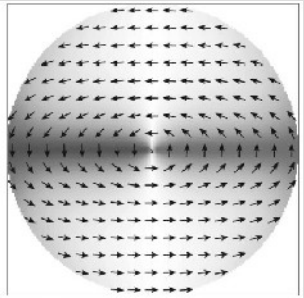


'S' state



- At least 8 nearly-equivalent ground-states for a rectangular dot
- Numerical simulation becomes important

Magnetic vortex



P.-O. Jubert & R. Allenspach, PRB 70, 144402/1-5 (2004)

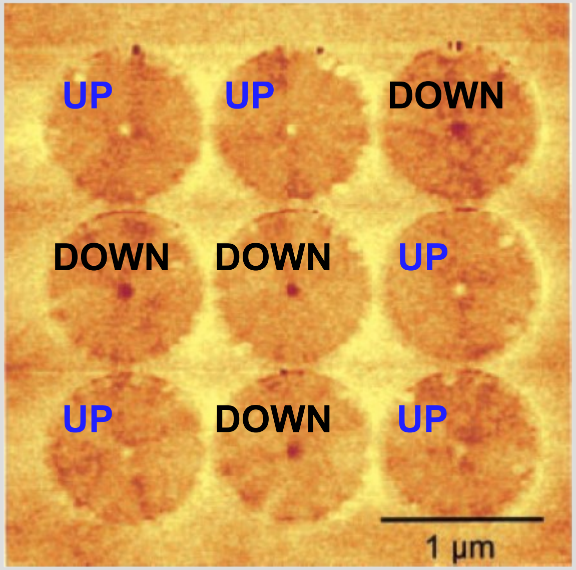


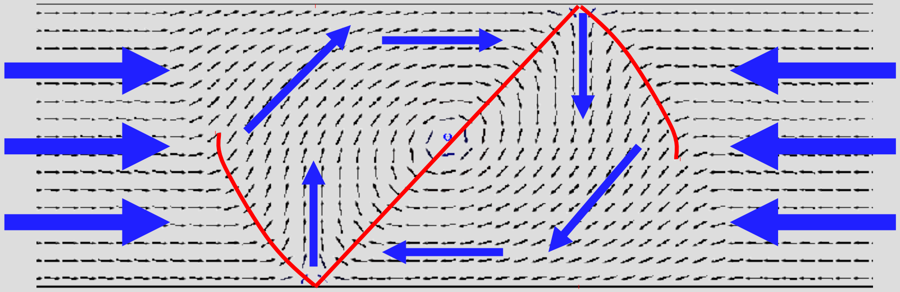
Fig. 2. MFM image of an array of permalloy dots 1 µm in diameter and 50 nm thick.

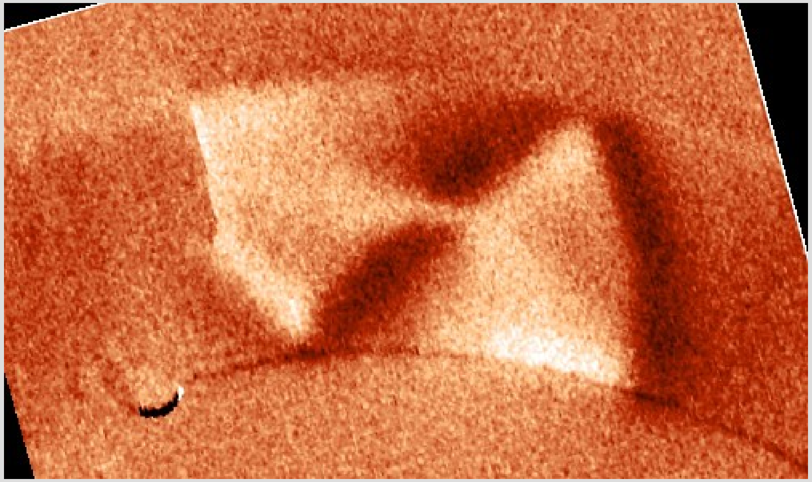
T. Shinjo et al., Science 289, 930 (2000)

T. Okuno et al., JMMM240, 1 (2002)

Magnetic domain wall

Thick and large stripes





500-nm wide, 15nm FeNi thick stripes

Basics of precessional switching

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

$\gamma_0 = \mu_0\gamma \qquad \gamma = \dfrac{gq}{2m}$

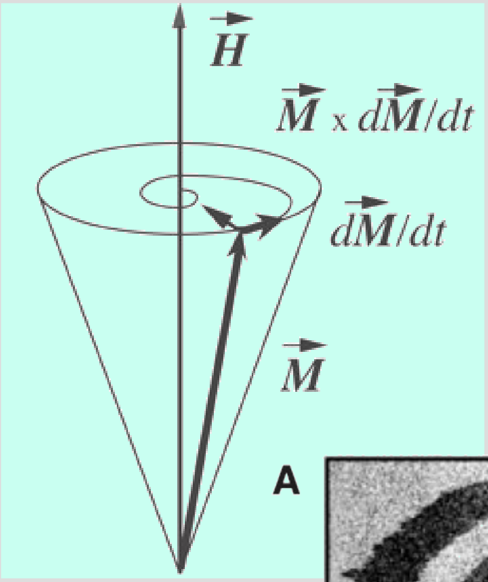
$\gamma/2\pi = 28\,\mathrm{GHz/T}$

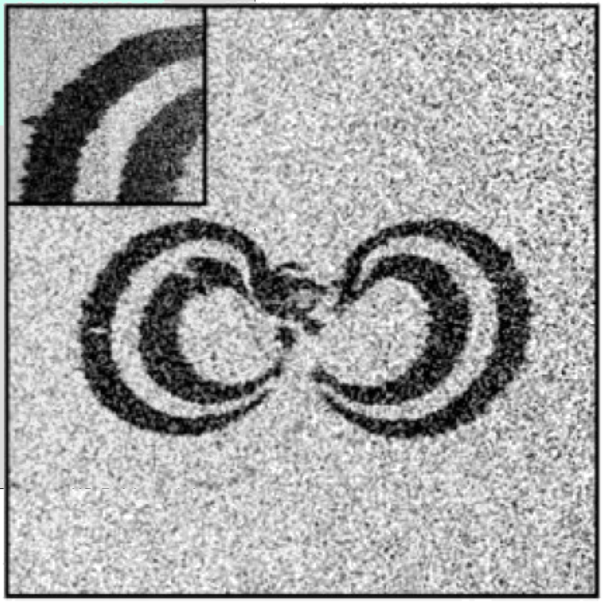
H_{eff} Effective field (including applied)

$$\mu_0 H_{\mathrm{eff}} = -\frac{\partial E_{\mathrm{mag}}}{\partial \mathbf{M}}$$

α Damping coefficient (10^{-3} > 10^{-1})

Démonstration: 1999





150 μm

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

Precessional trajectories using energy conservation

(1) $E = \frac{1}{2}\mu_0 M_s^2 N_z m_z^2 - K m_x^2 - \mu_0 M_s H m_y$ In-plane uniaxial anisotropy

(2) $m_x^2 + m_y^2 + m_z^2 = 1$

Starting condition: $m_x = 1$

(1) ➡ $e = \frac{1}{2} N_z m_z^2 - h_K m_x^2 - h m_y$

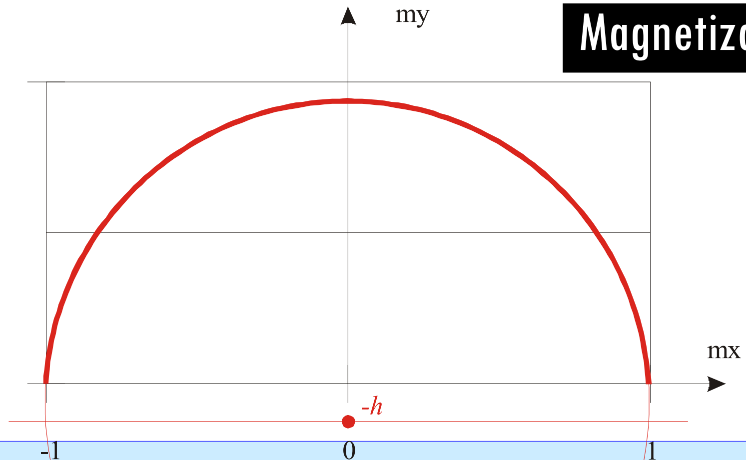
Using (2) ➡ $m_x^2 = 1 - \dfrac{2h}{N_z + h_K} m_y - \dfrac{N_z}{N_z + h_K} m_y^2$

Can be rewritten: $$m_x^2 + \frac{\left(m_y + h/N_z\right)^2}{1 + h_K/N_z} = 1 + \frac{h^2}{N_z(N_z + h_K)}$$

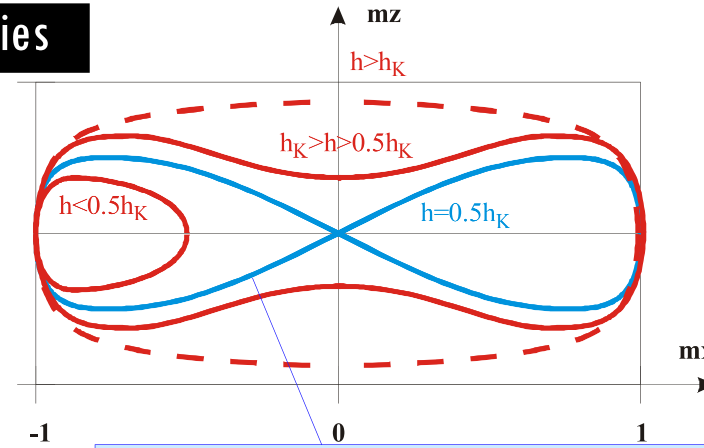
Using (2) ➡ $m_z^2 = \dfrac{2h}{N_z + h_K} m_y - \dfrac{h_K}{N_z + h_K} m_y^2$

Can be rewritten: $$\frac{m_z^2}{\left(\frac{h_K}{N_z + h_K}\right)} + \left(m_y - \frac{h}{h_K}\right)^2 = \left(\frac{h}{h_K}\right)^2$$

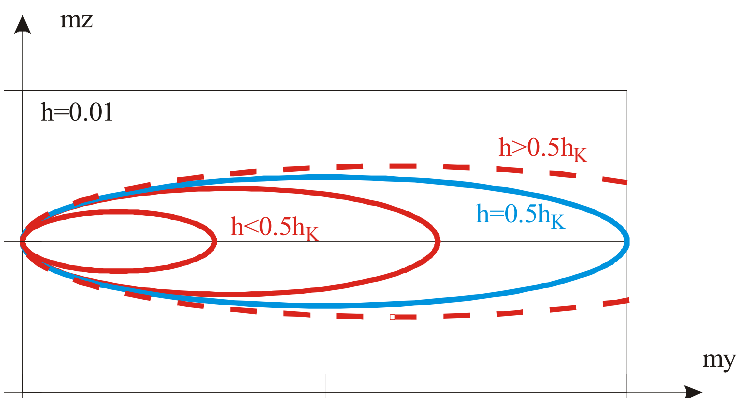
Magnetization trajectories



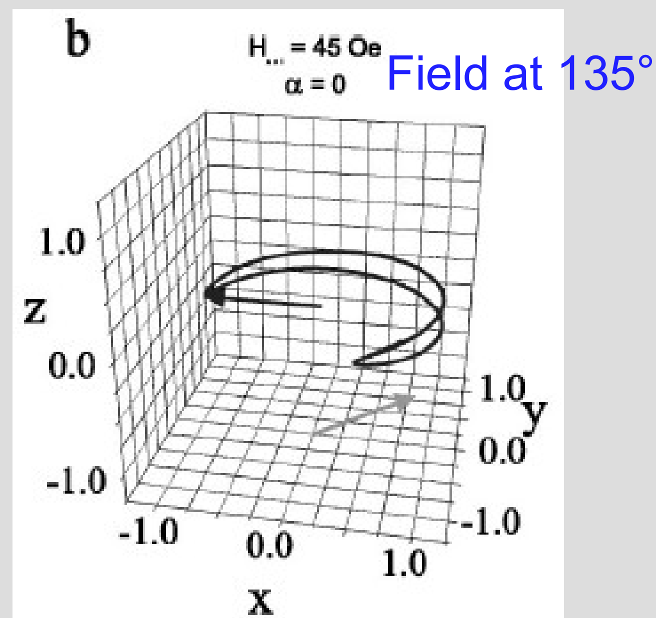
$$m_x^2 + \frac{\left(m_y + h/N_z\right)^2}{1+h_K/N_z} = 1 + \frac{h^2}{N_z(N_z+h_K)}$$



$$\omega \approx 0.847\gamma_0\sqrt{M_s(H-H_K)/2}$$



$$\frac{m_z^2}{\left(\frac{h_K}{N_z+h_K}\right)} + \left(m_y - \frac{h}{h_K}\right)^2 = \left(\frac{h}{h_K}\right)^2$$



M. Bauer et al., PRB61, 3410 (2000)

Probing surface magnetization

Surface techniques at 0K

- Mossbauer with probe layers

Plot *m*(*t*) at 0K:

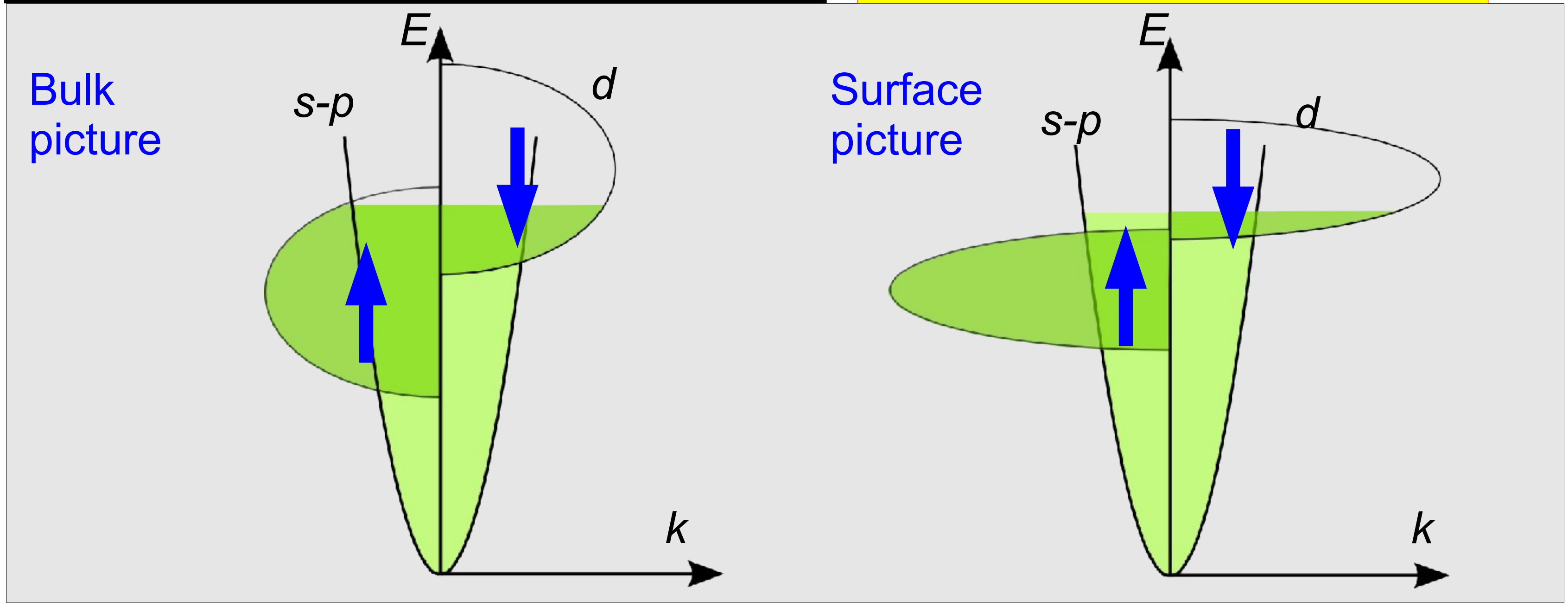
- Magnetometry
- XMCD

Some results

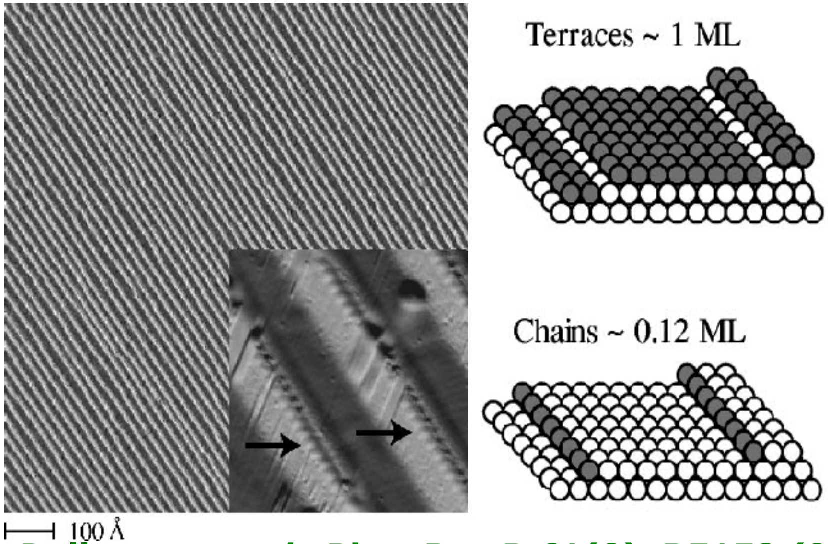
- Fe/W(110) : 0.14ML(+0.35μ_B)
- UHV/Fe(110); Ag/Fe(110): 0.26ML(+0.65μ_B)
- Cu/Ni(111): -0.5ML
- Overlayers: Pd/Ni(111)/Re(0001)

(Too) simple picture: band narrowing at surfaces

Enhanced moment at surfaces



Co/Pt(997)



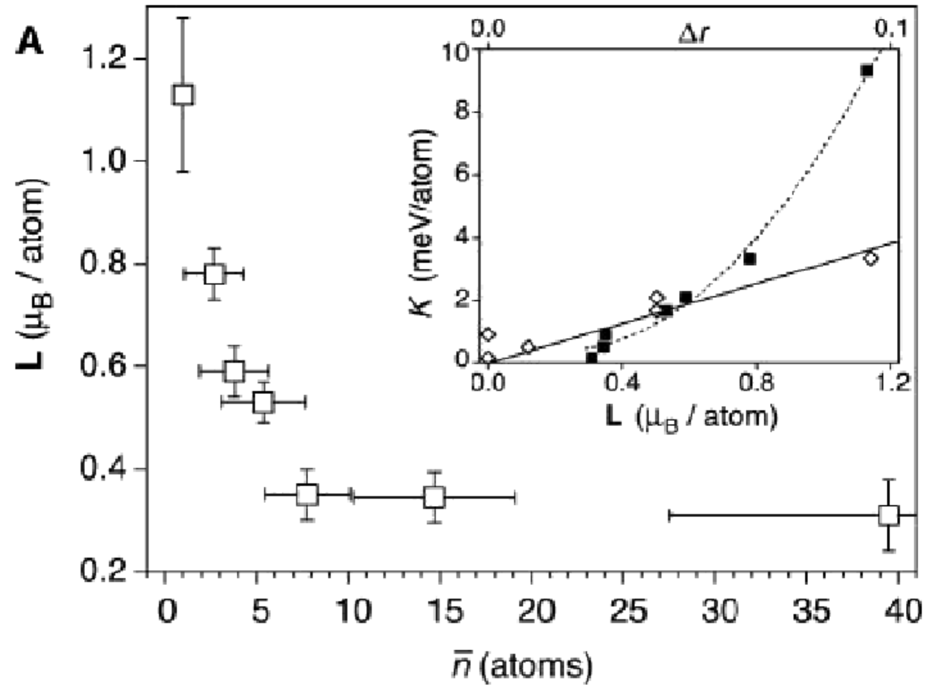
A. Dallmeyer *et al.*, Phys.Rev.B 61(8), R5153 (2000)

Conclusions

- 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)

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**

Elements of theory

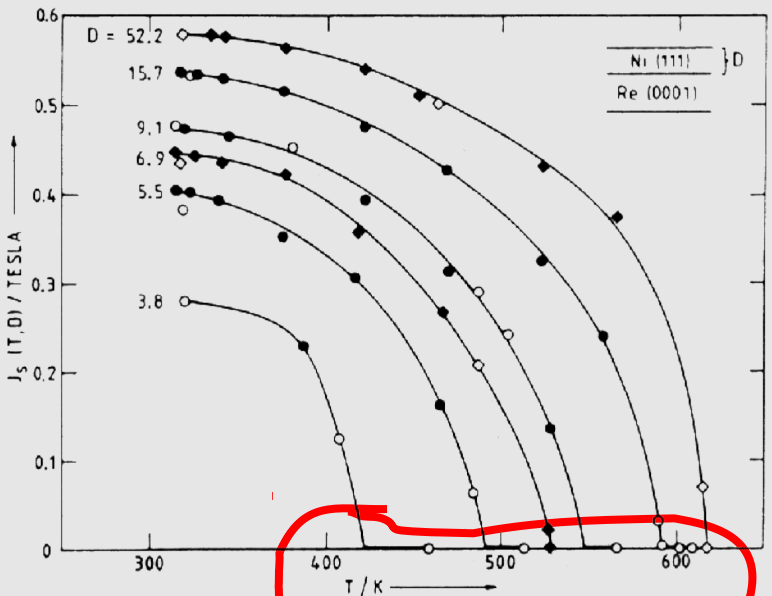
- Ising (1925). No magnetic order at T>0K in 1D Ising chain.
- Bloch (1930). No magnetic order at T>OK in 2D Heisenberg.
  (spin-waves; isotropic Heisenberg)
- → N. D. Mermin, H. Wagner, PRL17, 1133 (1966)
- Onsager (1944) + Yang (1951).
  2D Ising model: Tc>0K

Magnetic anisotropy stabilizes ordering

Experiments

Ni(111)/Re(0001)

R. Bergholz and U. Gradmann, JMMM45, 389 (1984)



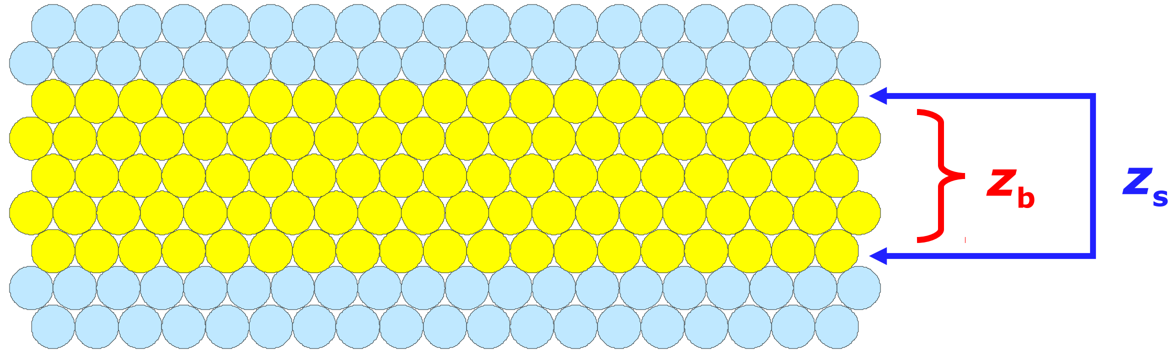
Tc interpreted with molecular field

Naïve model

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

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

Less naïve...

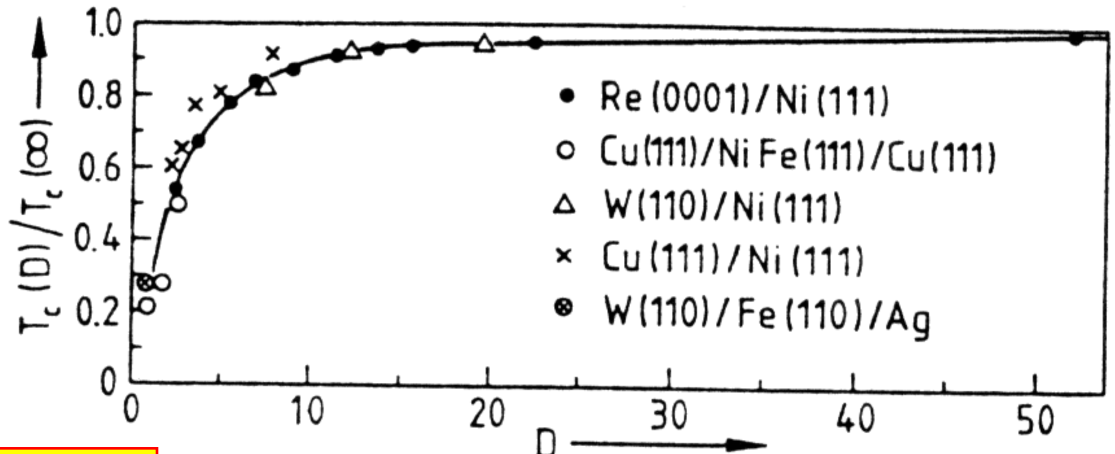
Thickness-dependent molecular field

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

$$\lambda = 1$$

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

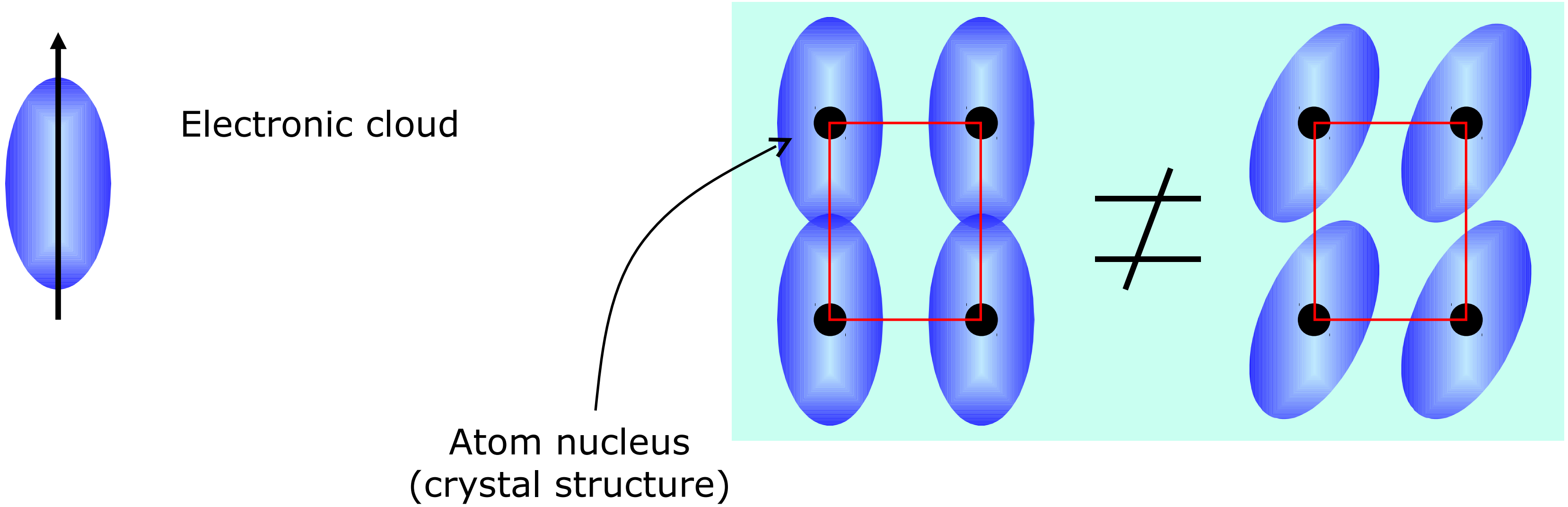
Experiments



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

Conclusion:
Naïve views are roughly correct

Magnetocrystalline anisotropy energy



Spin-orbit coupling ⇨ the energy of both spin and orbital moment depends on orientation

Series development on an angular basis:

Anisotropy energy **Normalized magnetization components**

$$E_{mc} = K_1 m_z^2 + K_2 m_z^4 + \ldots \quad \text{Uniaxial}$$

$$E_{mc} = K_4 (m_x^2 m_y^2 + m_y^2 m_z^2 + m_z^2 m_x^2) + \ldots \quad \text{Cubic}$$

…

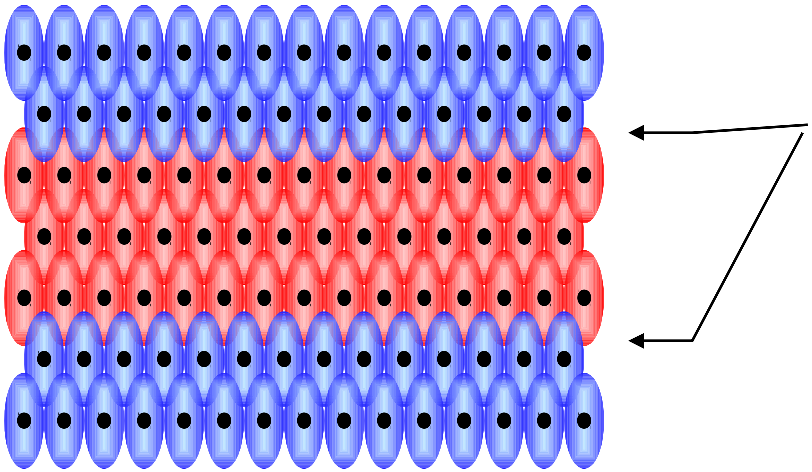
Alignement of magnetization is favored along given axes of the crystal

(Derived from slide of A. Thiaville – CNRS/Orsay)

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 »

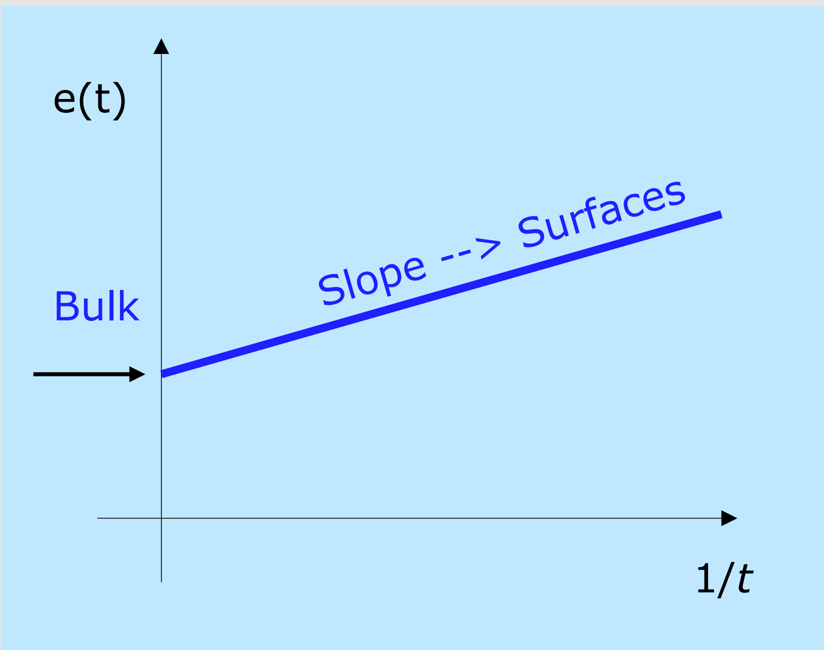
Pair model of Néel:

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

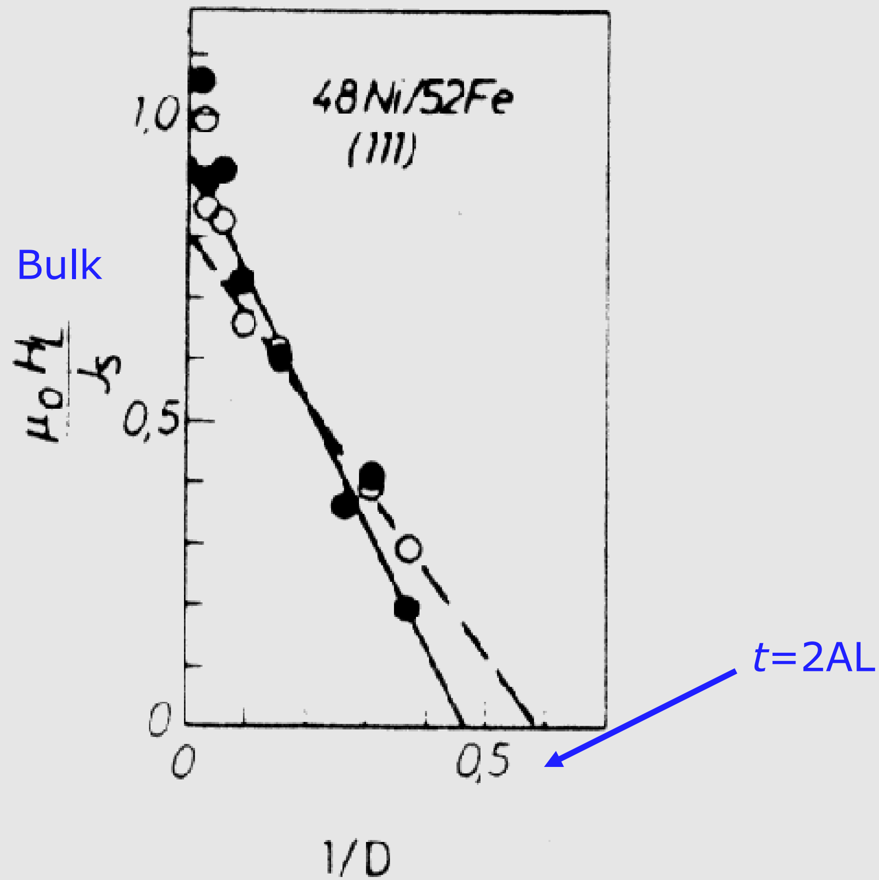
History of surface anisotropy : STEP 1 (1/t plot)

$$E_{tot}(t) = k_V t + 2k_S$$

$$\Rightarrow \quad e(t) = k_V + \frac{2k_S}{t}$$



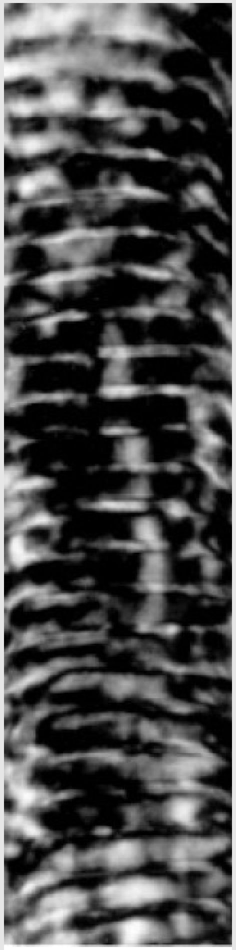
First example of perpendicular anisotropy



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

Main use in applications : perpendicular magnetic anisotropy in thin films

Materials and geometry

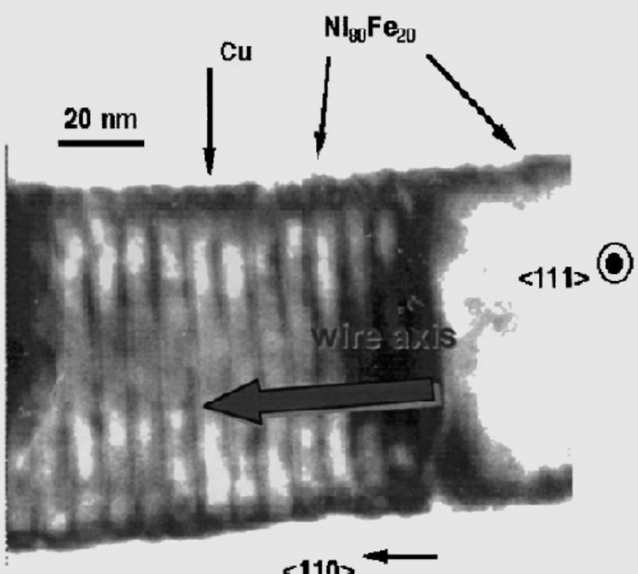


Interfacial elements with large spin-orbit: Pt, Au, Pd

Often: multilayers

Co/Au film

M. T. Johnson et al., Rep. Prog. Phys. 59, 1409 (1996)

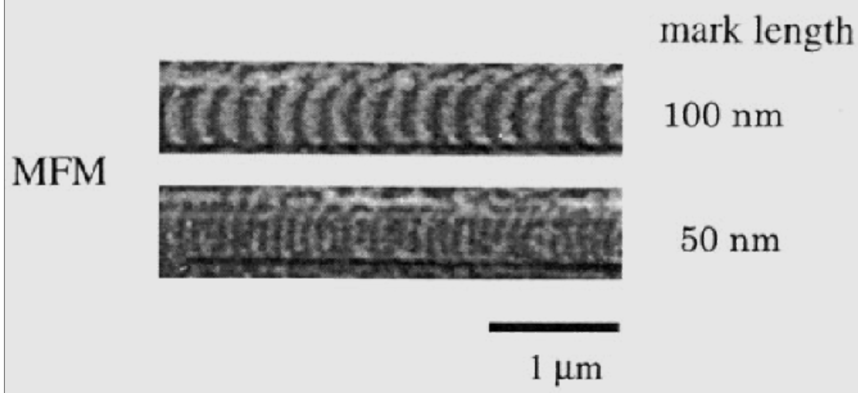


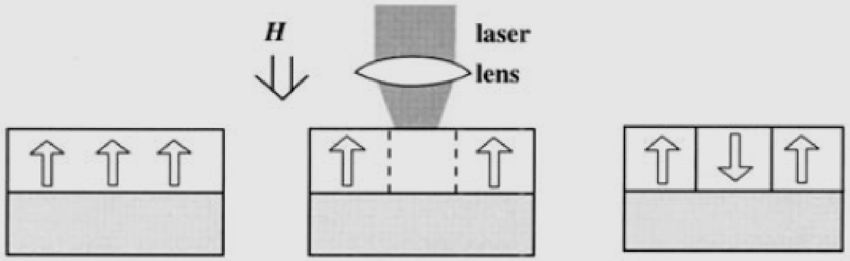
A. Fert et al., J. Magn. Magn. Mater. 200, 338 (1999)

Magneto-optical recording

Why: large magneto-optical response

Material: 3D-Rare-Earth based



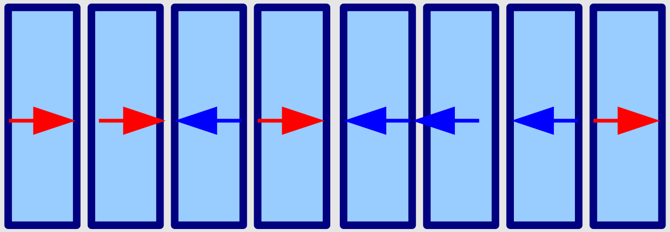


S. Tsunashima, J. Phys. D 34, R87 (2001)

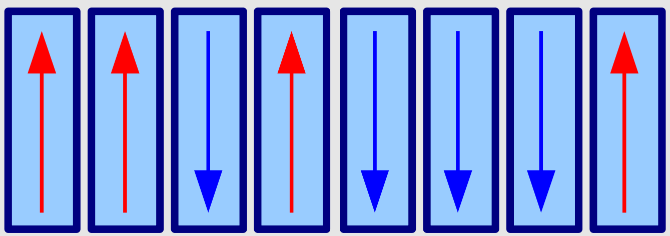
Main use in applications : perpendicular magnetic anisotropy

Decreased dipolar coupling in HDD media

Longitudinal recording (1956 -)



Perpendicular recording (2005 -)



S. N. Piramanayagam, J. Appl. Phys. 102, 011301 (2007)

⇨ High anisotropy with low spread angle

⇨ Reduced intra- and inter-grain dipolar coupling

Enhanced anisotropy for solid-state memories

Concerns MRAM: Magnetic Random Access Memories

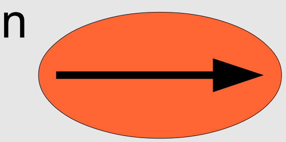
C. Chappert et al., The emergence of spin electronics in data storage, Nat. Mater. 6, 813 (2007)

Reminder for the thermal stability fo small flat elements:

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

⇨ In-plane magnetization

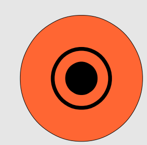
$$K = N \times \frac{1}{2}\mu_0 M_S^2$$



Issue: N is small with flat elements

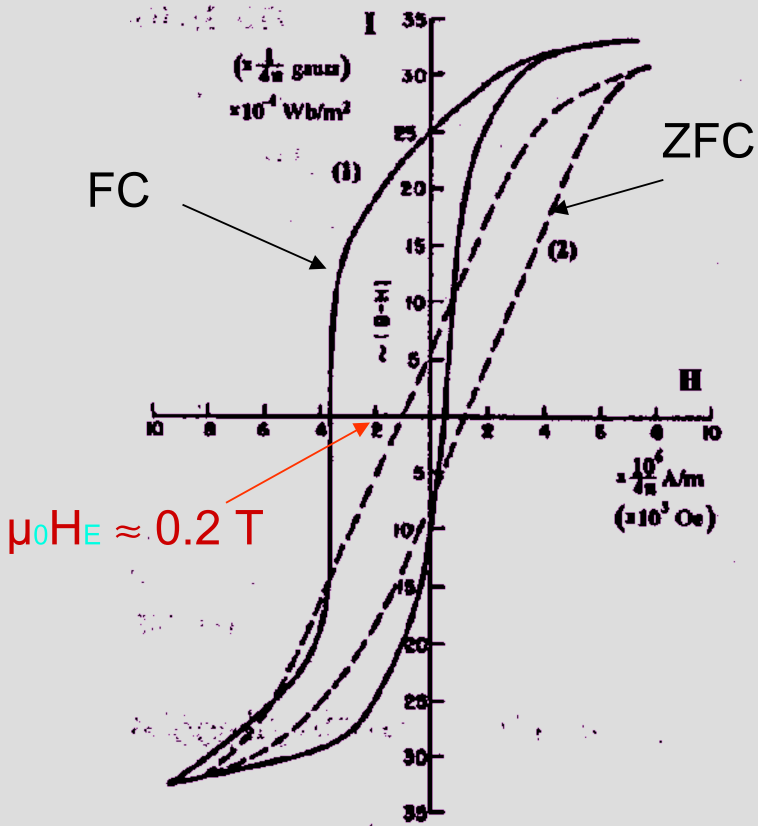
⇨ Perpendicular magnetization

$$K \approx \frac{1}{2}\mu_0 M_S^2$$

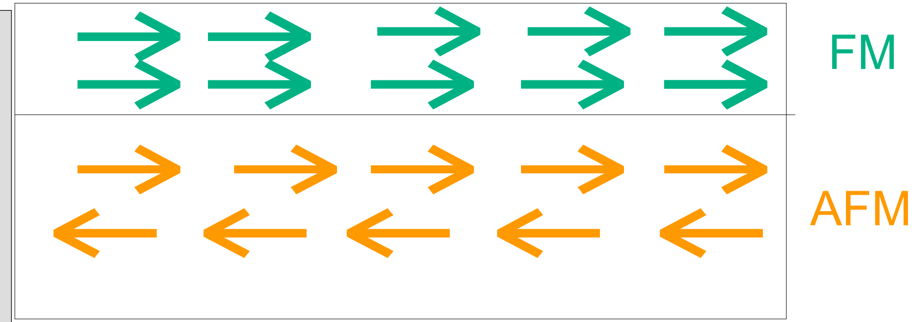


Seminal studies

Oxidized Co nanoparticles



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



Field-cooled hysteresis loops:

- **Increased coercivity**
- **Shifted in field**

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)

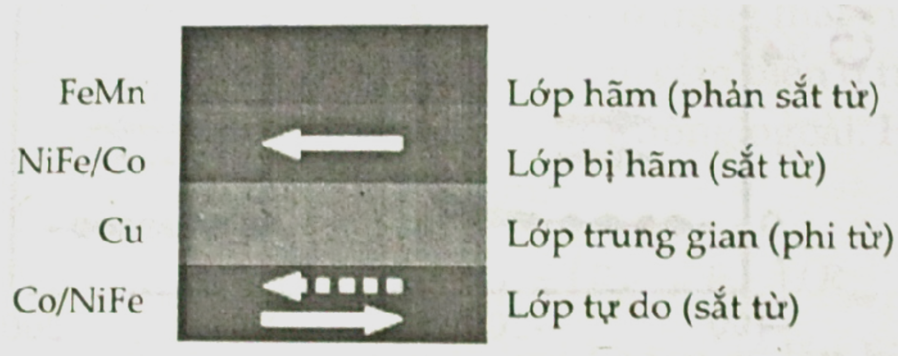
Increase coercivity of layers

Crude approximation for thin layers:

$$H_{F-AF} \approx H_F \left(1 + \frac{K_{AF} t_{AF}}{K_F t_F} \right)$$

Application

Concept of spin-valve in magneto-resistive elements



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

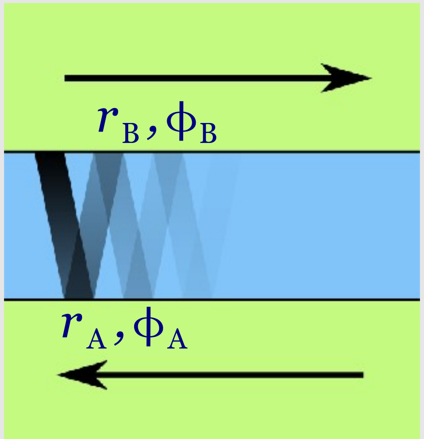
⇨ Sensors

⇨ Memory cells

⇨ Etc.

The physics

Spin-dependent quantum confinement in the spacer layer



Forth & back phase shift

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

Spin-independent

$$q = k^+ - k^-$$

Spin-dependent

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

Figures

Constructive and destructive interferences

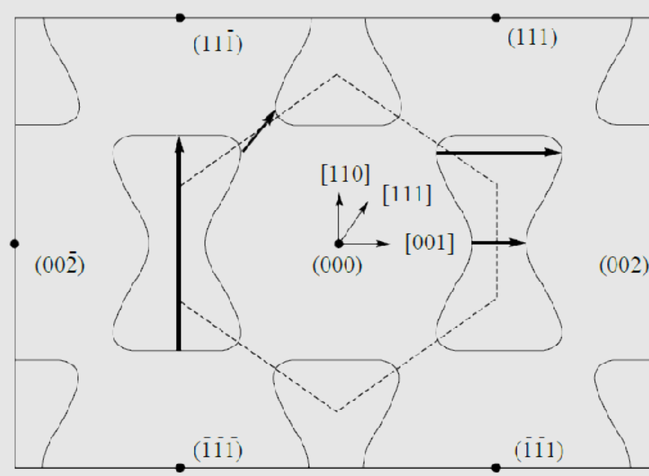
⇨ Maxima and minima of $n(\epsilon)$

Coupling strength:

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

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

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



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

Ti	V		Cr		Mn	Fe	Co	Ni	Cu	
No Coupling	9	3	7	7		Ferro-Magnet	Ferro-Magnet	Ferro-Magnet	8	3
	0.1	9	.24	18					0.3	10
2.89	2.62		2.50		2.24	2.48	2.50	2.49	2.56	
Zr	**Nb**		**Mo**		**Tc**	**Ru**		**Rh**		**Pd**	**Ag**
No Coupling	9.5	2.5	5.2	3		3	3	7.9	3	No Coupling	No Coupling
	.02	*	.12	11		5	11	1.6	9		
3.17	2.86		2.72		2.71	2.65		2.69		2.75	2.89
Hf	**Ta**		**W**		**Re**		**Os**	**Ir**		**Pt**	**Au**
No Coupling	7	2	5.5	3	4.2	3.5		4	3	No Coupling	No Coupling
	.01	*	.03	*	.41	10		1.85	9		
3.13	2.86		2.74		2.74		2.68	2.71		2.77	2.88

fcc bcc
hcp complex cubic

Element	
A_1 (Å)	ΔA_1 (Å)
J_1 (erg/cm²)	P (Å)
r_{ws} (Å)	

$$J(t)=\frac{A}{t^2}\sin\left(\frac{2\pi t}{P}+\Psi\right)$$

Illustration of coupling strength

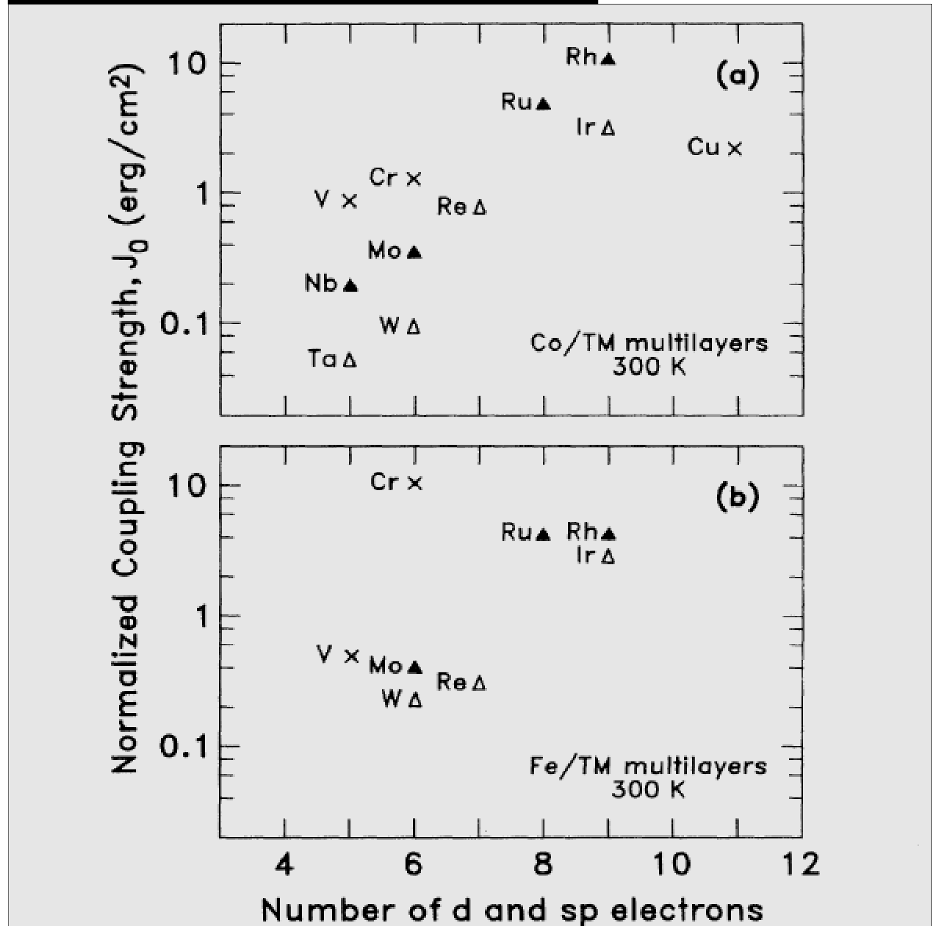
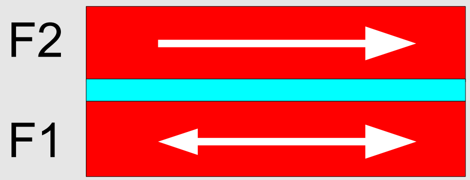


FIG. 3. Dependence of the normalized exchange coupling constant on the 3*d*, 4*d* and 5*d* transition metals in (a) Co/TM and (b) Fe/TM multilayers.

Note: $J(t)$ extrapolated for t=3Å

S. S. P. Parkin, Phys. Rev. Lett. 67, 3598 (1991)

Synthetic Ferrimagnets (SyF) – Crude description



Hypothesis:

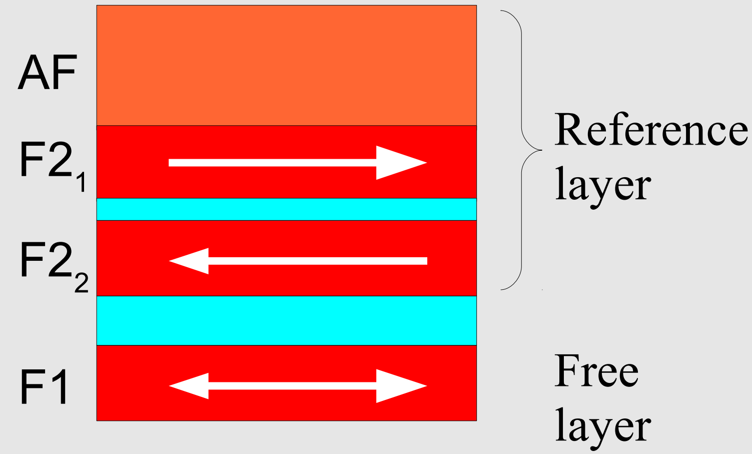
- Two layers rigidly coupled
- Reversal modes unchanged
- Neglect dipolar coupling

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

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

What use?

- Increase coercivity of pinned layers
- Decrease intra- and inter- dot dipolar coupling



Practical aspects

- Ru spacer layer (largest effect)
- Control thickness within a few Angströms !

Some reading (single-domain, domains and domain walls)

[1] Magnetic domains, A. Hubert, R. Schäfer, Springer (1999, reed. 2001)

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