Simple views on magnetization processes

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Sent to esm@magnetism.eu on 12 Sep.2010

Dear Institute,

I've always had a fascination with electromagnetism, and have pondered the theories of gravity. One thing I've come across in preliminary research is that the current theories largely fail to include human element in, as if we're just baseless objects trapped here without a role in the ultimate reason. (...)

Humans are magnets, too, as we possess iron. (…) If you take two magnets, they stick together when proper polars are placed near each other. What causes humans to act as the 2nd magnet in gravity is the iron found in humans. Earth, obviously the big magnet with the most iron, is able to control humans, the far smaller magnet with less iron. (…) Ultimately there is one controlling magnet for the entire universe somewhere in space holding it all together, like Galileo said.

Calculations of Earth's maximum gravitation pull could be made by testing individual boosters on humans and converting the thrust needed into some kind of formula which returns Earth's magnetic energical pull. (…) While it doesn't conclude why other things on Earth are in the same situation as us, it is also based on magnetism and humans have to have their own role in the matter.

Further research into it needs to be done as these are very preliminary original thoughts.

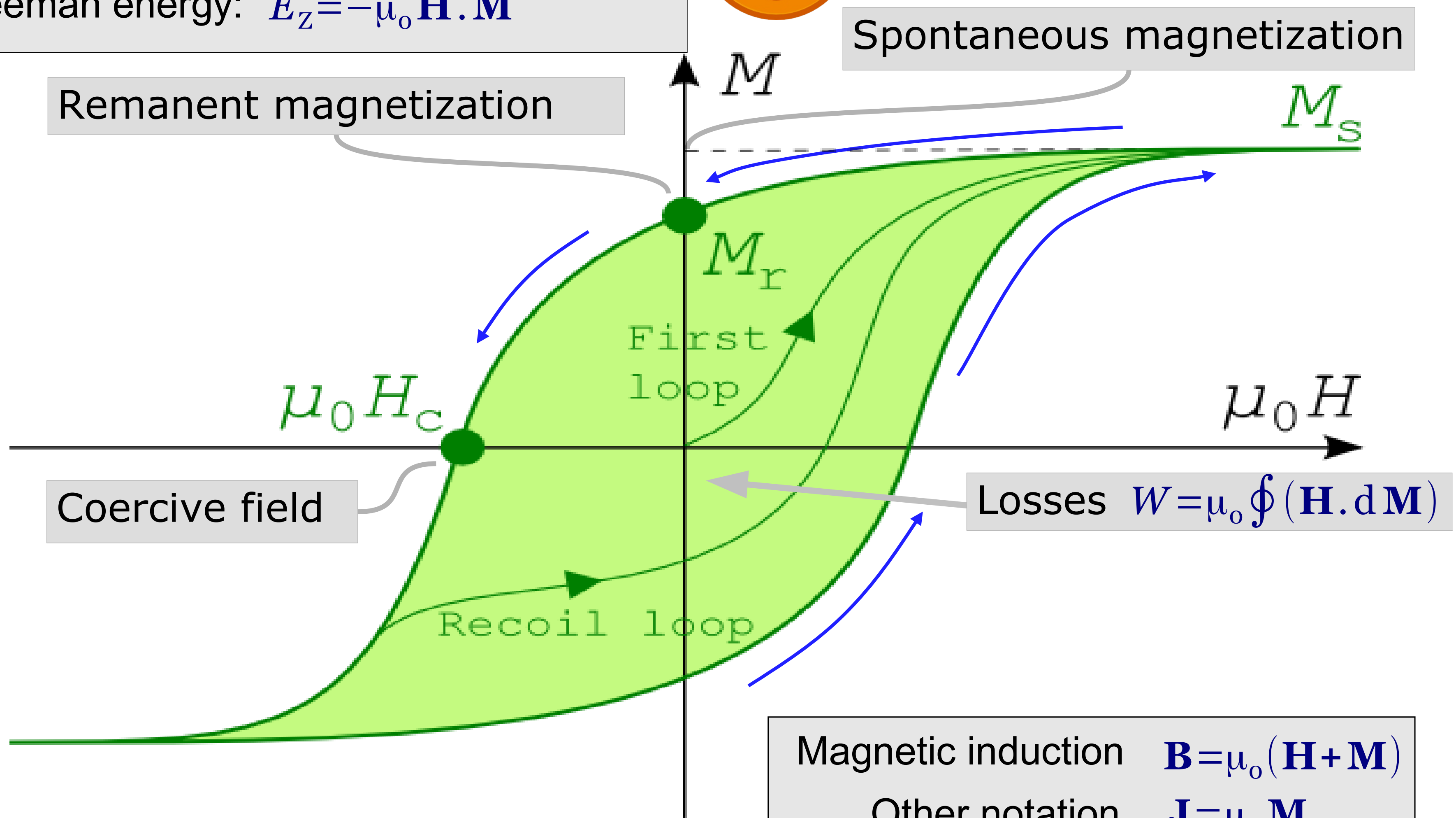
Regards,

XXX YYY.

Manipulation of magnetic materials:
↳ Application of a magnetic field

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

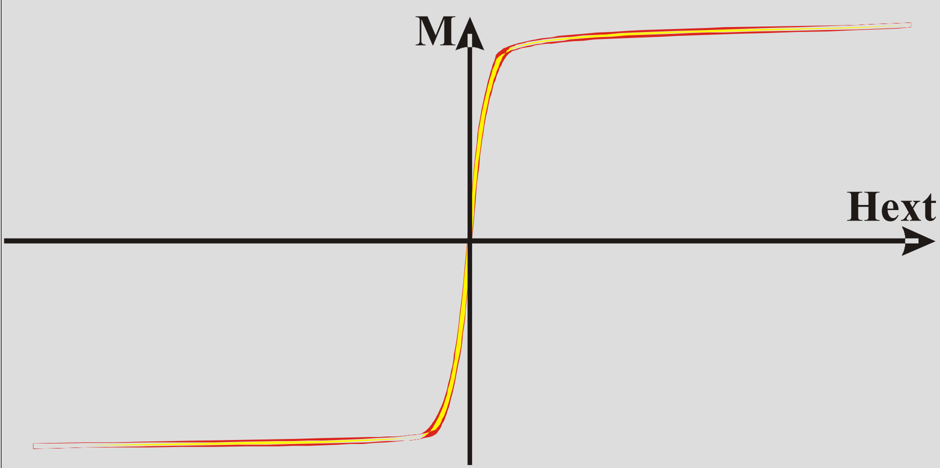
Spontaneous ≠ **S**aturation



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

Other notation $\mathbf{J} = \mu_0 \mathbf{M}$

Soft materials

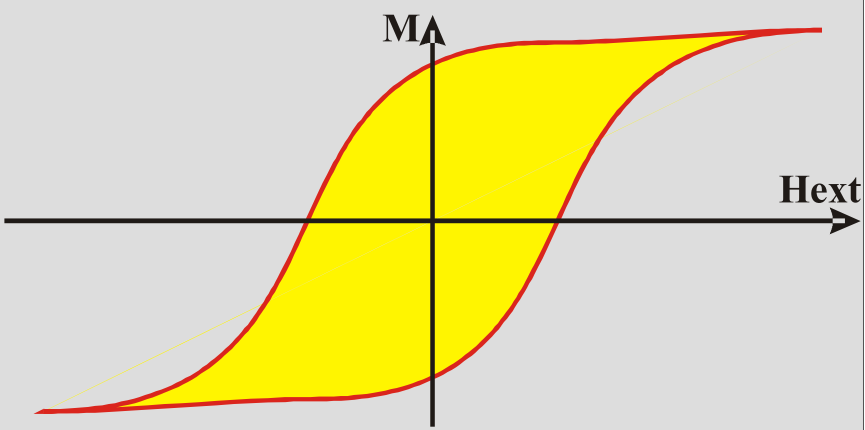


Transformers

Flux guides, sensors

Magnetic shielding

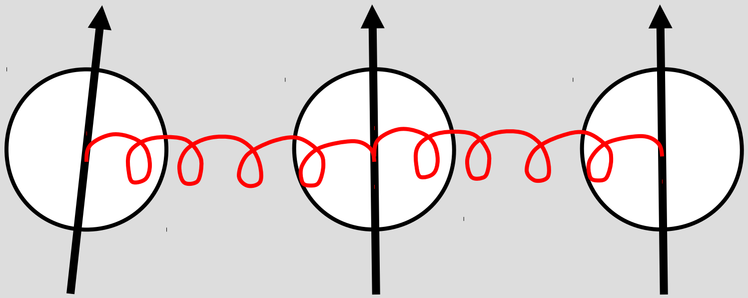
Hard materials



Permanent magnets, motors

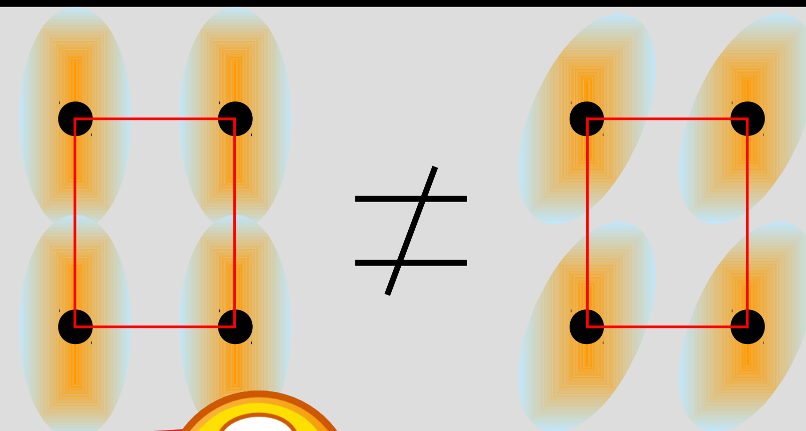
Magnetic recording

Echange energy

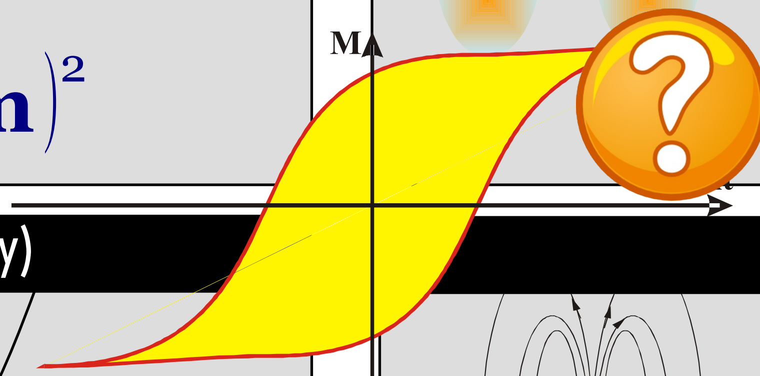


$$E_{ex}=A\left(\nabla.\mathbf{m}\right)^2$$

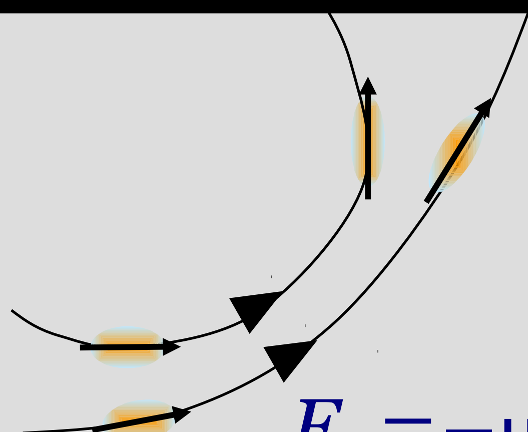
Magnetocrystalline anisotropy energy



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

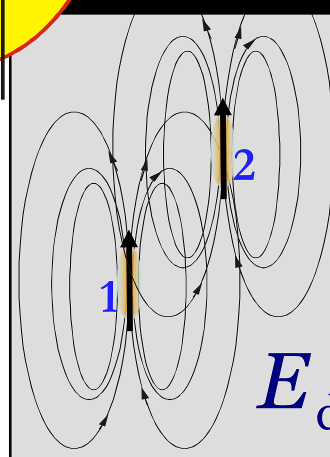


Zeeman energy (→ enthalpy)



$$E_d=-\mu_0\,\mathbf{M}.\mathbf{H}$$

Magnetostatic energy



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

Anisotropy exchange length

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

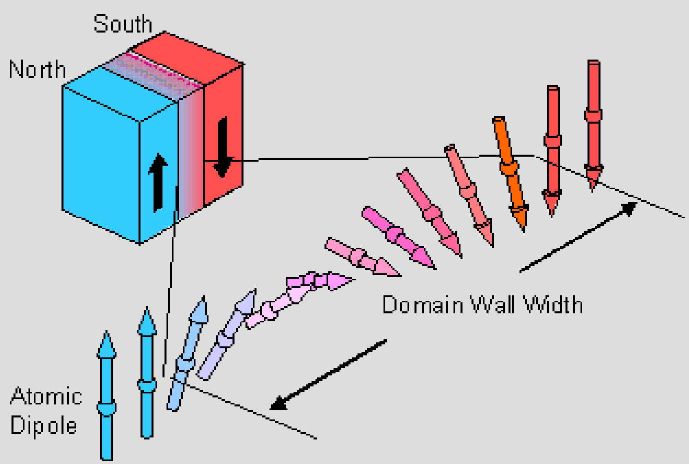
Exchange → J/m

Anisotropy → J/m^3

Anisotropy exchange length: $\Delta_u = \sqrt{A/K}$

$\Delta_u \approx 1$ nm → $\Delta_u \geq 100$ nm

Hard → Soft



Often called *Bloch parameter* or *domain-wall width*

Dipolar exchange length

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

Exchange → J/m

Dipolar energy → J/m^3

$$K_d = \frac{1}{2}\mu_0 M_s^2$$

Dipolar exchange length:

$$\Delta_d = \sqrt{A/K_d} = \sqrt{2A/\mu_0 M_s^2}$$

$\Delta_d \approx 3-10$ nm

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

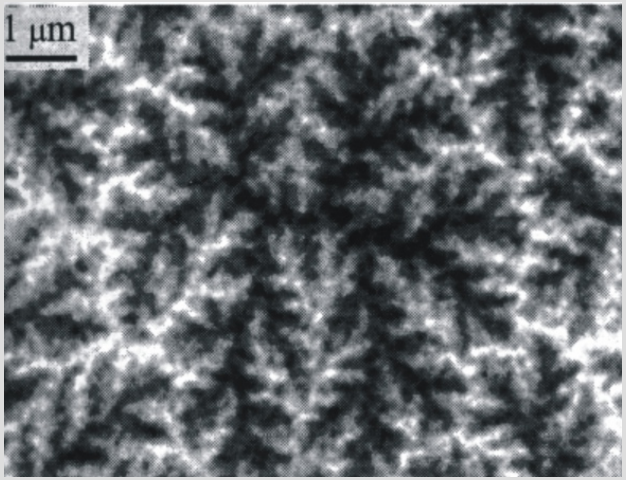
Often called *Exchange length*

Notice:

Other length scales: with field etc.

Bulk material

Numerous and complex magnetic domains

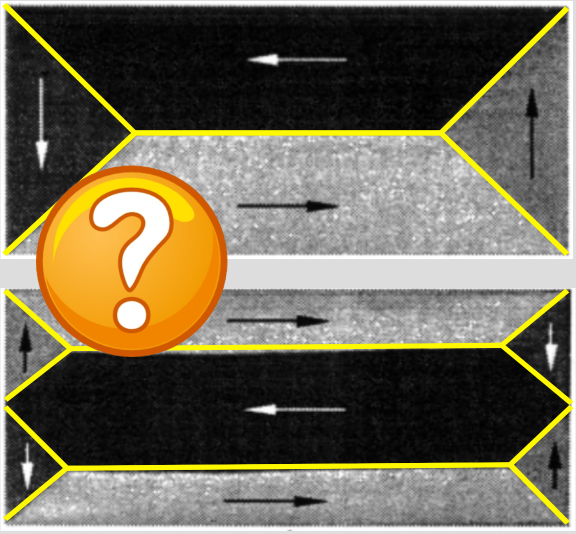


Co(1000) crystal – SEMPA

A. Hubert, *Magnetic domains*

Mesoscopic scale

Small number of domains, simple shape

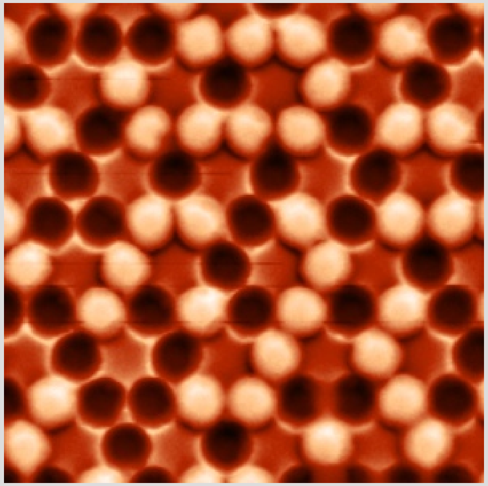


Microfabricated dots
Kerr magnetic imaging

A. Hubert, *Magnetic domains*

Nanometric scale

Magnetic single-domain



Nanofabricated dots
MFM

Sample courtesy:

N. Rougemaille, I. Chioar

Nanomagnetism ~ mesoscopic magnetism

Framework

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

(strong!)

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

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

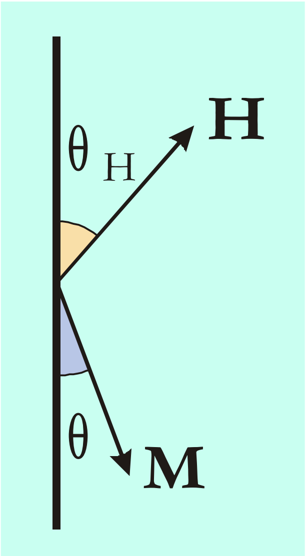
Dimensionless units:

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

$$h=H/H_a$$

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

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

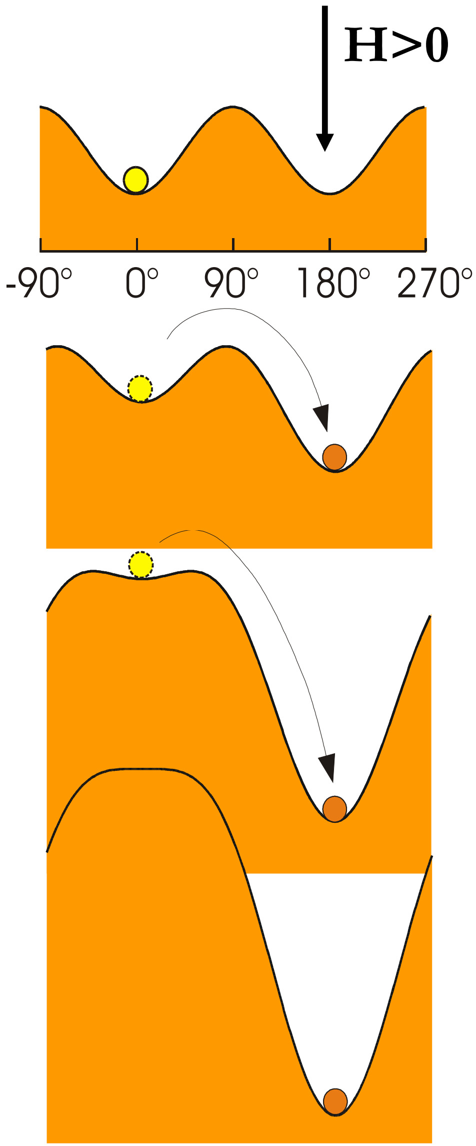


L. Néel, Compte rendu Acad. Sciences 224, 1550 (1947)
E. C. Stoner and E. P. Wohlfarth, *Phil. Trans. Royal. Soc. London* A240, 599 (1948)
***IEEE Trans. Magn.* 27(4), 3469 (1991) : reprint**

Names used

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

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



Equilibrium states

$$\partial_\theta e=2\sin\theta(\cos\theta-h) \qquad \partial_\theta e=0 \Rightarrow \begin{cases}\cos\theta_m=h\\ \theta\equiv 0[\pi]\end{cases}$$

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

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

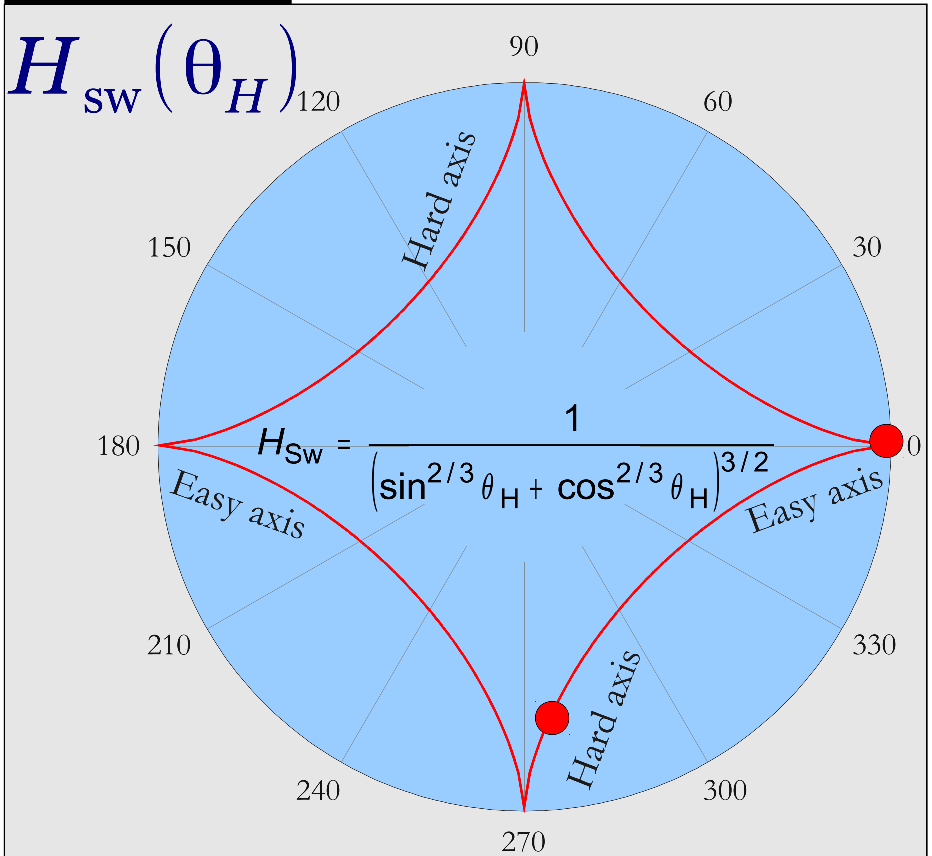
Switching

$$h=1$$

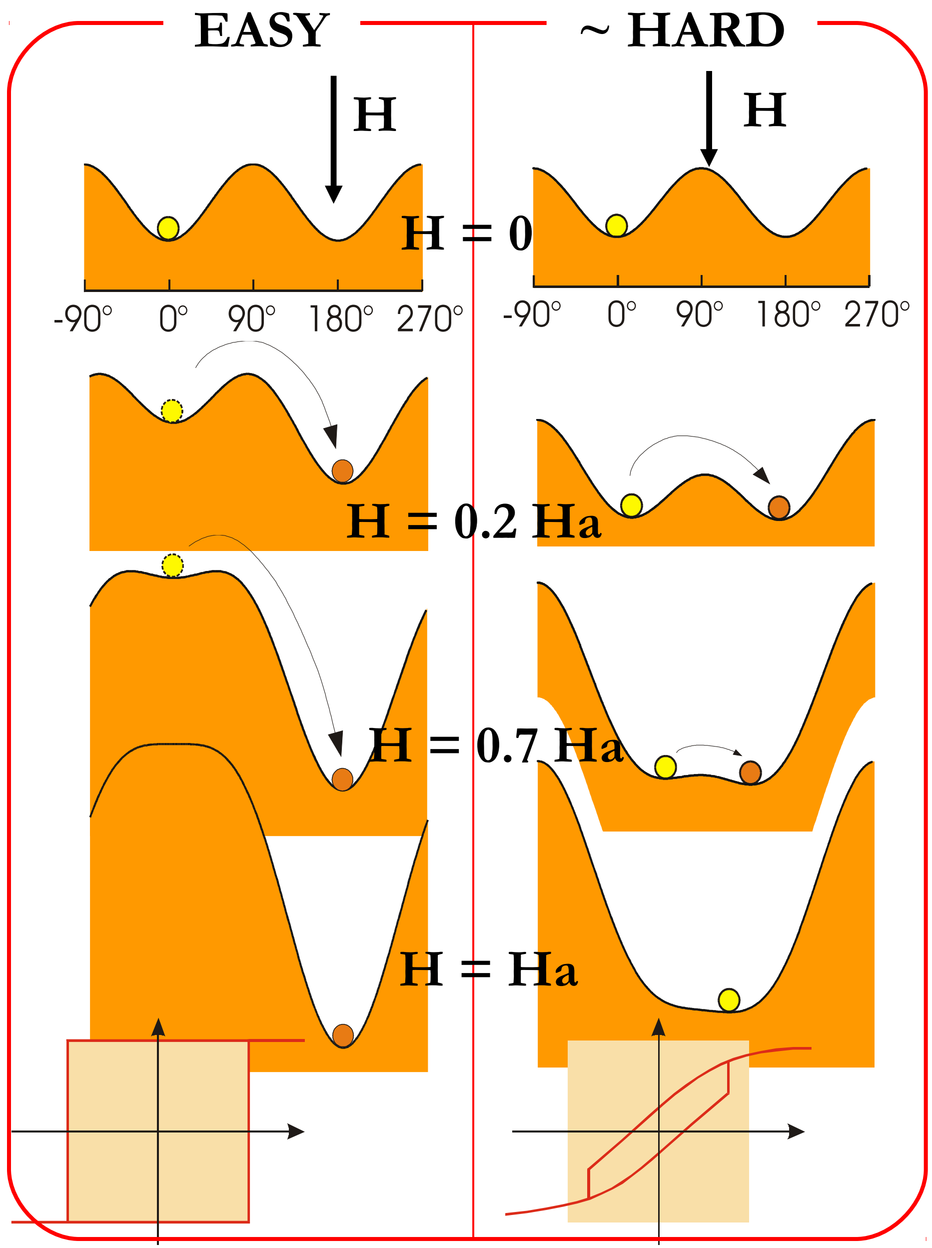
$$H=H_a=2K/\mu_0 M_s$$

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

'Astroid' curve



➢ $H_{Sw}(\theta)$ is a <u>one</u> signature of reversal modes



J. C. Slonczewski, Research Memo RM 003.111.224, IBM Research Center (1956)

Switching field = Reversal field

A value of field at which an irreversible (abrupt) jump of magnetization angle occurs.

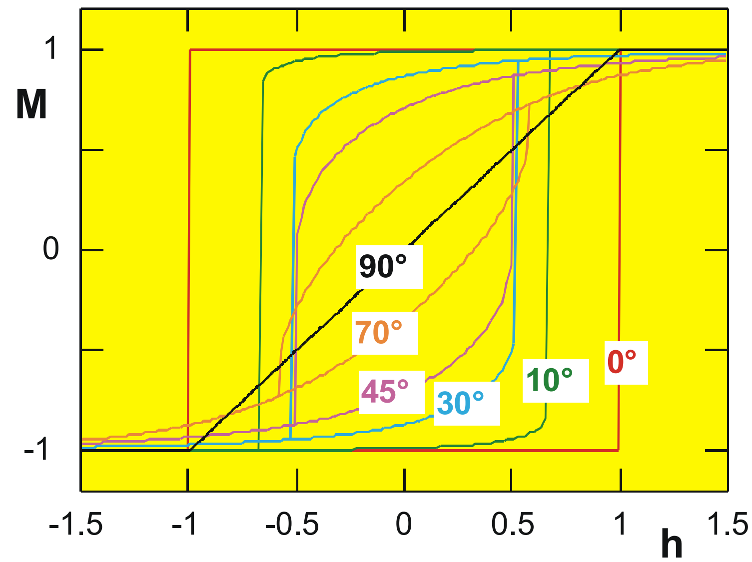
Can be measured only in single particles.

Coercive field

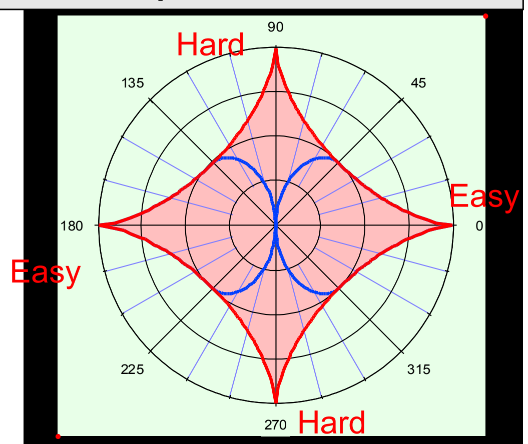
The value of field at which **M.H=0** $(\theta=\theta_H\pm\pi/2)$

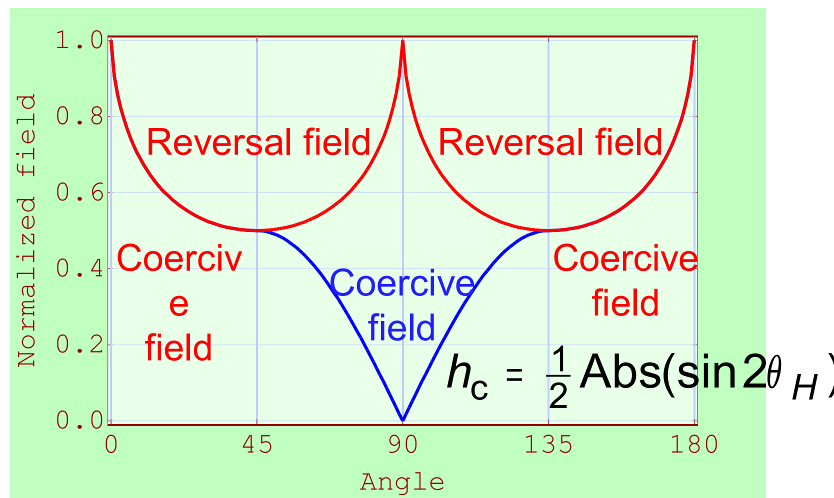
A quantity that can be measured in real materials (large number of 'particles').

May be or may not be a measure of the mean switching field at the microscopic level

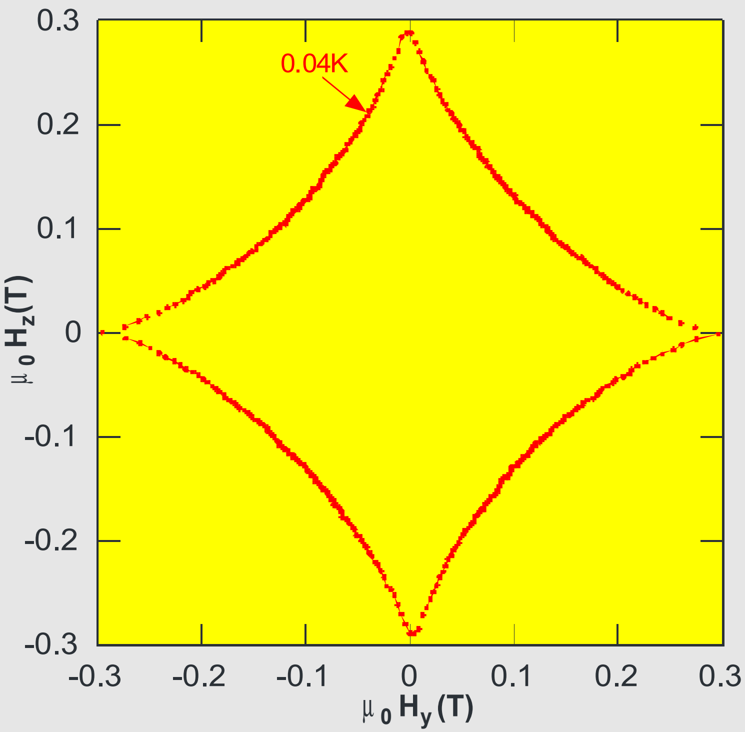


$$h_{Sw} = \frac{1}{\left(\sin^{2/3}\theta_H + \cos^{2/3}\theta_H\right)^{3/2}}$$

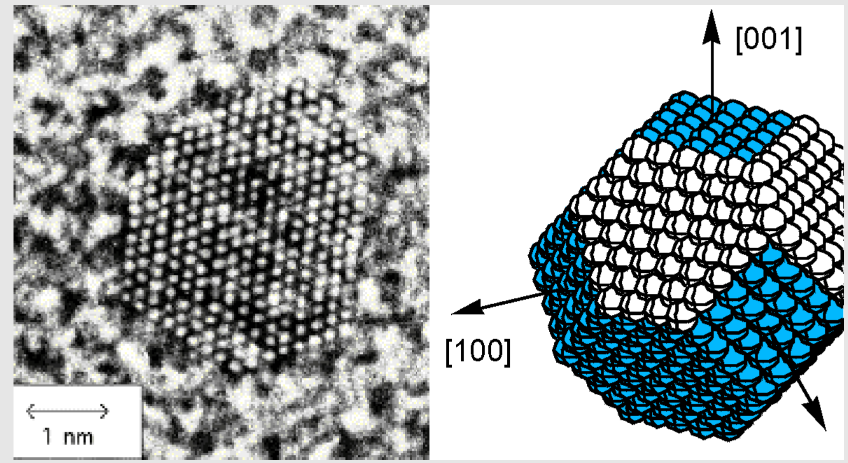




Experimental evidence

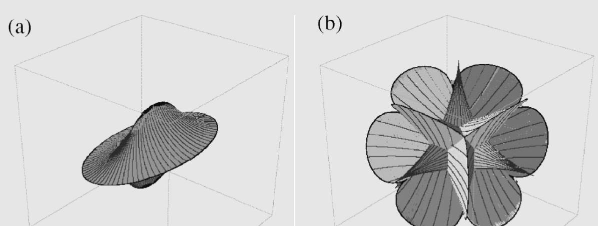


First evidence: W. Wernsdorfer et al., Phys. Rev. Lett. 78, 1791 (1997)

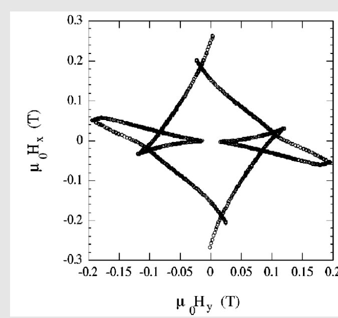


M. Jamet et al., Phys. Rev. Lett., 86, 4676 (2001)

Extensions: 3D, arbitrary anisotropy etc.



A. Thiaville et al., PRB61, 12221 (2000)

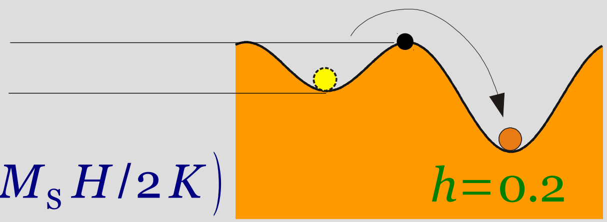


M. Jamet et al., PRB69, 024401 (2004)

Barrier height

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

Δe



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

Thermal activation

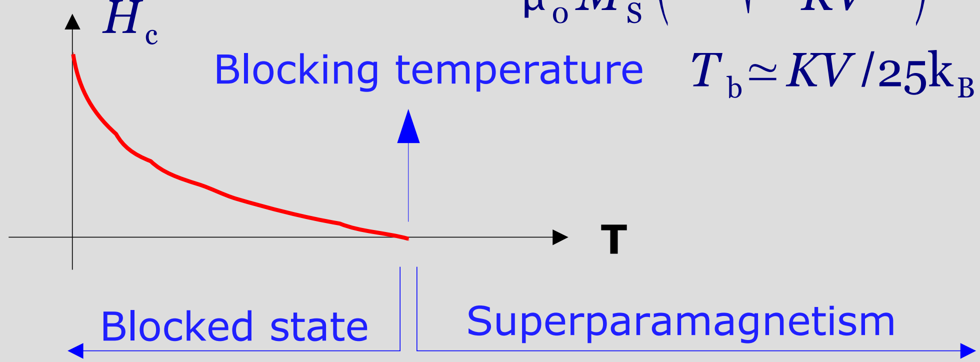
Brown, Phys.Rev.130, 1677 (1963)

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

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

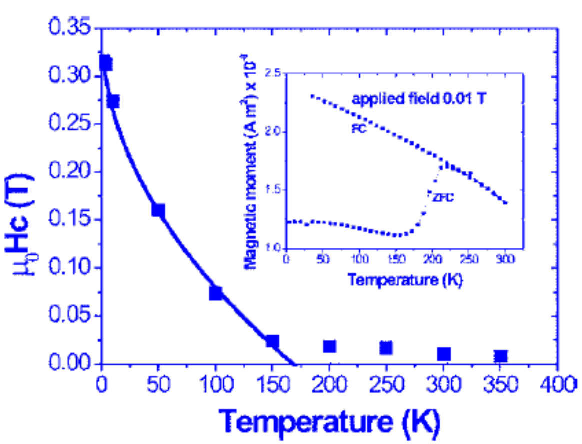
Lab measurement: $\tau \approx 1\ \mathrm{s} \Longrightarrow \Delta \mathcal{E} \approx 25 k_B T$

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



$$T_b \simeq KV / 25 k_B$$

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



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

Formalism

C. P. Bean & J. D. Livingston, J. Appl. Phys. 30, S120 (1959)

Energy

$$E = KV.f(\theta,\varphi) - \mu_0 \mu H$$

Partition function

$$Z = \sum \exp(-\beta E)$$

Average moment

$$<\mu> = \frac{1}{\beta\mu_0 Z}\frac{\partial Z}{\partial H}$$

Isotropic case

$$Z = \int_{-M}^{M} \exp(-\beta E) \mathrm{d}\mu$$

Note: equivalent to integration over solid angle

$$<\mu> = M[\mathrm{cotanh}(x) - 1/x]$$

Langevin function

Infinite anisotropy

$$Z = \exp(\beta\mu_0 MH) + \exp(-\beta\mu_0 MH)$$

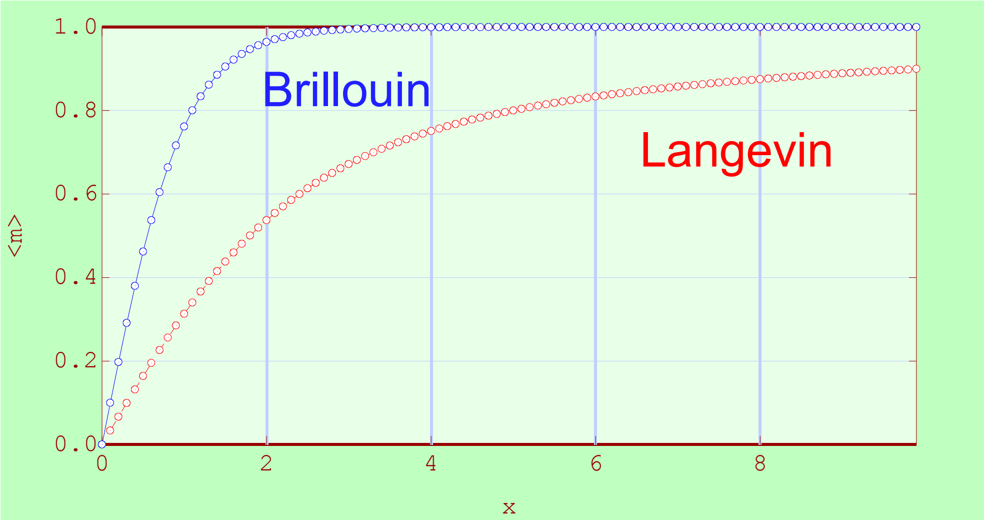
$$<\mu> = M.\tanh(x)$$

Brillouin ½ function

Note:

Use the moment M of the particule, not spin ½ .

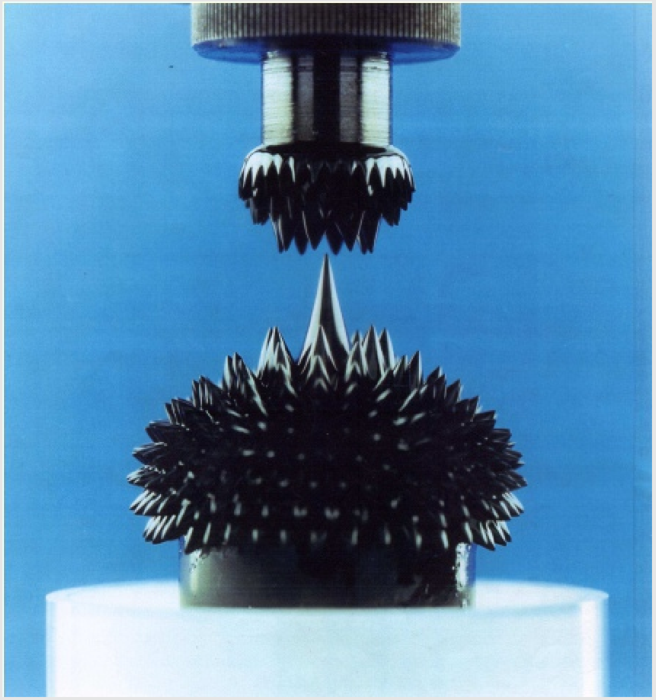
$$x = \beta\mu_0 MH$$



Ferrofluids

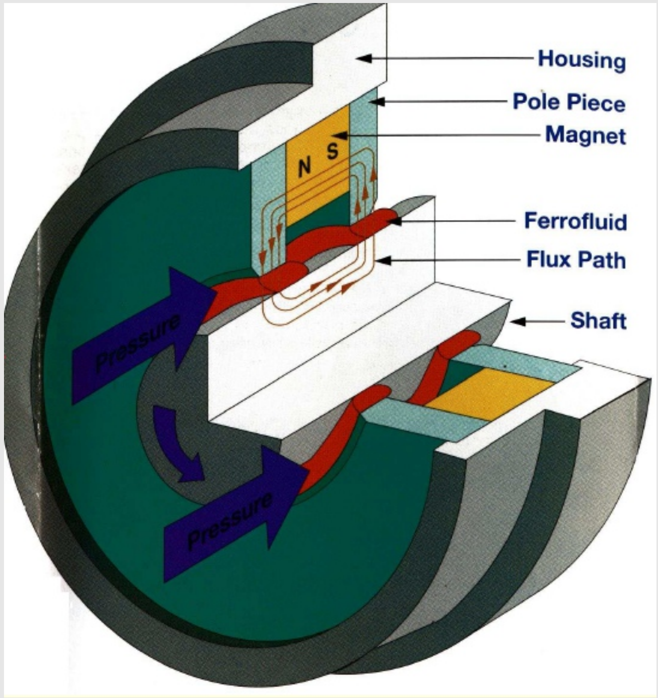
⇨ Principle

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)

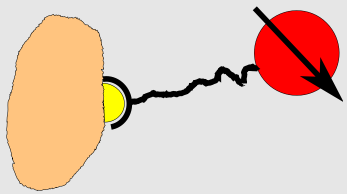
http://esm.neel.cnrs.fr/2007-cluj/slides/vekas-slides.pdf

Health and biology

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

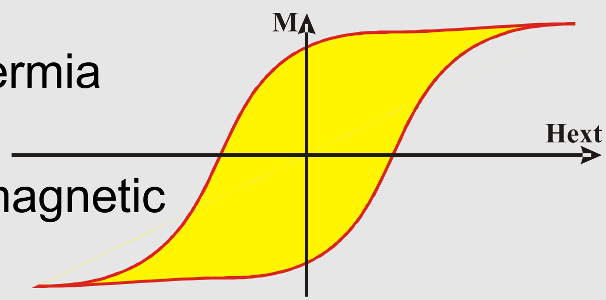
⇨ Cell sorting

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



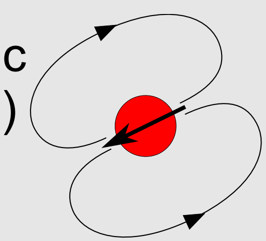
⇨ Hyperthermia

Use ac magnetic field



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

⇨ Contrast agent in Magnetic Resonance Imaging (MRI)



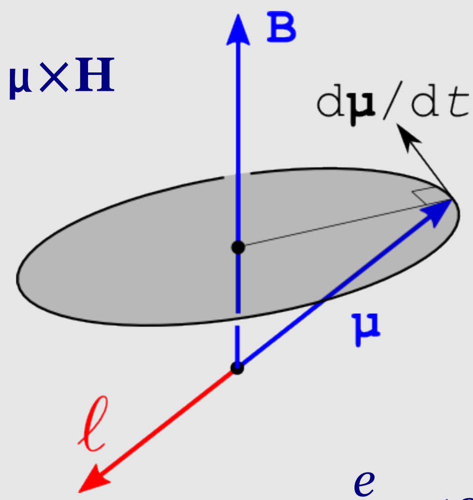
RAM (radar absorbing materials)

⇨ Principle

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

$$\frac{\mathrm{d}\boldsymbol{\ell}}{\mathrm{d}t}=\boldsymbol{\Gamma}=\mu_o\boldsymbol{\mu}\times\mathbf{H}=\mu_o\gamma\boldsymbol{\ell}\times\mathbf{H}$$

$$\frac{\mathrm{d}\boldsymbol{\mu}}{\mathrm{d}t}=\mu_o\gamma\boldsymbol{\mu}\times\mathbf{H}$$

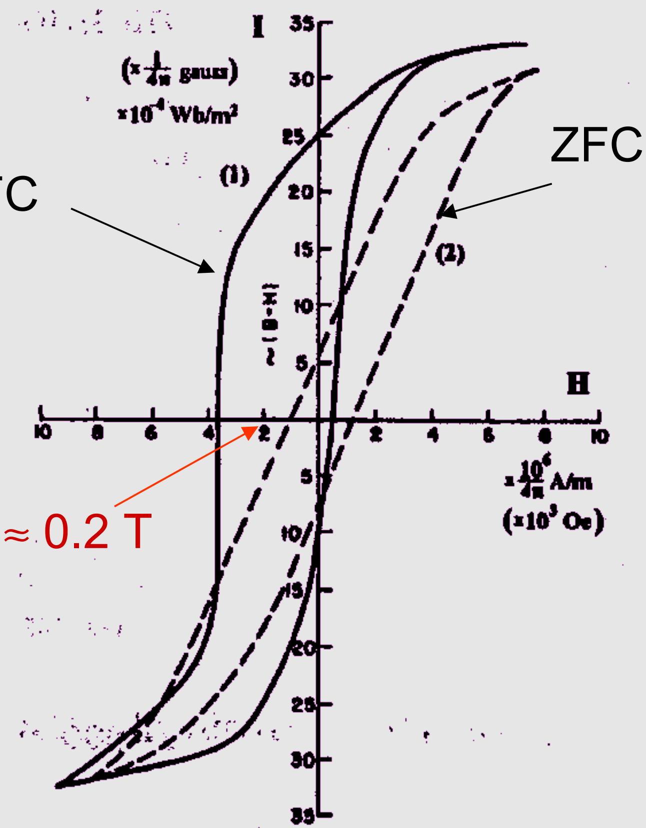


$$\gamma=-g_J\frac{e}{2m_e}<0$$

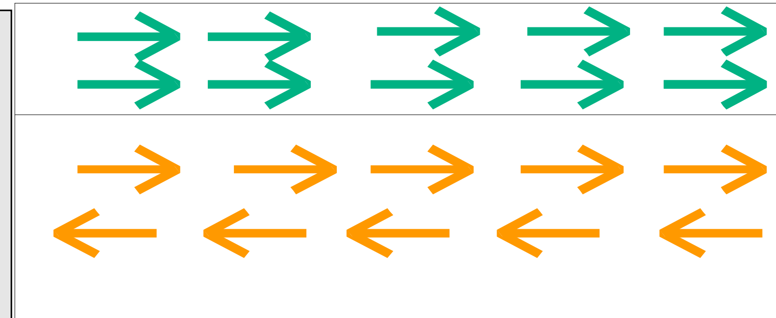
$$\gamma_s/2\pi \approx 28\ \mathrm{GHz/T}$$

Seminal studies

Oxidized Co nanoparticles



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



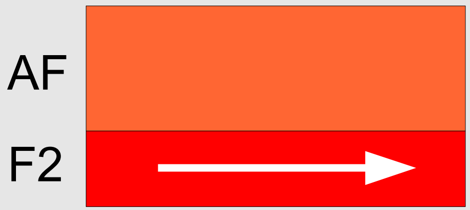
Field-cooled hysteresis loops:

- **Increased coercivity**
- **Loop shifted along field axis**

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

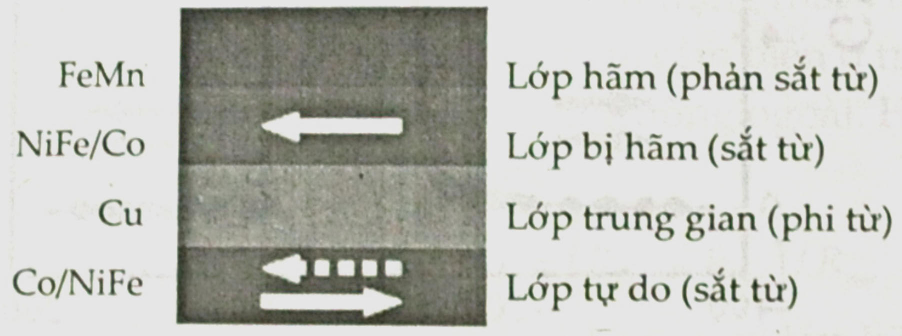


Crude approximation for thin layers:

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

Application

Concept of spin-valve in magneto-resistive elements

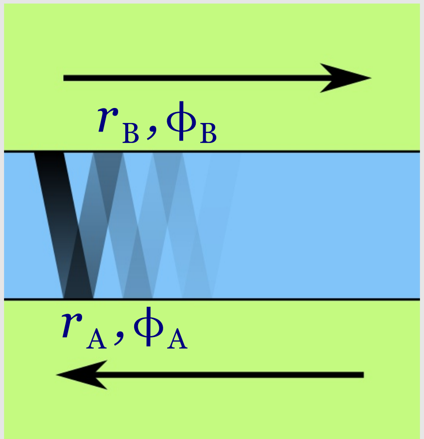


B. Diény et al., Phys. Rev. B 43, 1297 (1991)

- ⇨ 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

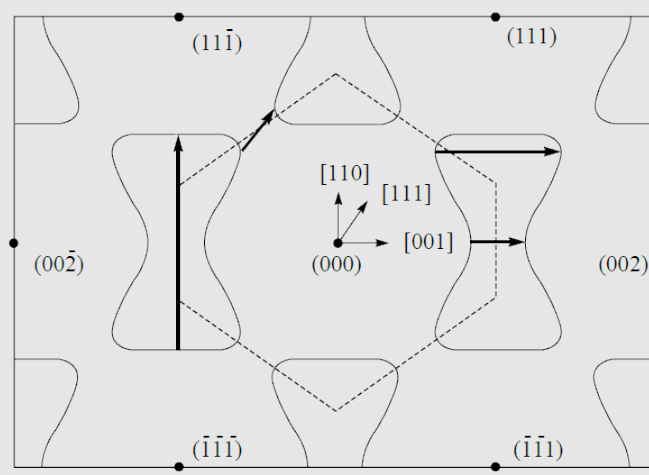
⇨ Maxima and minima of $n(\epsilon)$

Coupling strength:

$E_S = J(t)\cos\theta$ in J/m^2

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

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



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

Element	Structure	A_1 (Å)	ΔA_1 (Å)	J_1 (erg/cm²)	P (Å)	r_{ws} (Å)
Ti	hcp	No Coupling				2.89
V	bcc	9	3	0.1	9	2.62
Cr	bcc	7	7	.24	18	2.50
Mn	complex cubic					2.24
Fe	bcc	Ferro-Magnet				2.48
Co	hcp	Ferro-Magnet				2.50
Ni	fcc	Ferro-Magnet				2.49
Cu	fcc	8	3	0.3	10	2.56
Zr	hcp	No Coupling				3.17
Nb	bcc	9.5	2.5	.02	*	2.86
Mo	bcc	5.2	3	.12	11	2.72
Tc	hcp					2.71
Ru	hcp	3	3	5	11	2.65
Rh	fcc	7.9	3	1.6	9	2.69
Pd	fcc	No Coupling				2.75
Ag	fcc	No Coupling				2.89
Hf	hcp	No Coupling				3.13
Ta	bcc	7	2	.01	*	2.86
W	bcc	5.5	3	.03	*	2.74
Re	hcp	4.2	3.5	.41	10	2.74
Os	hcp					2.68
Ir	fcc	4	3	1.85	9	2.71
Pt	fcc	No Coupling				2.77
Au	fcc	No Coupling				2.88

fcc bcc hcp complex cubic

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

Illustration of coupling strength

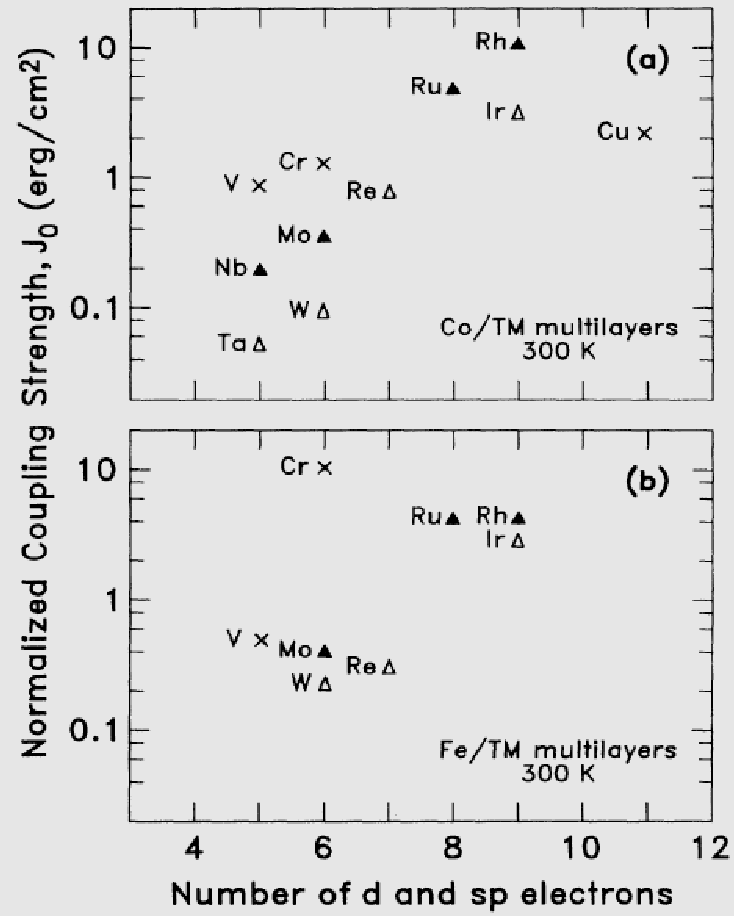
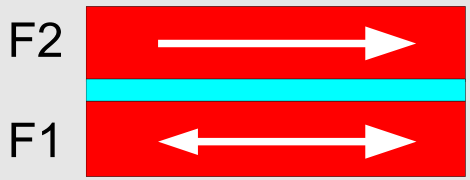


FIG. 3. Dependence of the normalized exchange coupling constant on the 3*d*, 4*d* and 5*d* transition metals in (a) Co/TM and (b) Fe/TM multilayers.

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

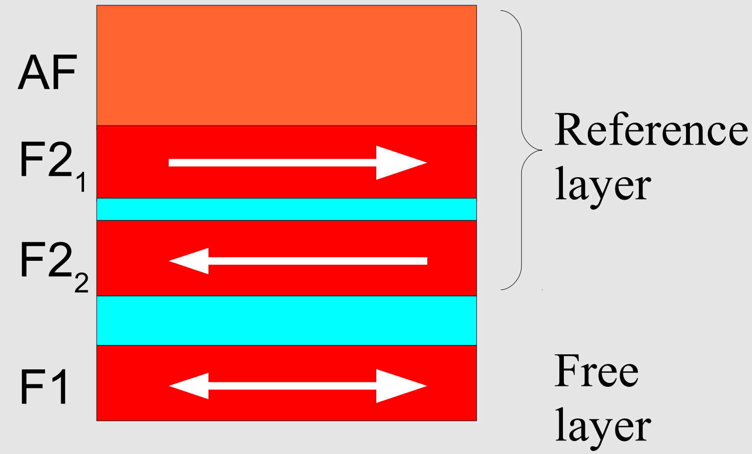
$$M=\frac{\left|e_1 M_1 - e_2 M_2\right|}{e_1+e_2}$$

$$K=\frac{e_1 K_1 + e_2 K_2}{e_1+e_2}$$

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

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 !

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

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

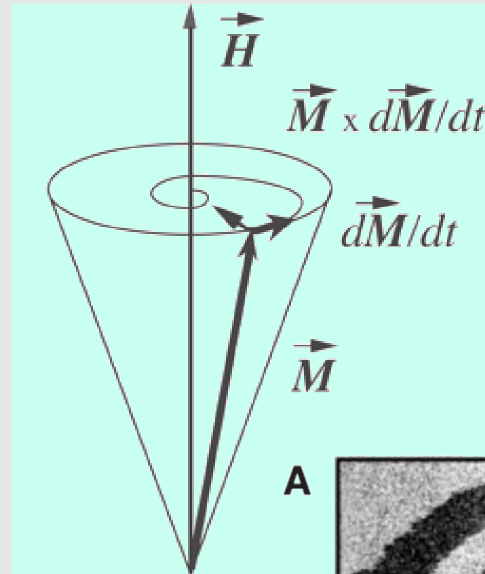
$$\gamma / 2\pi = 28\,\mathrm{GHz/T}$$

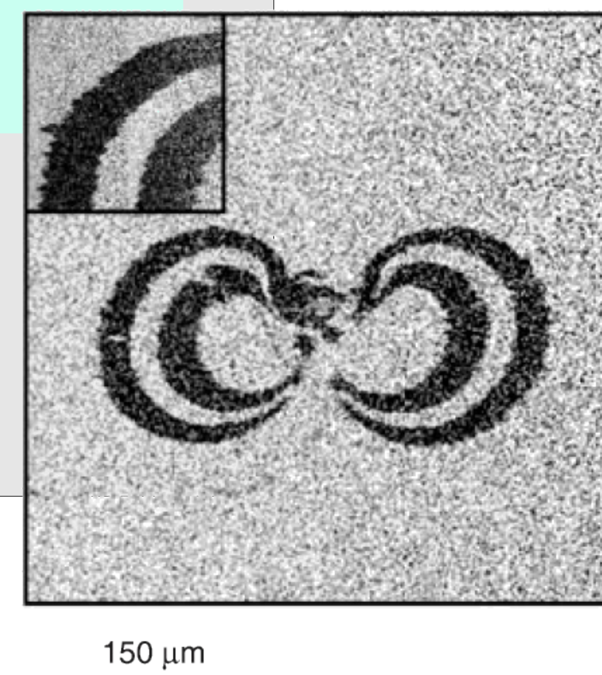
H_{eff} Effective field (including applied)

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

α Damping coefficient ($10^{-3} \rightarrow 10^{-1}$)

Démonstration: 1999





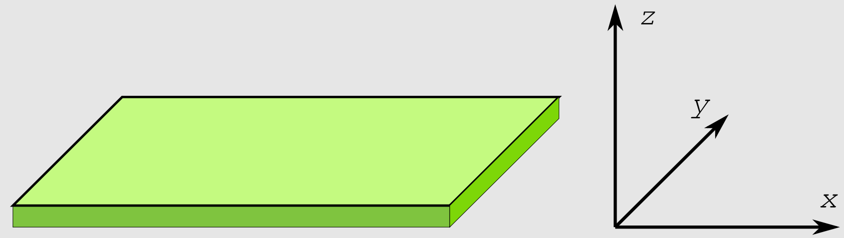
C. Back et al., Science 285, 864 (1999)

Precessional trajectory 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 along *x*

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

Starting condition: $m_x=+1$



(1) ➡ $e=E/K_d=N_z m_z^2 - h_K m_x^2 - 2hm_y$ with : $e(t=0)=-h_K$

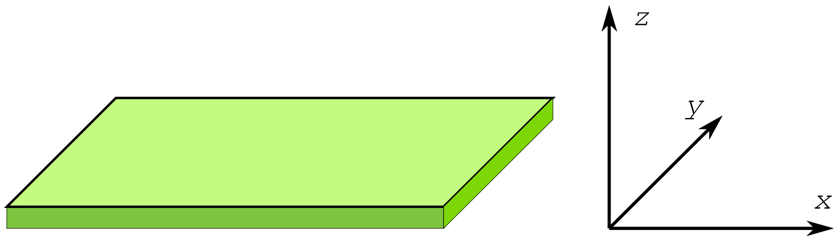
Using (2) ➡ $m_x^2 = 1 - \frac{2h}{N_z+h_K} m_y - \frac{N_z}{N_z+h_K} m_y^2$

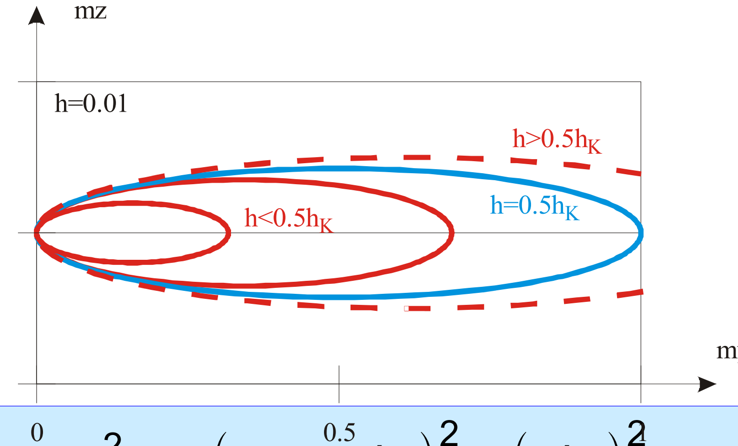
Can be rewritten: $m_x^2 + \frac{(m_y + h/N_z)^2}{1+h_K/N_z} = 1 + \frac{h^2}{N_z(N_z+h_K)}$

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

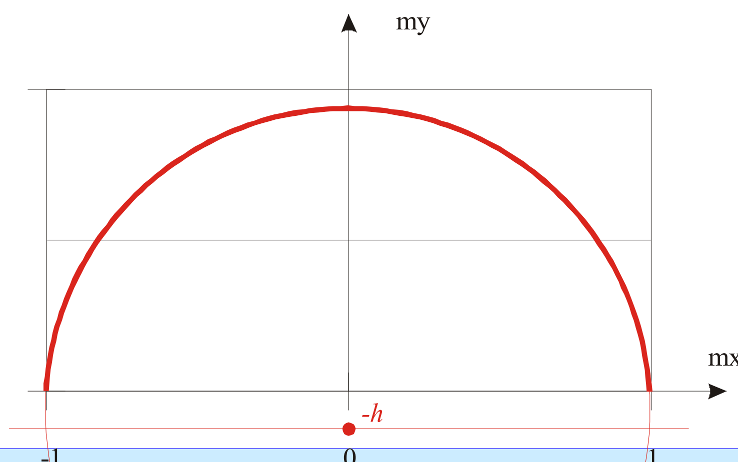
Can be rewritten: $\frac{m_z^2}{\left(\frac{h_K}{N_z+h_K}\right)} + \left(m_y - \frac{h}{h_K}\right)^2 = \left(\frac{h}{h_K}\right)^2$

Magnetization trajectories

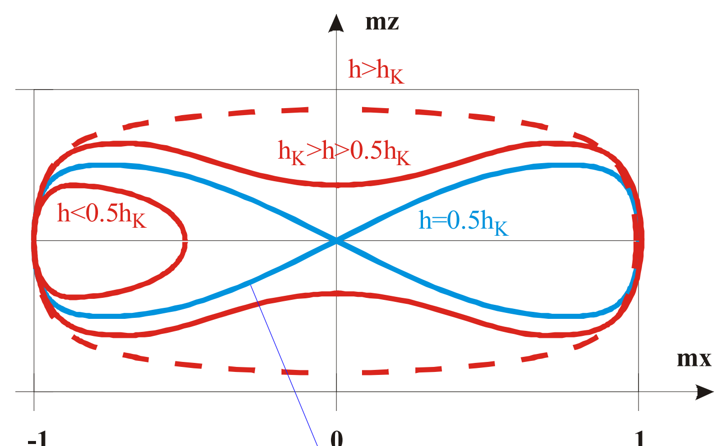




$$\frac{m_z^2}{\left(\frac{h_K}{N_z+h_K}\right)} + \left(m_y - \frac{h}{h_K}\right)^2 = \left(\frac{h}{h_K}\right)^2$$



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

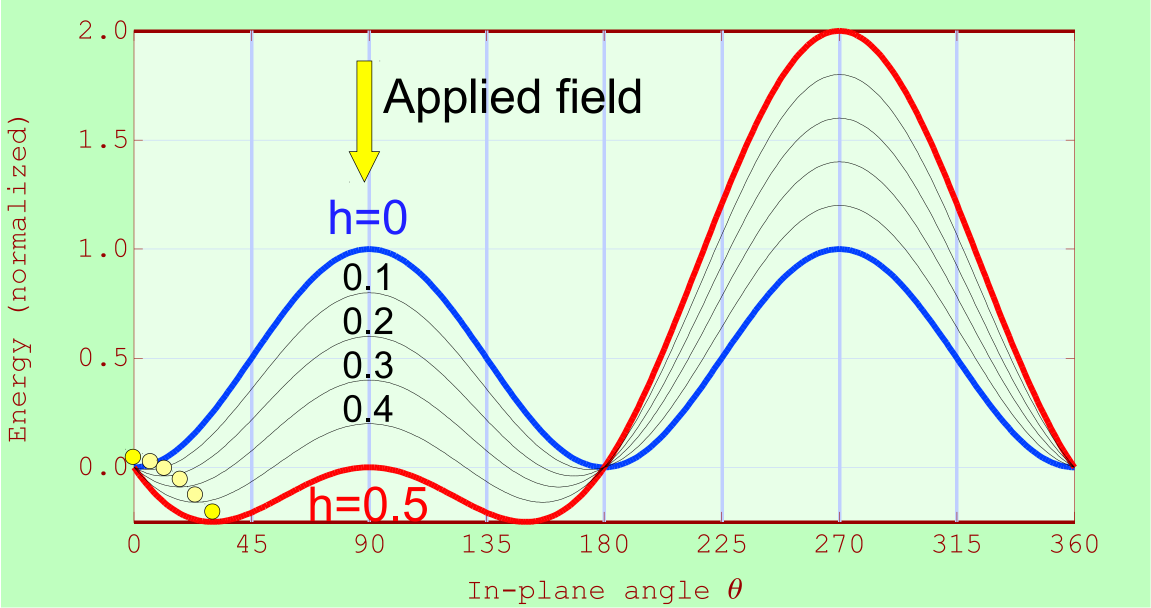


$$\omega \approx 0.847\gamma_0\sqrt{M_s(H-H_K)/2}$$

Stoner-Wohlfarth versus precessional switching

Stoner-Wohlfarth model: describes processes where the system follows quasistatically energy minima, e.g. with slow field variation

Precessional switching: occurs at short time scales, e.g. when the field is varied rapidly



Relevant time scales

Precession period

$2\pi / \gamma = 35$ ps.T

⇒ 25 - 500 ps

Precession damping

$1/(2\pi\alpha)$ per period

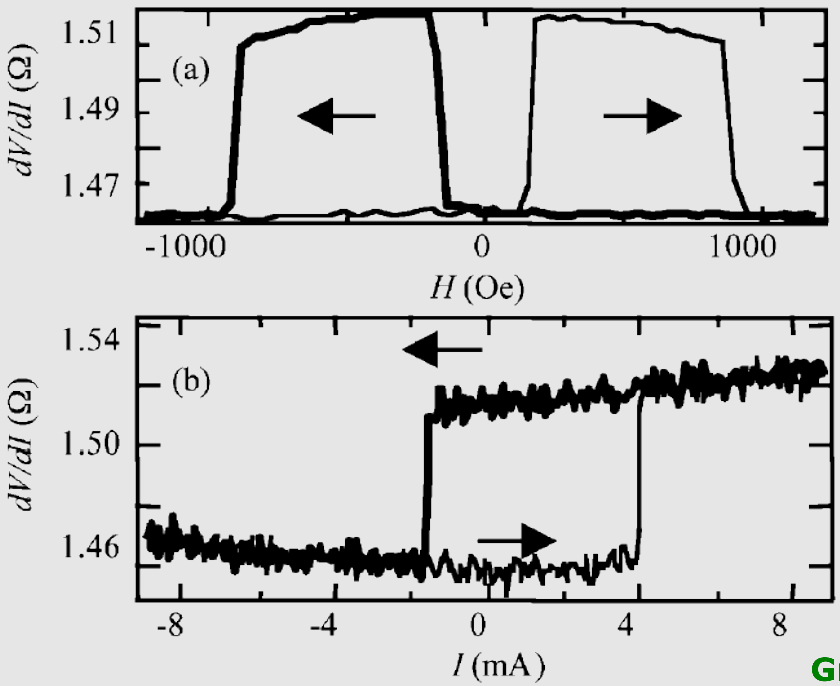
($\alpha = 0.01 - 0.5$)

Notice Magnetization reversal allowed for $h>0.5h_K$ (more efficient than classical reversal

Facts

Can be viewed as the reverse of GMR effect

J. C. Slonczewski (1996)
L. Berger (1996)



Conventionnal hysteresis loop

Current-induced magnetization reversal

Group Myers et Ralph, Cornell University (2000)

Related physics

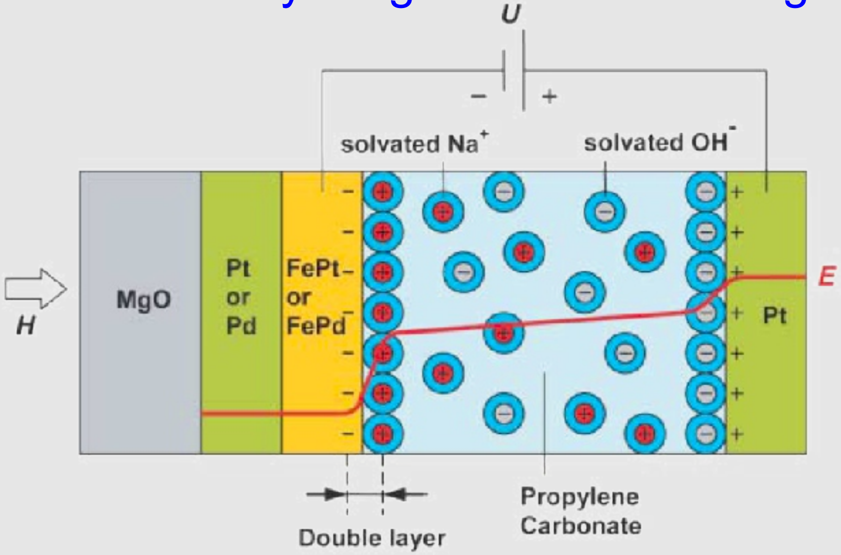
- Pure spin current
- Spin injection (eg in semiconductor)
- Non-local reversal

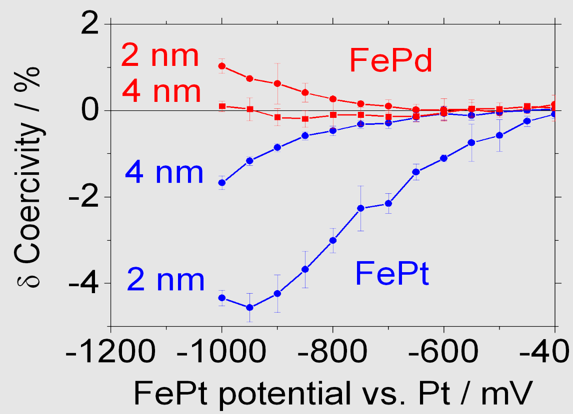
Motivations for technology

- Simplified architectures (MRAMs etc.)
- Fully electronic read/write
- Domain wall motion (memory, logic)
- Agile GHz oscillators

Facts

Seminal study : slight variation of magnetic anisotropy





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

Recent

⇨ Magnetization switching with pulse of E-field **Y. Shiota et al., Nature Mater.11, 39 (2012)**

⇨ E-field-induced ferromagnetic resonance **T. Nozaki et al., Nature Phys. 8, 491 (2012)**

Motivations for technology

- Drastically reduce Joule heating
- Gateable properties

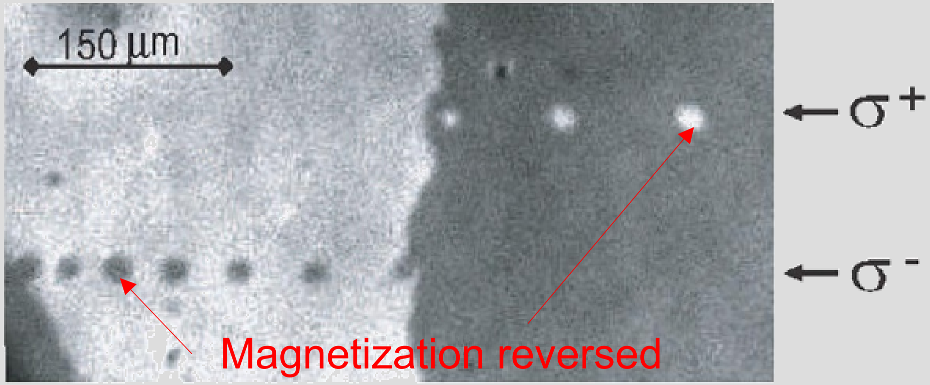
Principle

Combined heating
+ inverse Faraday effect

Magneto-optical
material. Tc=500K
$Gd_{22}Fe_{74.6}Co_{3.4}$

Ti:S laser:
λ=800nm; $\Delta\tau$=40fs.

Local reversal with controlled power



C. D. Stanciu et al., Phys. Rev. Lett. 99, 047601 (2007)

Physics

- Ultra-fast magnetization process (<1ps)
- Exchange-related precession for RE – 3d alloys

Technology

- Ultrafast writing
- Heat-assisted writing

Still other means

- Strain (or sound waves)
- Heat
- …

Anisotropy exchange length

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

Exchange → J/m

Anisotropy → J/m^3

Anisotropy exchange length:

$$\Delta_u = \sqrt{A/K}$$

$\Delta_u \approx 1$ nm → $\Delta_u \geq 100$ nm

Hard Soft

Relevant for Bloch domain walls

Often called *Bloch parameter* or *domain-wall width*

Dipolar exchange length

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

Exchange → J/m

Dipolar energy → J/m^3

$$K_d = \frac{1}{2}\mu_0 M_s^2$$

Dipolar exchange length:

$$\Delta_d = \sqrt{A/K_d} = \sqrt{2A/\mu_0 M_s^2}$$

$$\Delta_d \approx 3-10 \text{ nm}$$

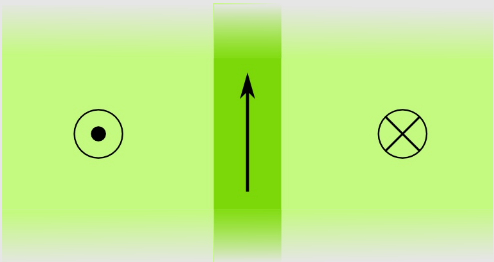
Single-domain critical size relevant for nanoparticules made of soft magnetic material

Often called *Exchange length*

Notice:

Other length scales: with field etc.

Bloch domain wall in the bulk (2D)

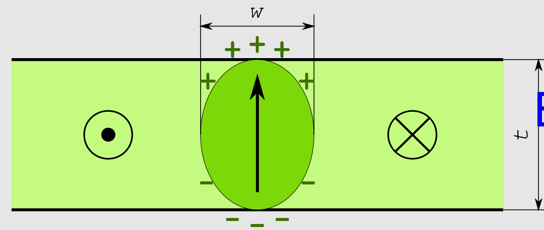


- ⇨ No magnetostatic energy
- ⇨ Width $\Delta_u = \sqrt{A/K}$
- ⇨ Areal energy $\gamma_W = 4\sqrt{AK}$

Other angles & anisotropy

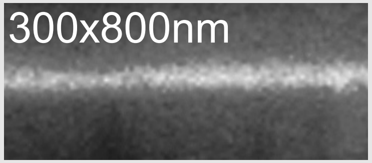
F. Bloch, Z. Phys. 74, 295 (1932)

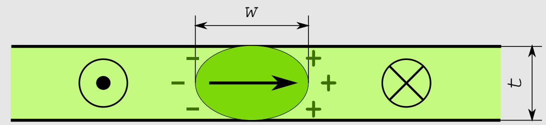
Domain walls in thin films (2D → 1D)



Bloch wall

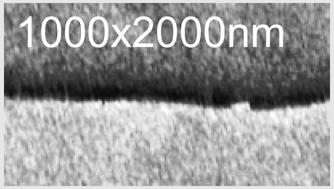
$t \gtrsim w$





Néel wall

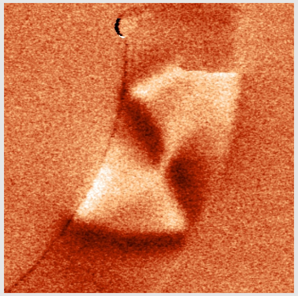
$t \lesssim w$



- ⇨ Contains magnetostatic energy
- ⇨ No exact analytics

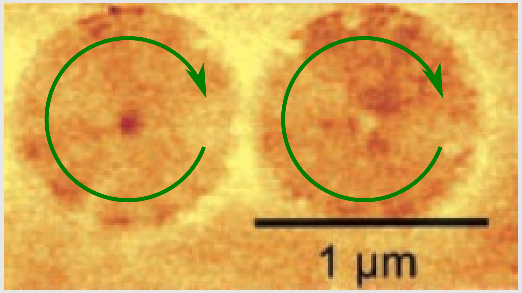
L. Néel, C. R. Acad. Sciences 241, 533 (1956)

Constrained walls (eg : in stripes)



Permalloy (15nm)
Stripe 500nm

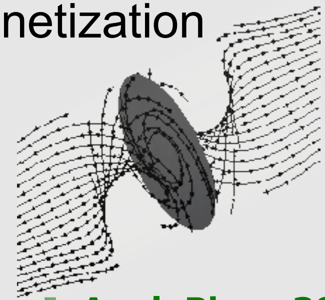
Magnetic vortex (1D → 0D)



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

Bloch point (0D)

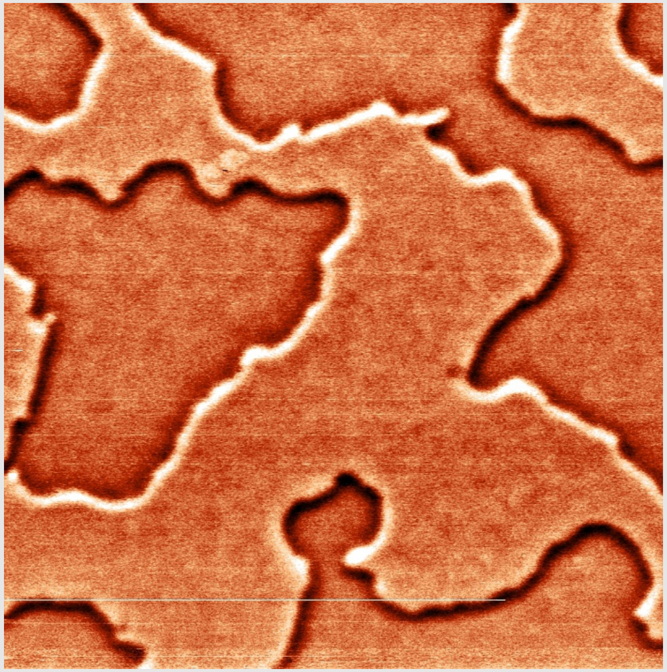
- ⇨ Point with vanishing magnetization



W. Döring, J. Appl. Phys. 39, 1006 (1968)

Magnetic history

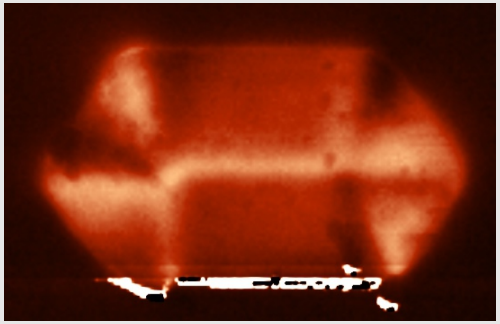
- Non-magnetized sample (virgin state)
- Demagnetized sample



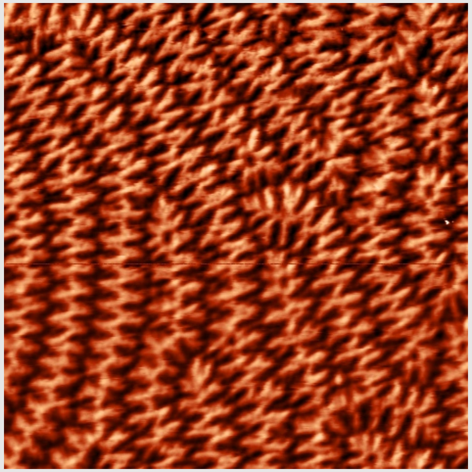
4nm FePt film
MFM, 1.5μm
Perpendicular magnetization
Sample courtesy : A. Marty

Magnetostatics

- Ground-state driven by decrease of magnetostatic energy (flux closure)



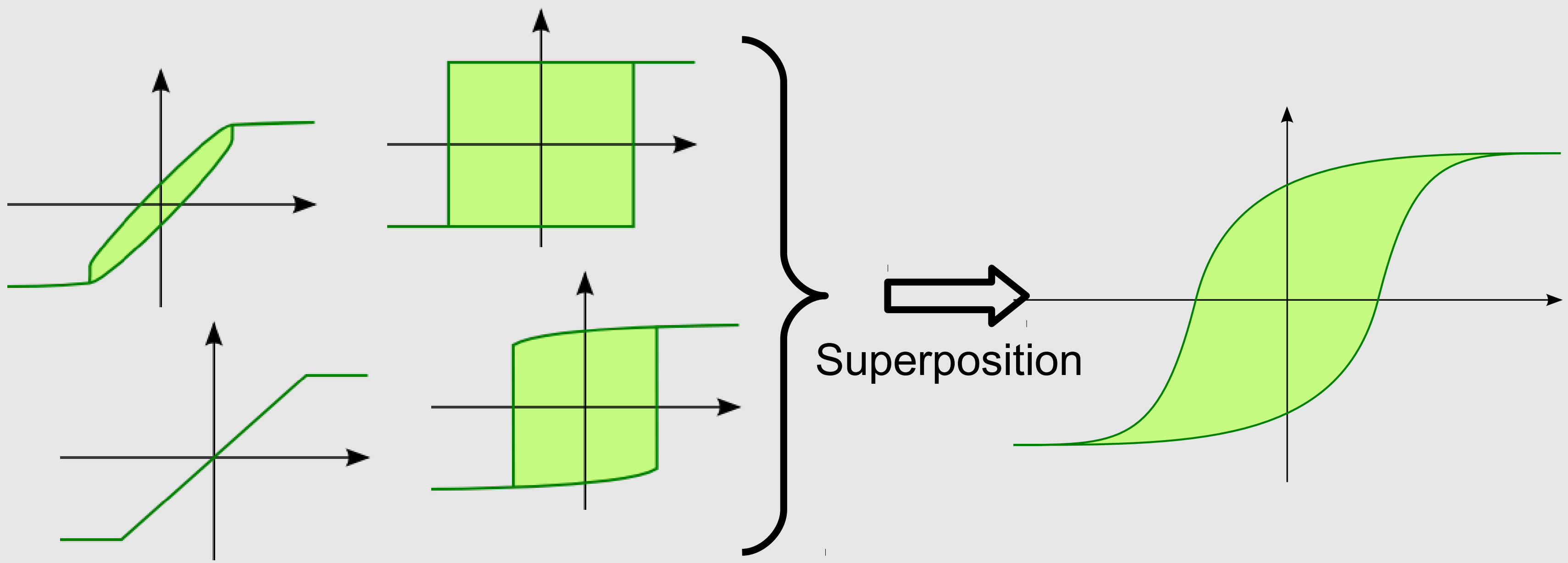
Fe self-assembled dot
MFM, 1.5μm



NdFeB film with low Hc
MFM, 15μm
Sample courtesy : N. Dempsey

Physics : coercivity determined dual grains

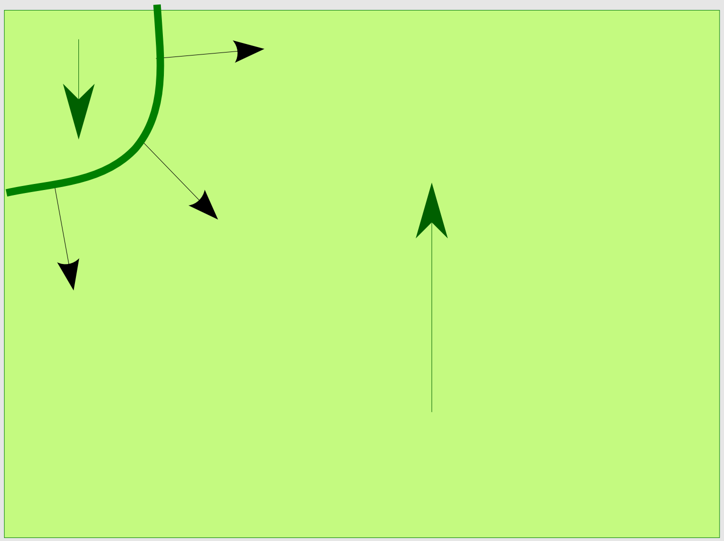
⇨ Different loops with distribution



⇨ Practical Victorino FRANCO

⇨ Next lecture : learn from loops

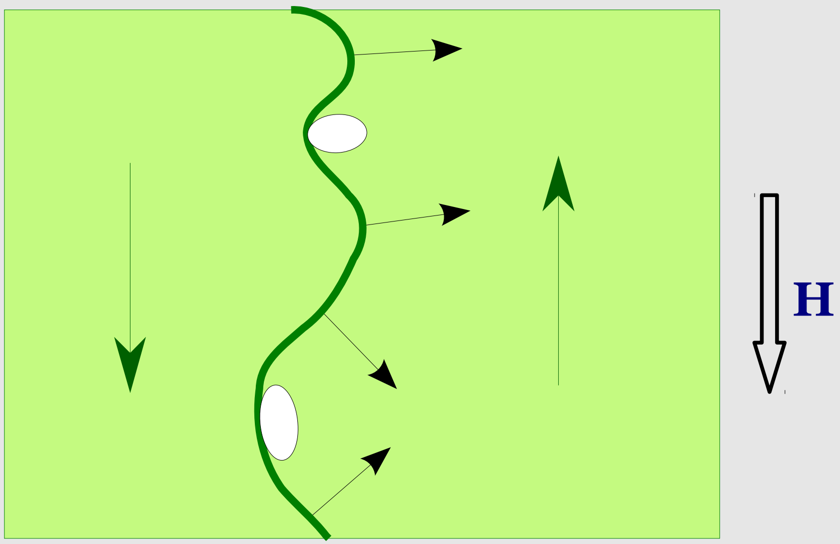
Coercivity determined by nucleation



⇨ Physics has some similarity with that of grains

⇨ Concept of nucleation volume

Coercivity determined by propagation

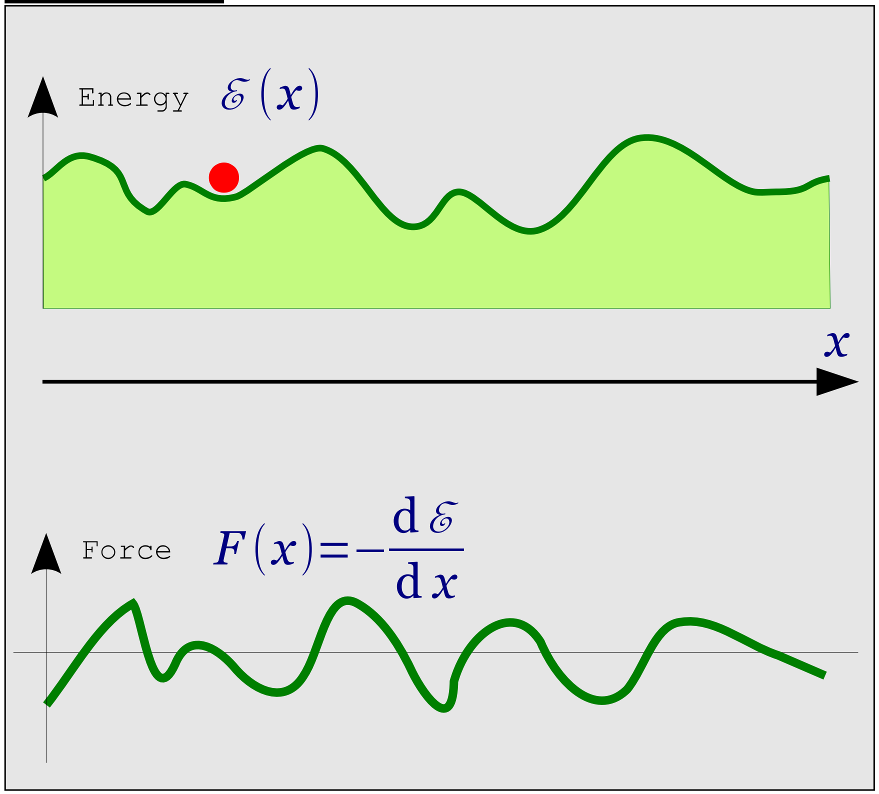


⇨ Physics of surface/string in heterogeneous landscape

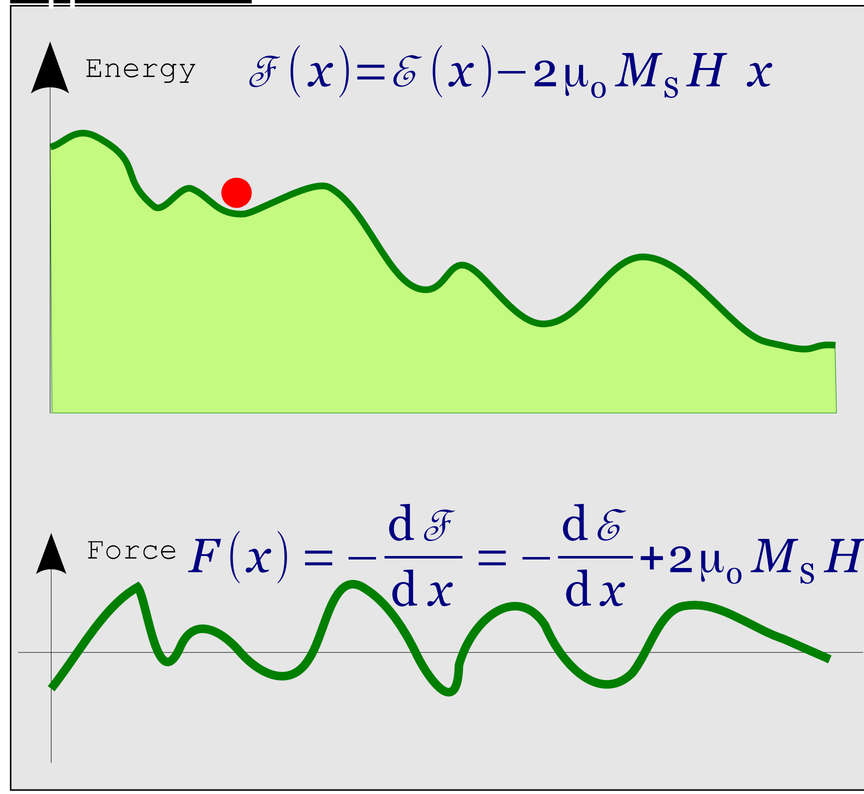
⇨ Modeling necessary

Hypothesis : translational invariance along the wall → 1d model (variable x)

Zero field



Applied field



Propagation field : $H_p = \dfrac{1}{2\mu_0 M_s} \mathrm{Max}\left(\dfrac{\mathrm{d}\mathcal{E}}{\mathrm{d}x}\right)$ → Search for : $\dfrac{\mathrm{d}^2\mathcal{E}}{\mathrm{d}x^2} = 0$

E. Kondorski, *On the nature of coercive force and irreversible changes in magnetisation*, Phys. Z. Sowjetunion 11, 597 (1937)

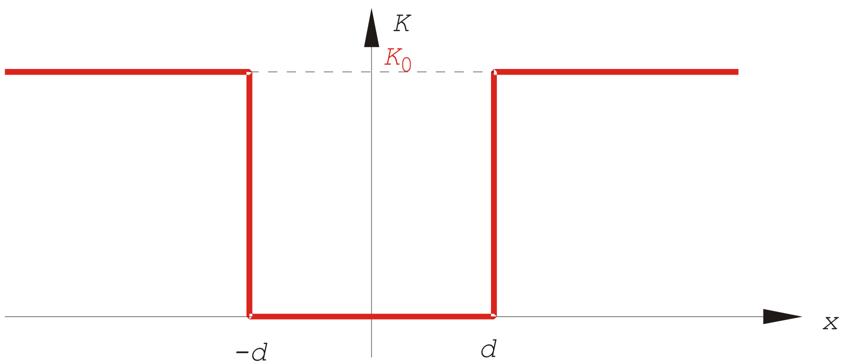
Coercivity in extended systems – Kondorski model, an example

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.



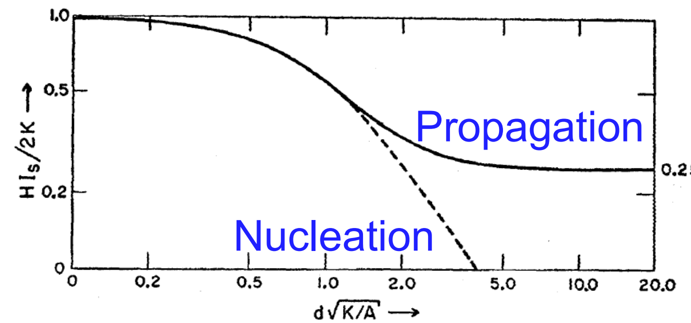


FIG. 1. The nucleation field (dashed) and coercive force (full curve) in terms of the coercive force of perfect material, $HI_s/2K$, as functions of the defect size, d.

See practical : **http://magnetism.eu/esm/2009/slides/fruchart-tutorial.pdf**

Brown's paradox

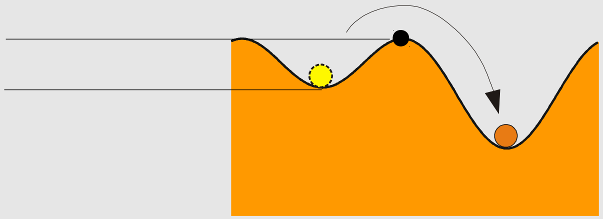
In most systems $H_c \ll \frac{2K}{\mu_0 M_S}$

Micromagnetic analytics or simulations

⇨ Link Hc with microstructure

⇨ Issue : microscopic knowledge

Reminder : single-domain

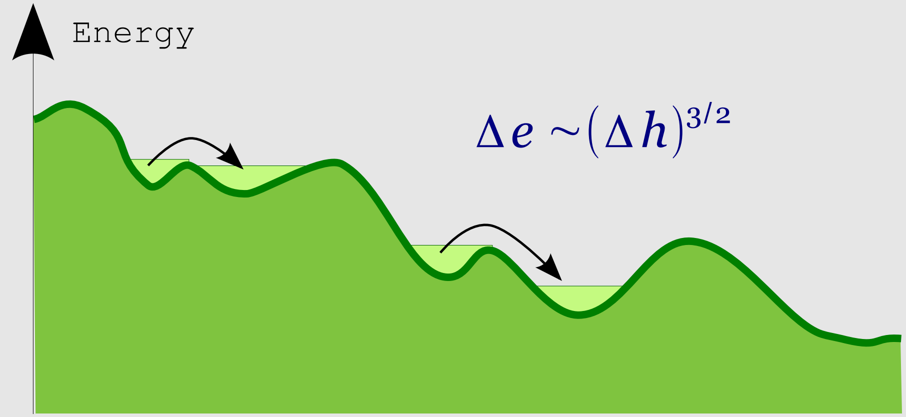


$\Delta e \sim (\Delta h)^2$ for $\theta_H = 0°$

$\Delta e \sim (\Delta h)^{3/2}$ for $\theta_H \neq 0°$

with: $\Delta h = h_c(T = 0\ K) - h$

Kondorski model (1d)



⇨ Notice : other exponents for other situations and model

Thermally-activated DW motion:
→ Creep regime

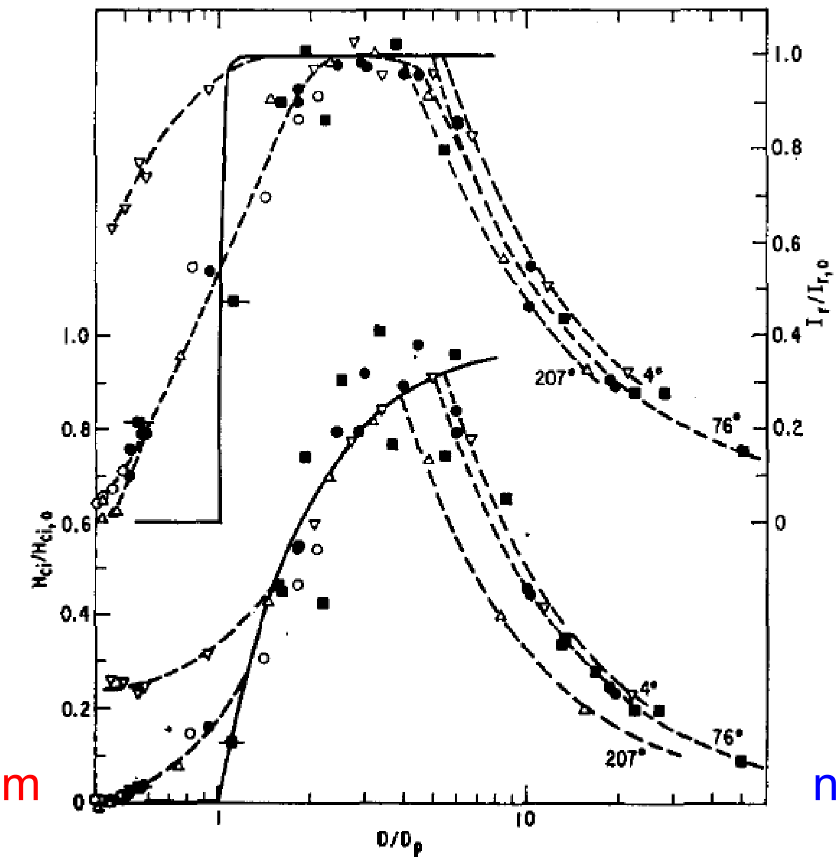


FIG. 1. Particle size dependence of essentially spherical, randomly oriented, iron particles. Calculated curve given by solid line. Diameters $D = \hat{d}_v$. Data at 76°K obtained from electron microscopic examination ■, calculated from I_r/I_s vs temperature O, and from smoothed data of H_{ci} vs D ●.

Towards superparamagnetism

Towards nucleation-propagation and multidomain

E. F. Kneller & F. E. Luborsky,
Particle size dependence of coercivity and remanence of single-domain particles,
J. Appl. Phys. 34, 656 (1963)

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

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

[2] R. Skomski, Simple models of Magnetism, Oxford (2008).

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

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

[5] Lecture notes from undergraduate lectures, plus various slides: http://perso.neel.cnrs.fr/olivier.fruchart/slides/

[6] D. Givord, Q. Lu, M. F. Rossignol, P. Tenaud, T. Viadieu, Experimental approach to coercivity analysis in hard magnetic materials, J. Magn. Magn. Mater. 83, 183-188 (1990).

[7] D. Givord, M. Rossignol, V. M. T. S. Barthem, The physics of coercivity, J. Magn. Magn. Mater. 258, 1 (2003).

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

[9] Lecture notes in magnetism: http://magnetism.eu/esm/repository.html

Moment and anisotropy of ultrathin films

U. Gradmann, Handbook of magnetic materials vol. 7, K. H.K. Buschow Ed., Elsevier, Magnetism of transition metal films, 1 (1993)

M. Farle, Ferromagnetic resonance of ultrathin metallic layers, Rep. Prog. Phys. 61, 755 (1998)

P. Poulopoulos et al., K. Baberschke, Magnetism in thin films, J. Phys.: Condens. Matter 11, 9495 (1999)

H. J. Elmers, Ferromagnetic Monolayers, Int. J. Mod. Phys. B 9 (24), 3115 (1995)

O. Fruchart, Epitaxial self-organization: from surfaces to magnetic materials, C. R. Phys. 6, 61 (2005)

O. Fruchart et al., Magnetism in reduced dimensions, C. R. Phys. 6, 921 (2005)

Perpendicular anisotropy

M. T. Johnson et al., Magnetic anisotropy in metallic multilayers, Rep. Prog. Phys. 59, 1409 (1996)

Exchange-bias

J. Nogues et al., I. K. Schuller, Exchange bias, J. Magn. Magn. Mater 192 (2), 203 (1999).

Magneto-elasticity in thin films

D. Sander, The correlation between mechanical stress and magnetic anisotropy in ultrathin films, Rep. Prog. Phys. 62, 809 (1999)

Theory (misc)

T. Asada et al., G. Bihlmayer, S. Handschuh, S. Heinze, P. Kurz, S. Blügel, First-principles theory of ultrathin magnetic films, J. Phys.: Condens. Matter 11, 9347 (1999)

F. J. Himpsel et al., Magnetic Nanostructures, Adv. Phys. 47 (4), 511 (1998)

P. Bruno, Theory of interlayer exchange interactions in magnetic multilayers, J. Phys.: Condens. Matter 11, 9403 (1999)

F. E. Gabaly et al., Noble metal capping effects on the spin-reorientation transitions of Co/Ru(0001), N. J. Phys. 10, 073024 (2008)