An overview of magnetization reversal

I. Some basics:
Single-domain concepts and their use in materials

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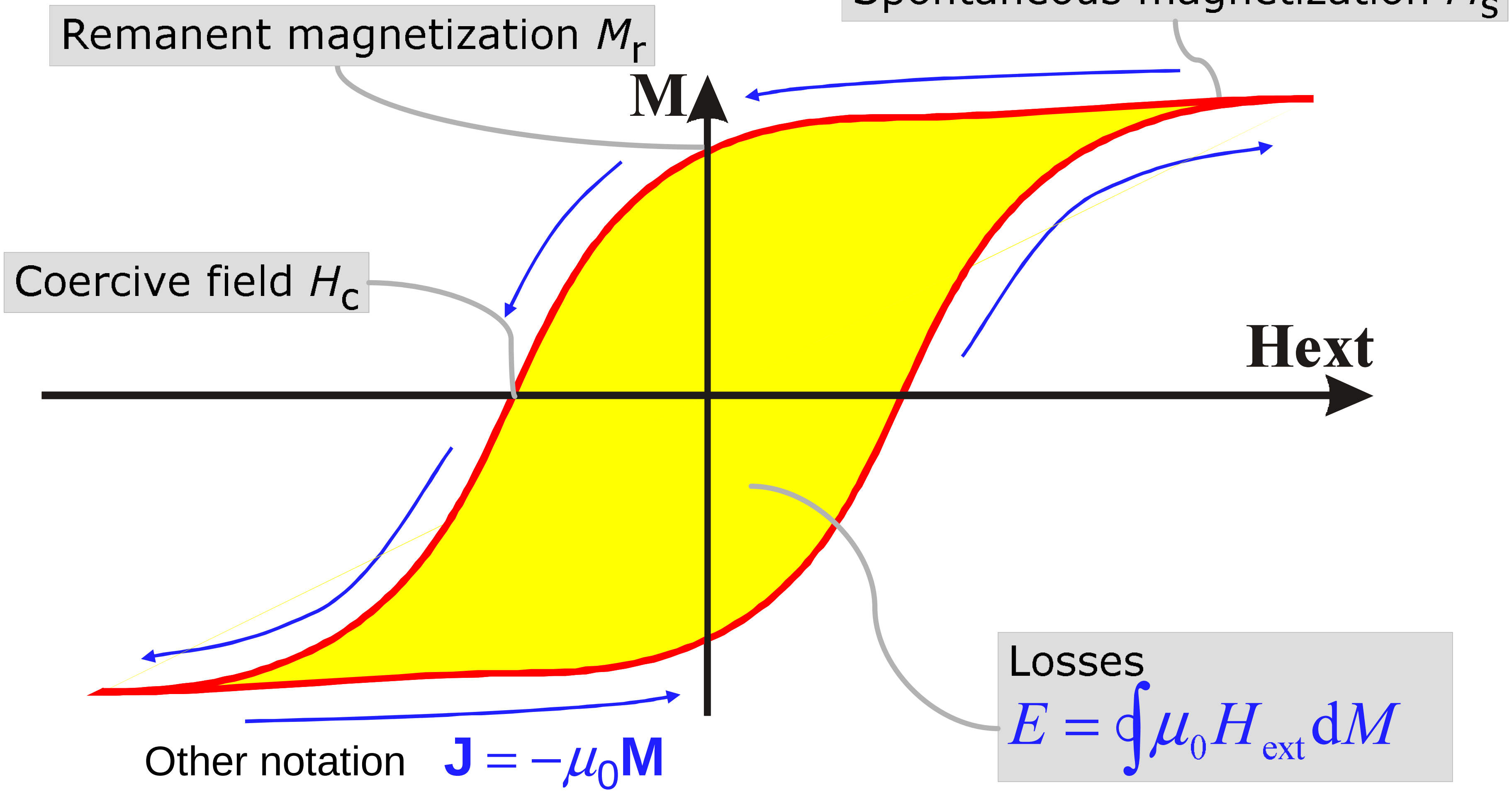
Manipulation of magnetic materials:

Application of a magnetic field

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

See: E. Brück, V. Pop

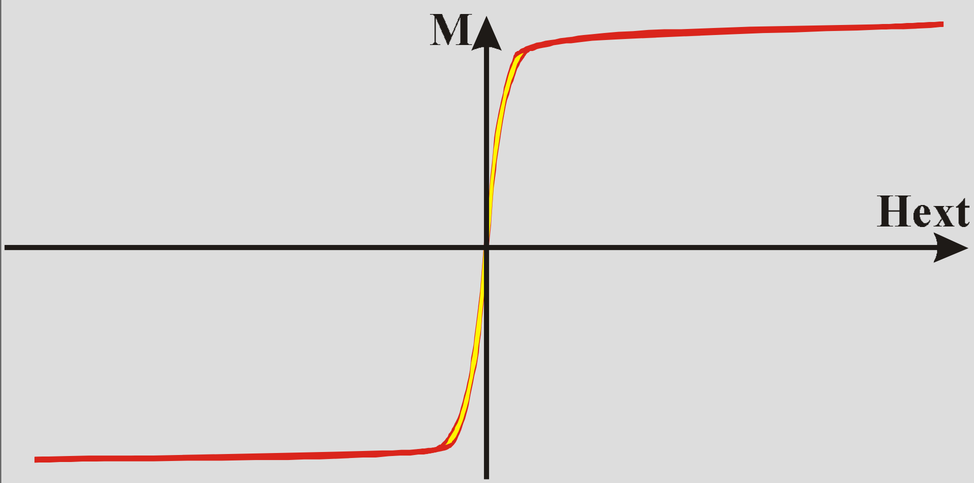


Other notation $\mathbf{J} = -\mu_0 \mathbf{M}$

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

Institut Néel, Grenoble, France

Soft materials

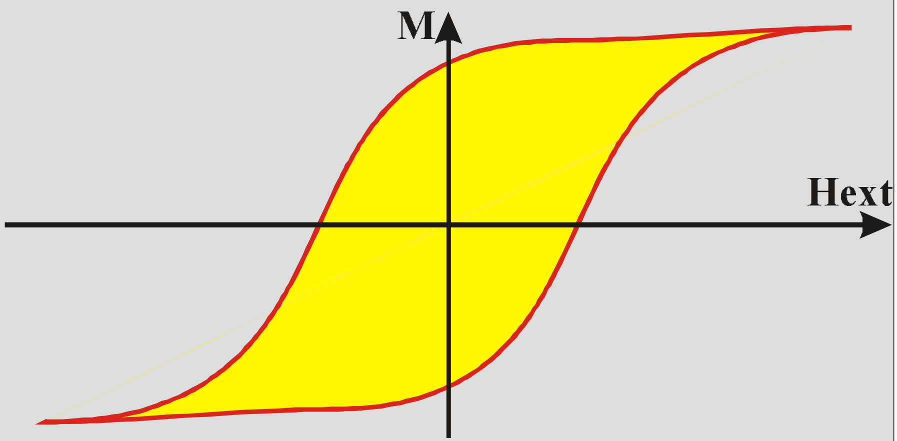


Transformers

Flux guides, sensors

Magnetic shielding

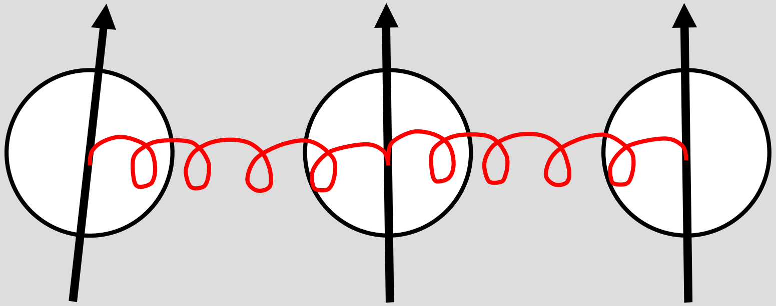
Hard materials



Permanent magnets, motors

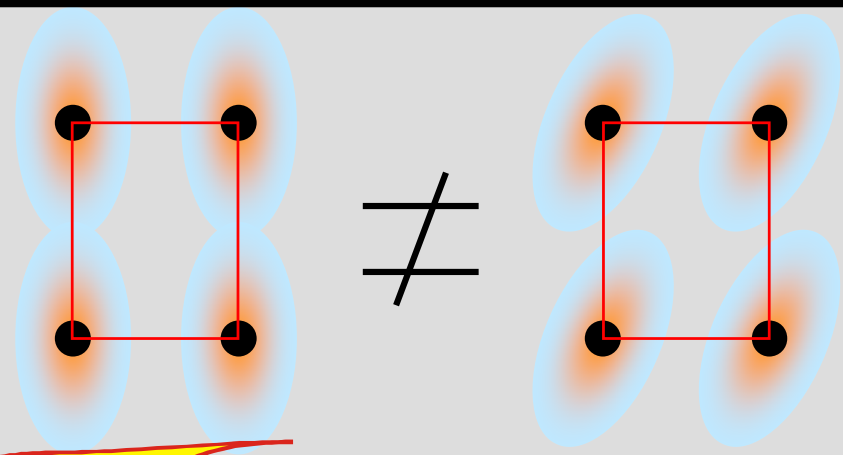
Magnetic recording

Echange energy

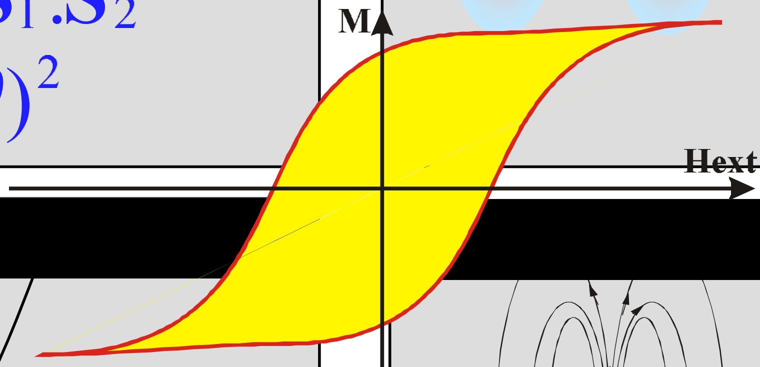


$$E_{\mathrm{Ech}} = -J_{1,2}\,\vec{\mathbf{S}}_1 . \vec{\mathbf{S}}_2 = A(\nabla\theta)^2$$

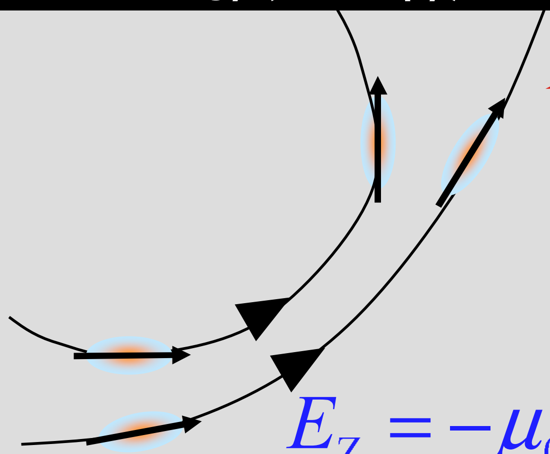
Magnetocrystalline anisotropy energy



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

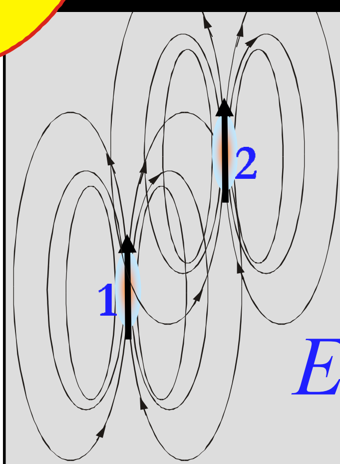


Zeeman energy (enthalpy)



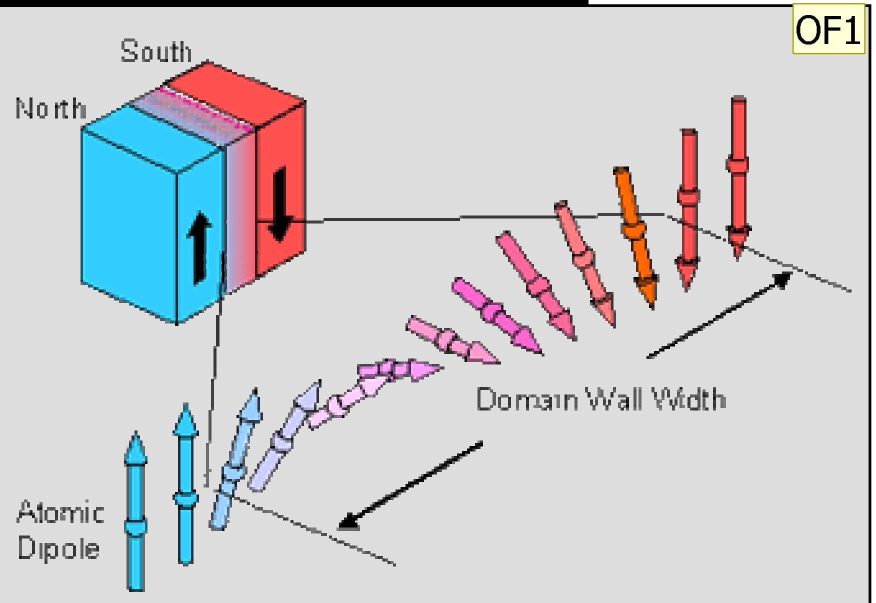
$$E_Z = -\mu_0 \vec{\mathbf{M}}_{\mathrm{S}} . \vec{\mathbf{H}}$$

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

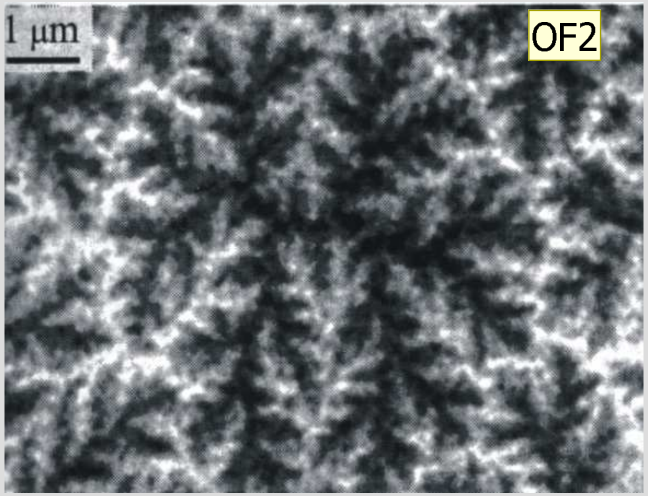
Hard — Soft

Diapositive 6

OF1 Si temps, refaire schéma en français
Olivier Fruchart; 22/03/2005

Bulk material

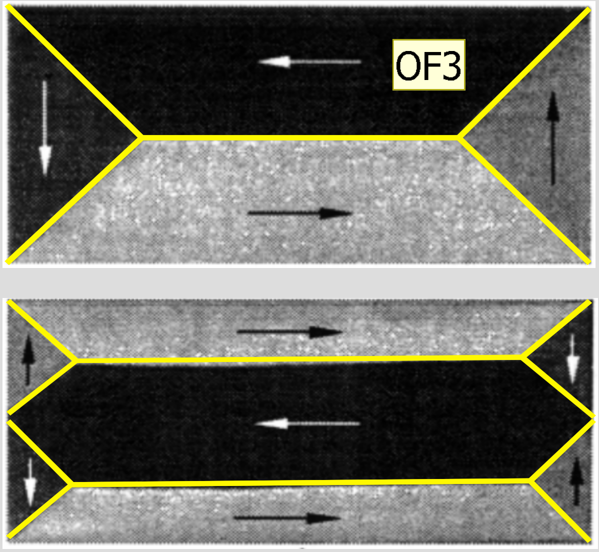
Numerous and complex magnetic domains



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

Mesoscopic scale

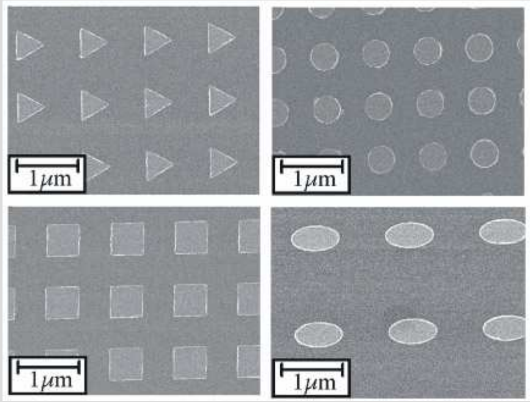
Small number of domains, simple shape

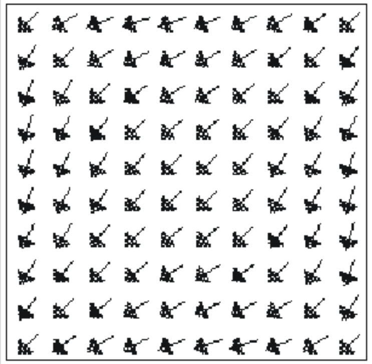


Microfabricated dots
Kerr magnetic imaging
A. Hubert, *Magnetic domains*

Nanometric scale

Magnetic single-domain





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

Nanomagnetism ~ mesoscopic magnetism

Diapositive 7

OF2 hubert-fig2-39[Co(1000) crystal - SEMPA].tif
Olivier Fruchart; 22/03/2005

OF3 KTH 2001
Olivier Fruchart; 08/07/2005

I. Some basics (from single-domain to materials)

I.1. Macrospin models for coercivity

Framework

Approximation: (strong!) $\vec{m}(\vec{r}) = \vec{M} = Cte$

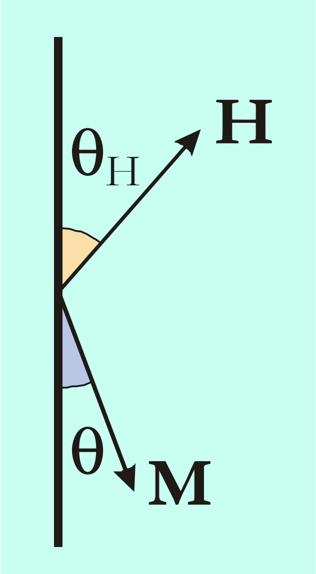
$$E_{tot} = V\left[K_{eff}\sin^2\theta - \mu_0 M_S H_{ext}\cos(\theta-\theta_H)\right]$$

$$K_{eff} = K_{mc} + K_d$$

Dimensionless units:

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

$$\begin{pmatrix} e = E/VK \\ h = H/H_a \\ H_a = 2K/\mu_0 M_S \end{pmatrix}$$

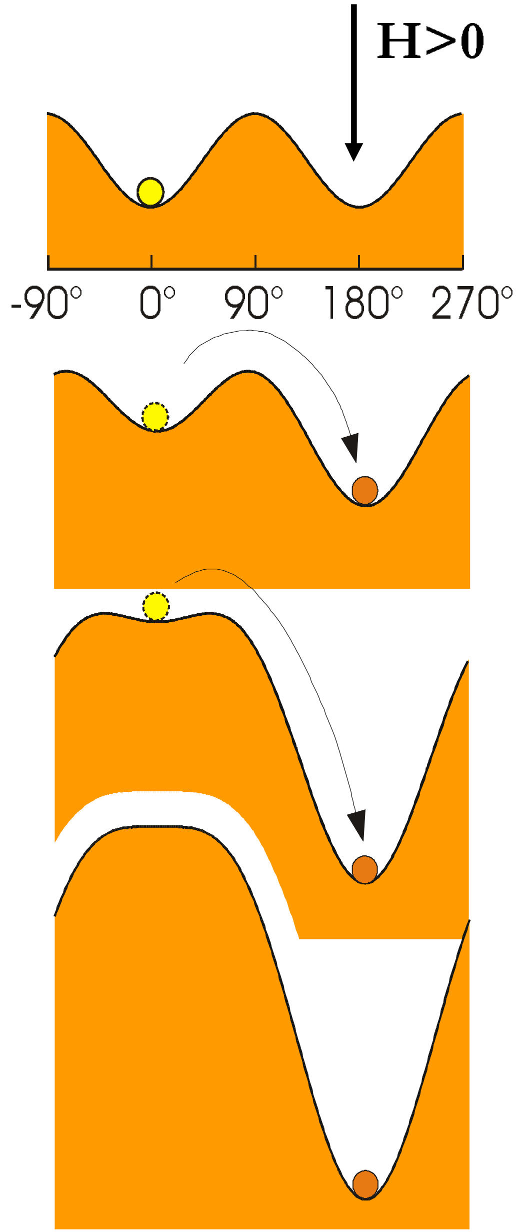


L. Néel, Compte rendu Acad. Sciences 224, 1550 (1947)
E. C. Stoner and E. P. Wohlfarth, *Phil. Trans. Royal. Soc. London* A240, 599 (1948)
IEEE Trans. Magn. 27(4), 3469 (1991) : reprint

Names used

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

$$e = \sin^2(\theta) + 2h\cos(\theta) \qquad (\theta_H = 180°)$$



Equilibrium states

$$\frac{\partial e}{\partial \theta} = 2\sin\theta(\cos\theta - h)$$

$$\frac{\partial e}{\partial \theta} = 0 \quad \Rightarrow \quad \cos(\theta_m) = h$$

$$\theta \equiv 0\ [\pi]$$

Stability

$$\frac{\partial^2 e}{\partial \theta^2} = 2\cos 2\theta - 2h\cos\theta$$

$$= 4\cos^2\theta - 2 - 2h\cos\theta$$

$$\frac{\partial^2 e}{\partial \theta^2}(0) = 2(1-h)$$

$$\frac{\partial^2 e}{\partial \theta^2}(\theta_m) = 2(h^2 - 1)$$

$$\frac{\partial^2 e}{\partial \theta^2}(\pi) = 2(1+h)$$

Energy barrier

$$\Delta e = e(\theta_{max}) - e(0)$$

$$= 1 - h^2 + 2h^2 - 2h$$

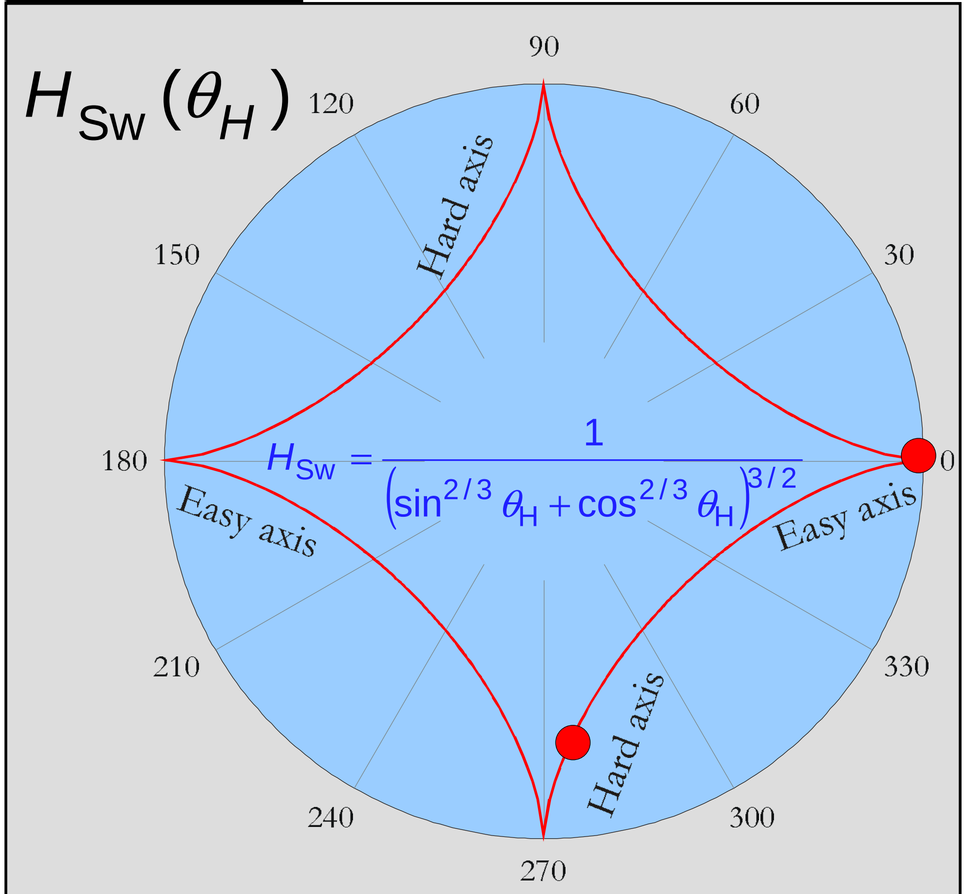
$$= (1-h)^2$$

Switching

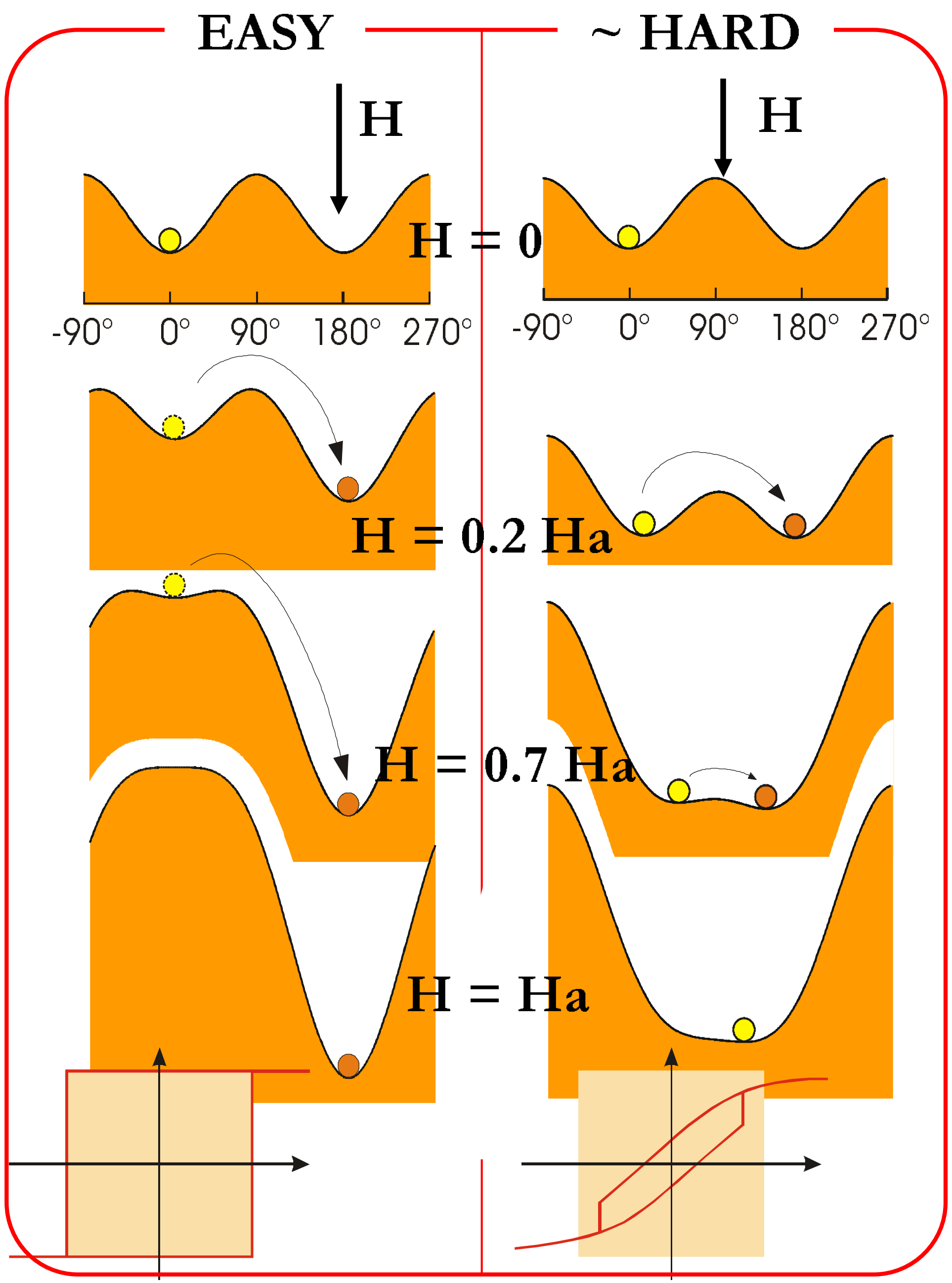
$$h = 1$$

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

'Astroid' curve



- $H_{Sw}(\theta)$ is a 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.

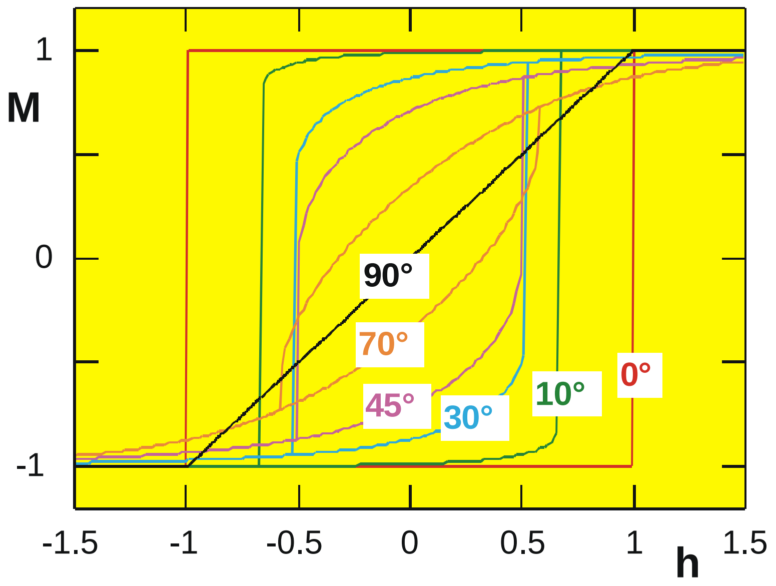
Can be measured only in single particles.

Coercive field

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

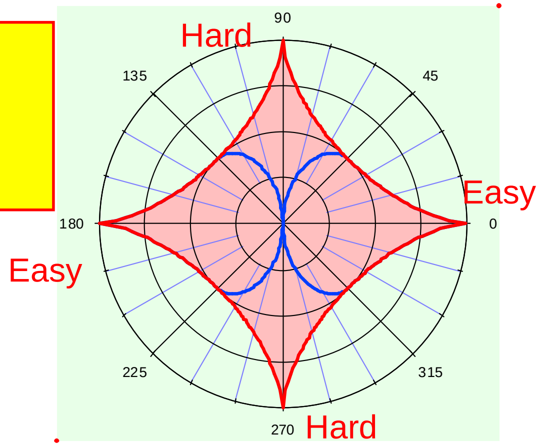
A quantity that can be measured in real materials (large number of ‘particles’).

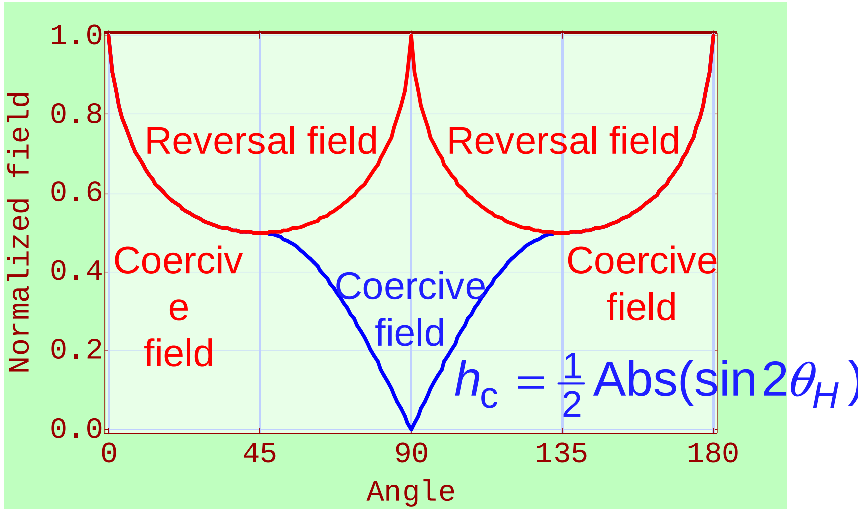
May be or may not be a measure of the mean switching field at the microscopic level



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

See: V. Pop (spring magnets etc)





research memorandum

IBM RESEARCH CENTER POUGHKEEPSIE, N Y

no. RM 003.111.224

date October 1, 1956

THEORY OF MAGNETIC HYSTERESIS IN FILMS AND ITS APPLICATION TO COMPUTERS

by

J. C. SLONCZEWSKI

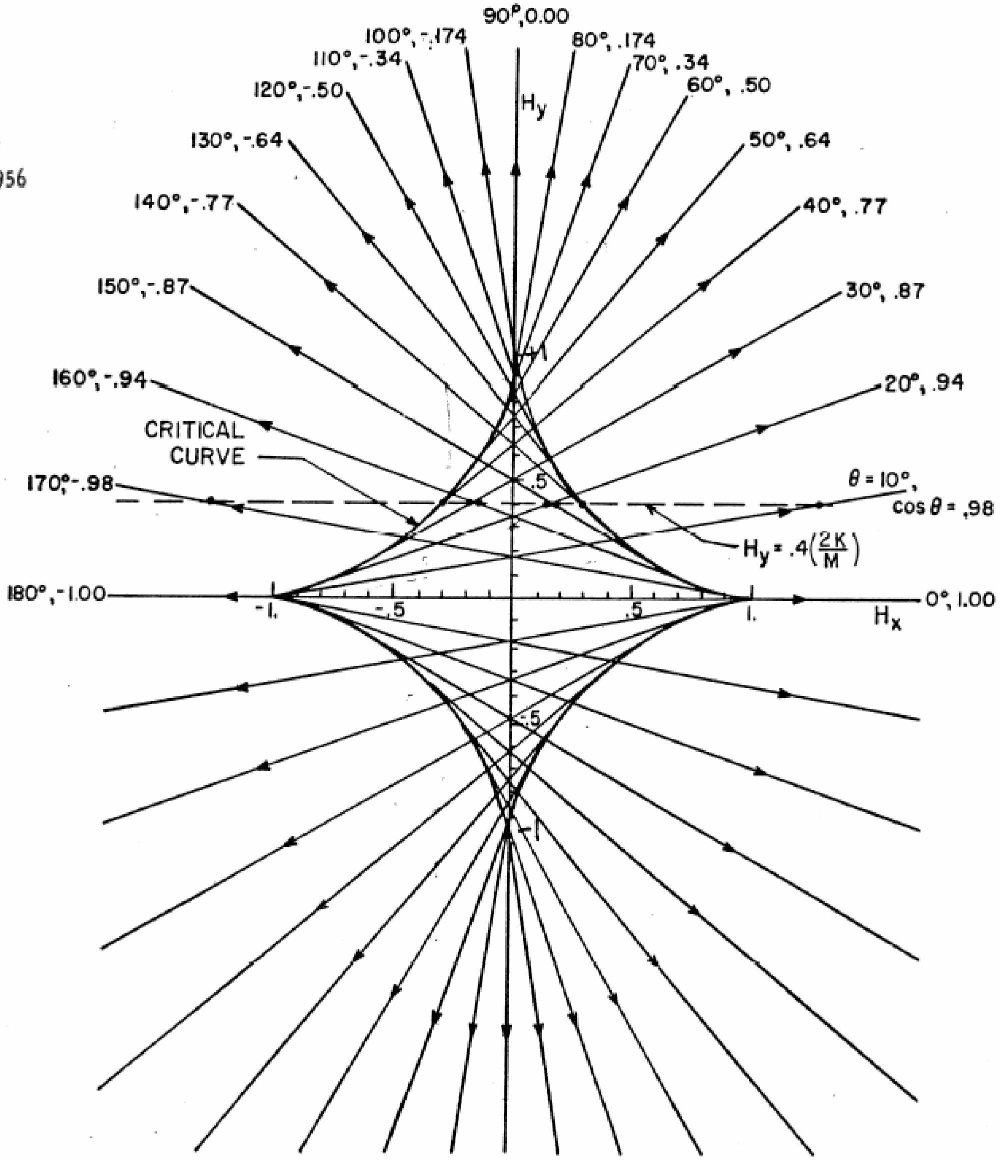


FIGURE 3. THE ORIENTATION OF M, INDICATED BY ARROWS, DEPENDS ON $\vec{H}$. H_x AND H_y ARE IN UNITS OF $\frac{2K}{M}$.

⇨ Each line shown is the locus of fields for which a stable/unstable equilibrium exists for a given angle θ of magnetization

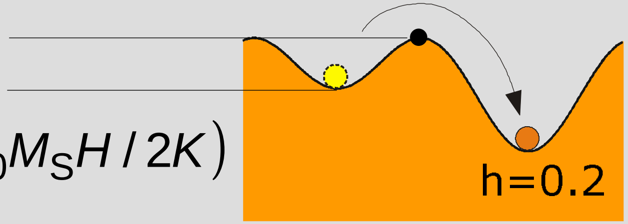
⇨ The Astroid is the envelop of this family of lines

⇨ Thus for each radial line the direction of magnetization can be determined graphically at any point

Barrier height

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

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



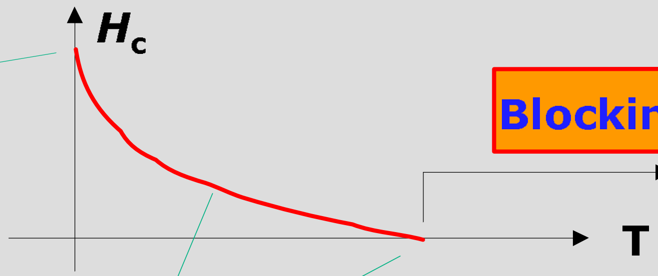
Thermal activation

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

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

Lab measurement : $\tau = 1\text{s}$ $\qquad \sim 25 k_B T$

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



Blocking temperature

$T_b \approx KV / 25 k_B$

Information about anisotropy density

Information about total effective anisotropy

Notice, for magnetic recording : $t \approx 10^9$s $\qquad KV_B \approx 40 - 60\, k_B T$

Formalism

Energy

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

$$\beta E = d.f(\theta,\varphi) - h\mu$$

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

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

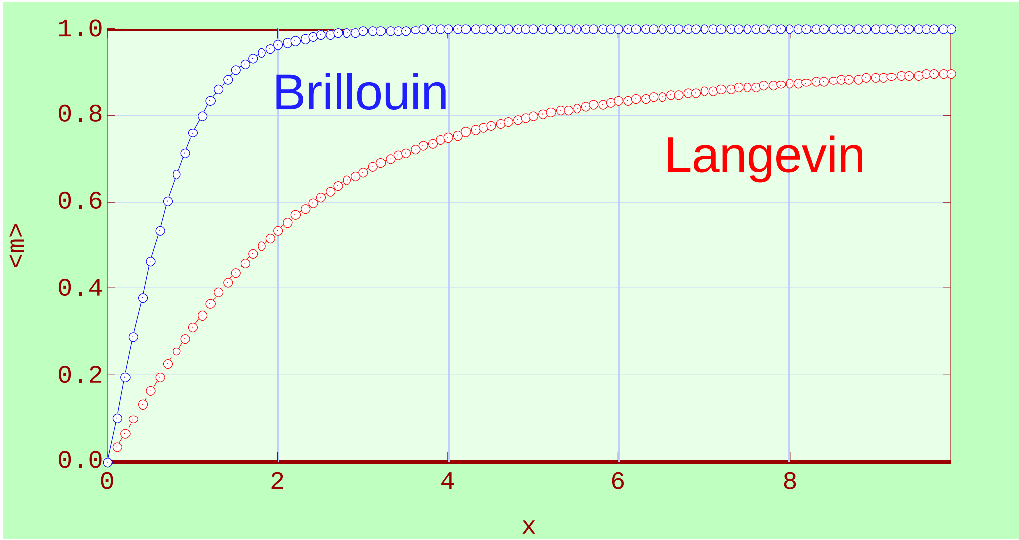
$$<\mu> = M.\tanh(x)$$

Brillouin ½ function

Note:

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

$$x = \beta \mu_0 MH$$



Classical spin with uniaxial anisotropy

Uniaxial anisotropy $\beta E = -dm^2 - hm$

H // anisotropy axis

$d = \beta K$ $K = K_V \times v$	Anisotropy
$h = \beta \mu_0 \mu H$	Zeeman

Exact solution

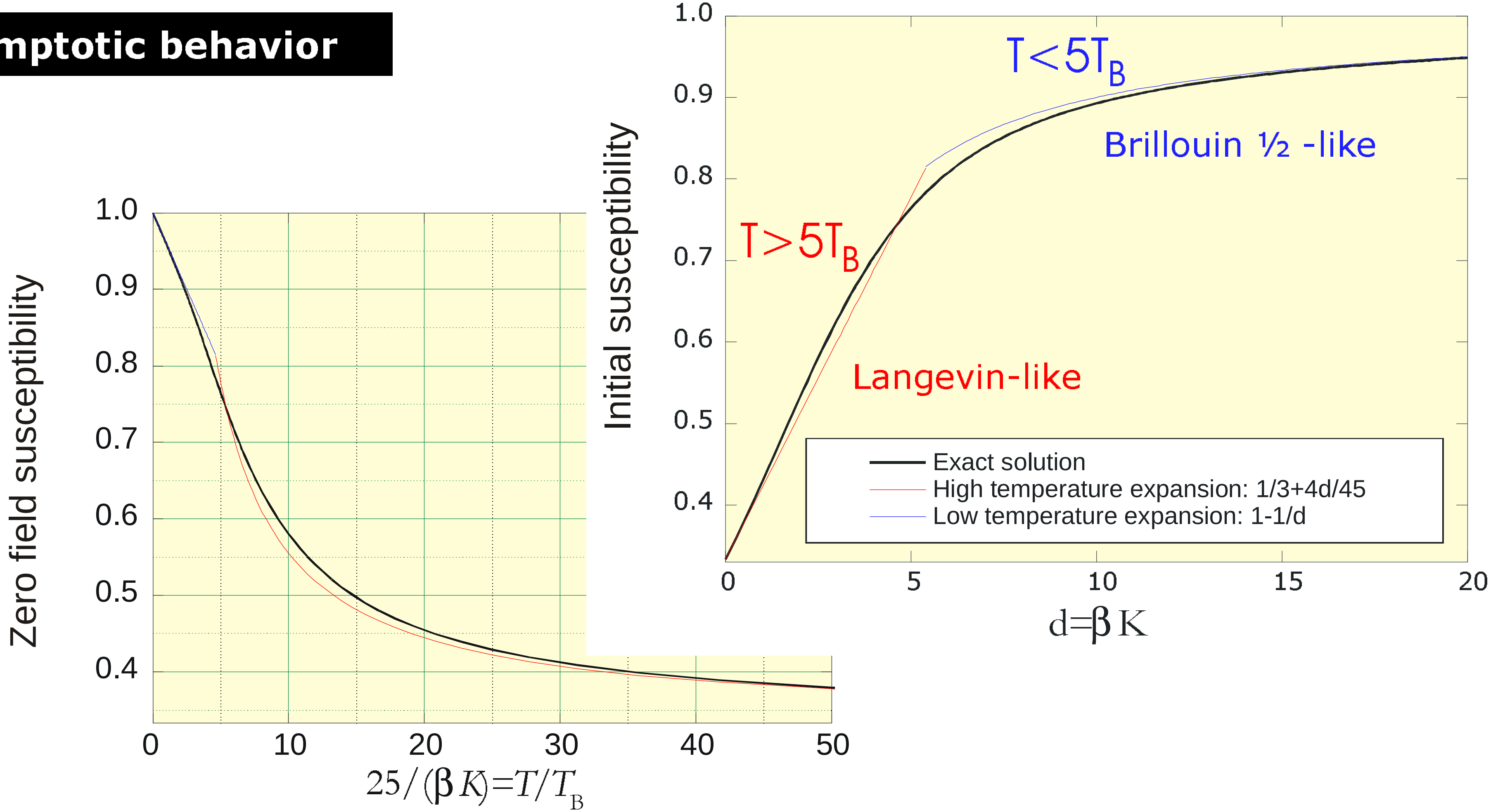
Partition function $Z = \int_{-1}^{1} \exp(dm^2 + hm)\mathrm{d}m$

Obstacle (?) $\int_0^t \exp(x^2)\mathrm{d}x = ?$ ⟵ Imaginary Error function, Erfi(t)

Magnetization $m = -h/2d + (2/\sqrt{\pi d}) \times \dfrac{\exp(d + h^2/4d)\sinh(h)}{\mathrm{Erfi}(\sqrt{d} + h/2\sqrt{d}) + \mathrm{Erfi}(\sqrt{d} - h/2\sqrt{d})}$

Zero field susceptibility $\chi = -1/2d + \exp(d)/(\sqrt{\pi d}\,\mathrm{Erfi}\sqrt{d})$

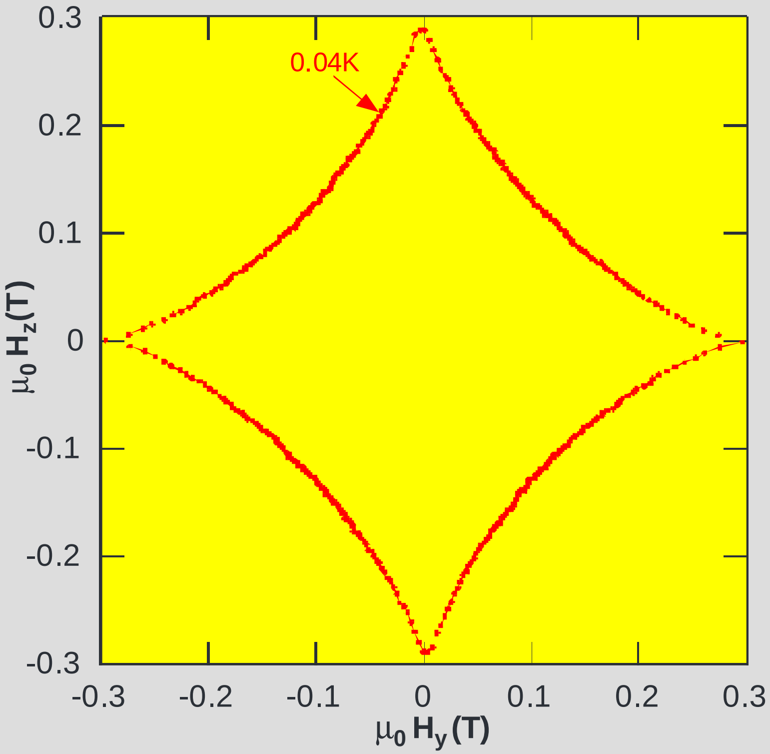
Asymptotic behavior



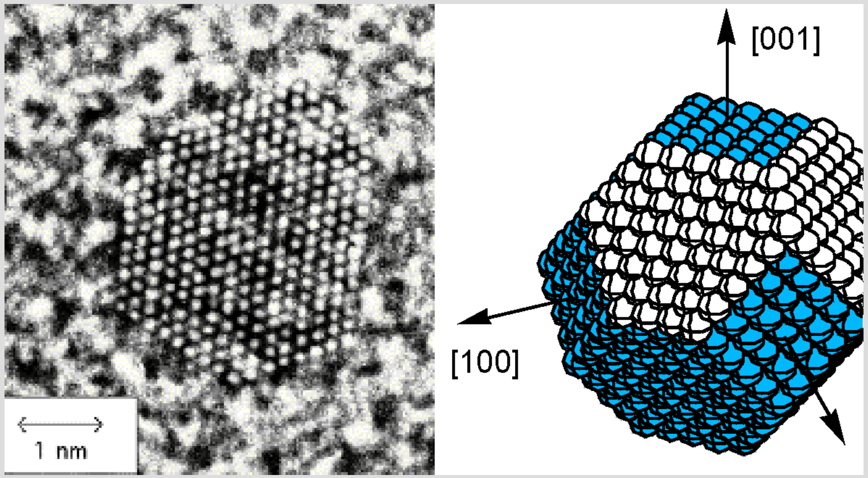
- Fitting yields an estimation of the magnetic moment per particle μ
- Fitting with inadequate functions yields errors on μ
- Cases other than isotropic and uniaxial//H + distributions: full fit required

R. W. Chantrell *et al.*, J. Magn. Magn. Mater. 53, 1999 (1985)
O. Fruchart *et al.*, J. Magn. Magn. Mater. 239, 224 (2002)

Experimental evidence

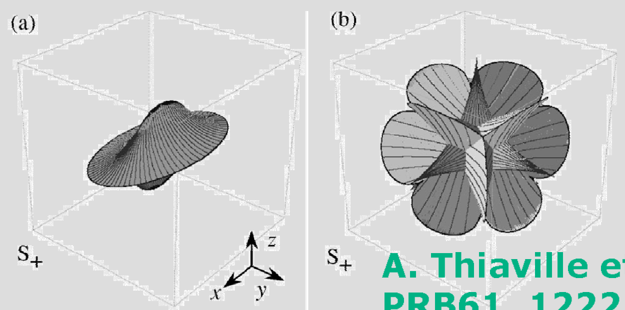


First evidence: **W. Wernsdorfer et al., Phys. Rev. Lett. 78, 1791 (1997)**

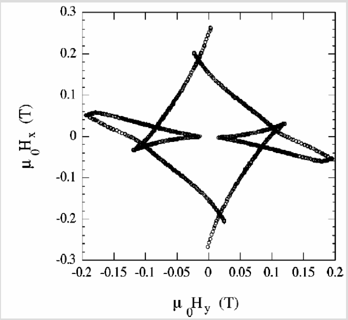


M. Jamet et al., Phys. Rev. Lett., 86, 4676 (2001)

Extensions: 3D, arbitrary anisotropy etc.



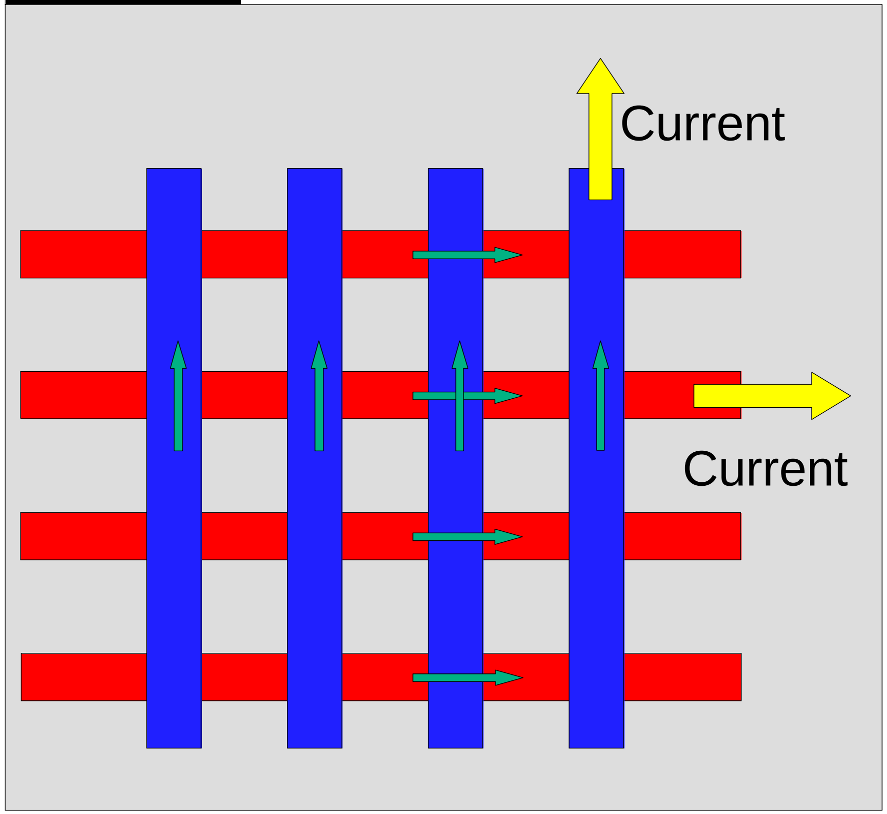
A. Thiaville et al., PRB61, 12221 (2000)



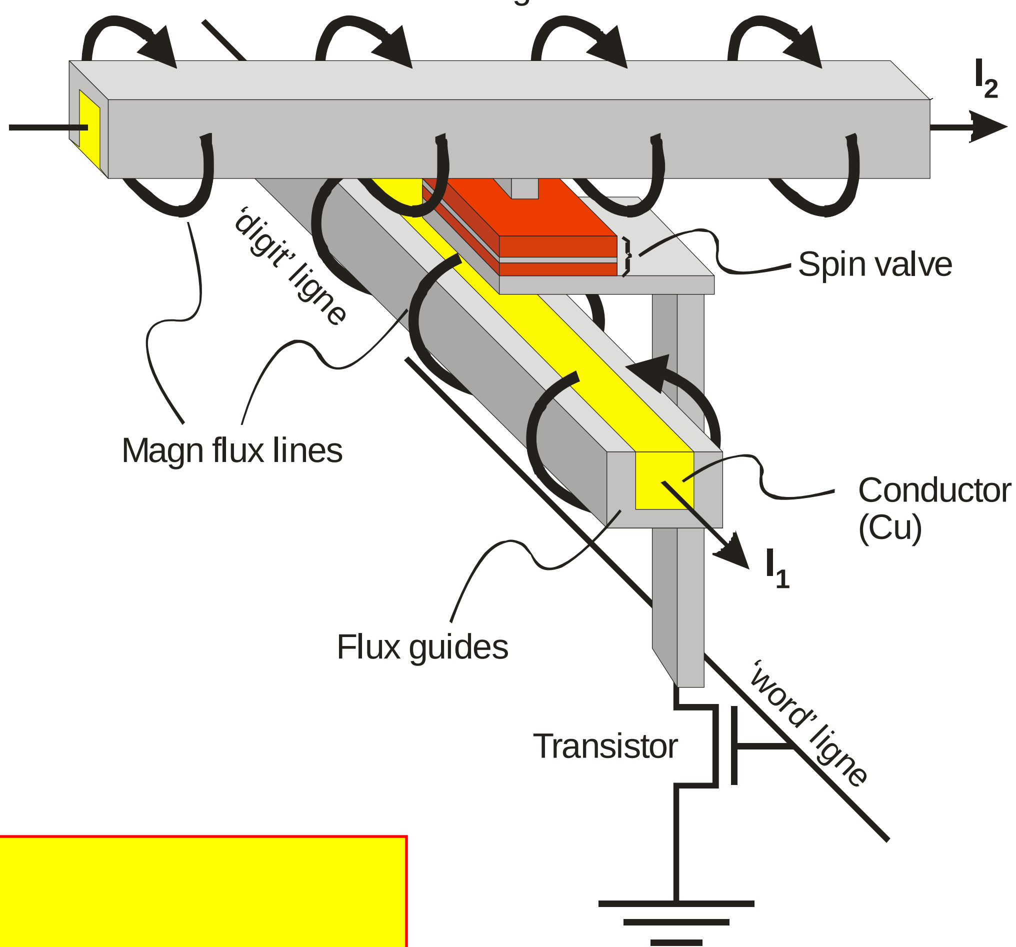
M. Jamet et al., PRB69, 024401 (2004)

MRAM = Magnetic Random Access Memory

Overview



Detail of a cell

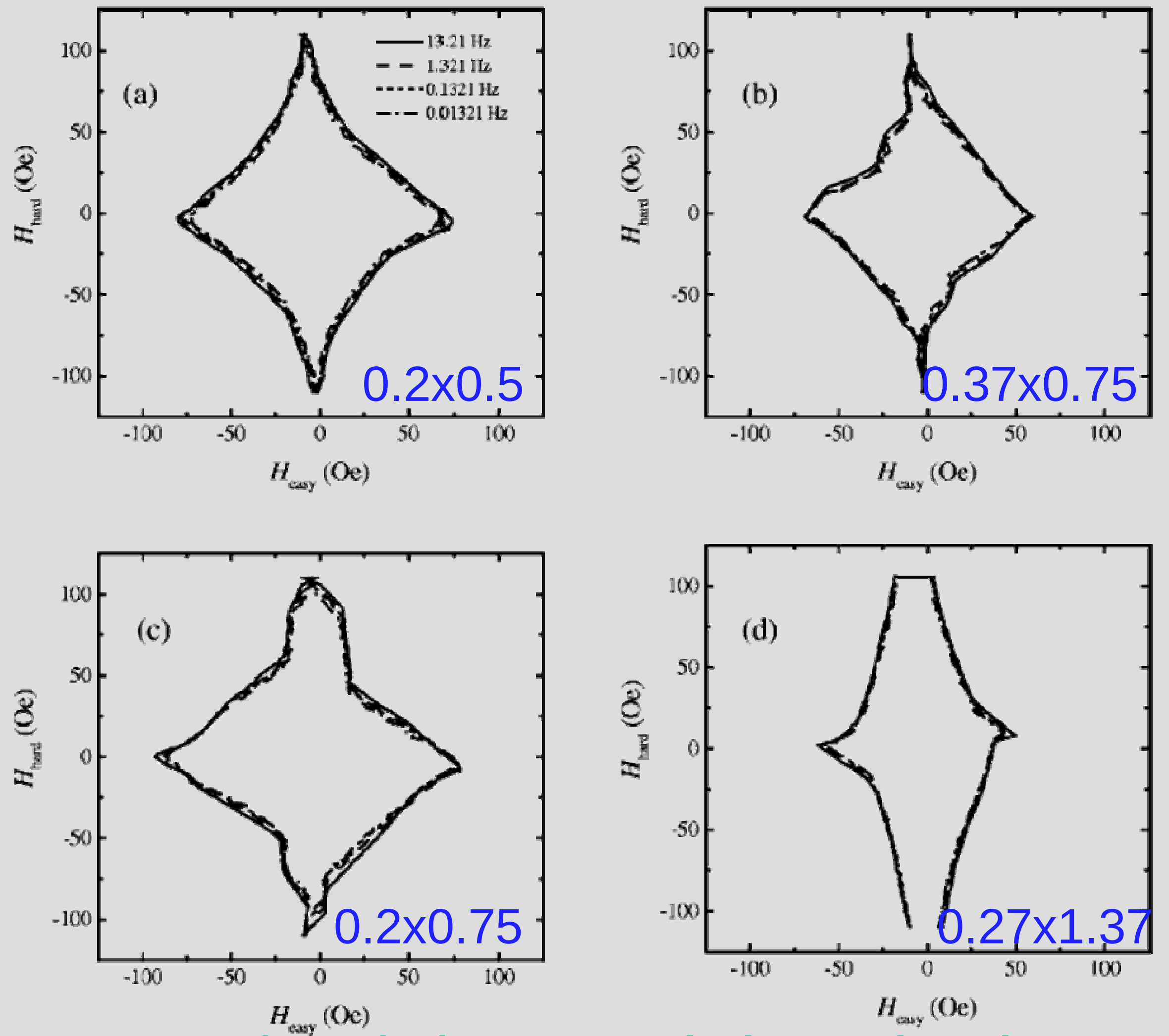


Main features:
Solid state memory
Non-volatile and fast
Complex, expensive, issues of reproductibility

Size-dependent magnetization reversal

Size in micrometers

Astroids of flat magnetic elements with increasing size



J. Z. Sun et al., Appl. Phys. Lett. 78 (25), 4004 (2001)

Conclusion over coherent rotation

- The simplest model
- Fails for most systems because they are too large: **apply model with great care!..**
- Hc<<Ha for most large systems (thin films, bulk): **do not use Hc to estimate K!**
  Early known as **Brown's paradox**

I.2. Coercivity in materials

Brown's paradox

In most systems $H_c \prec\prec \dfrac{2K}{\mu_0 M_s}$

Micromagnetic modeling

Exhibit analytic however realistic models for magnetization reversal

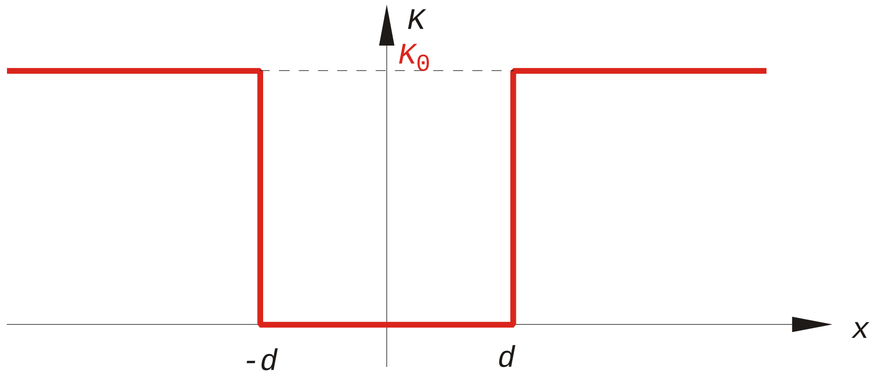
PHYSICAL REVIEW VOLUME 119, NUMBER 1 JULY 1, 1960

Reduction in Coercive Force Caused by a Certain Type of Imperfection

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

(Received February 1, 1960)

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



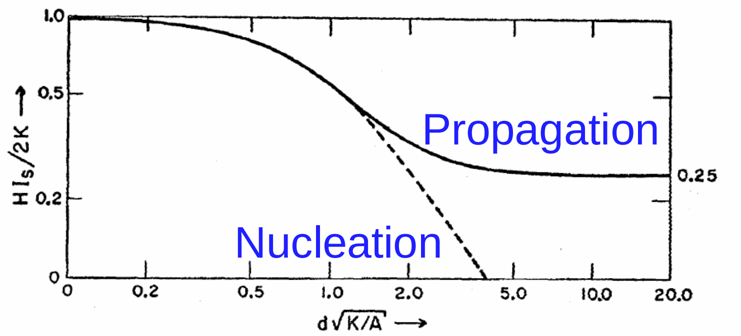
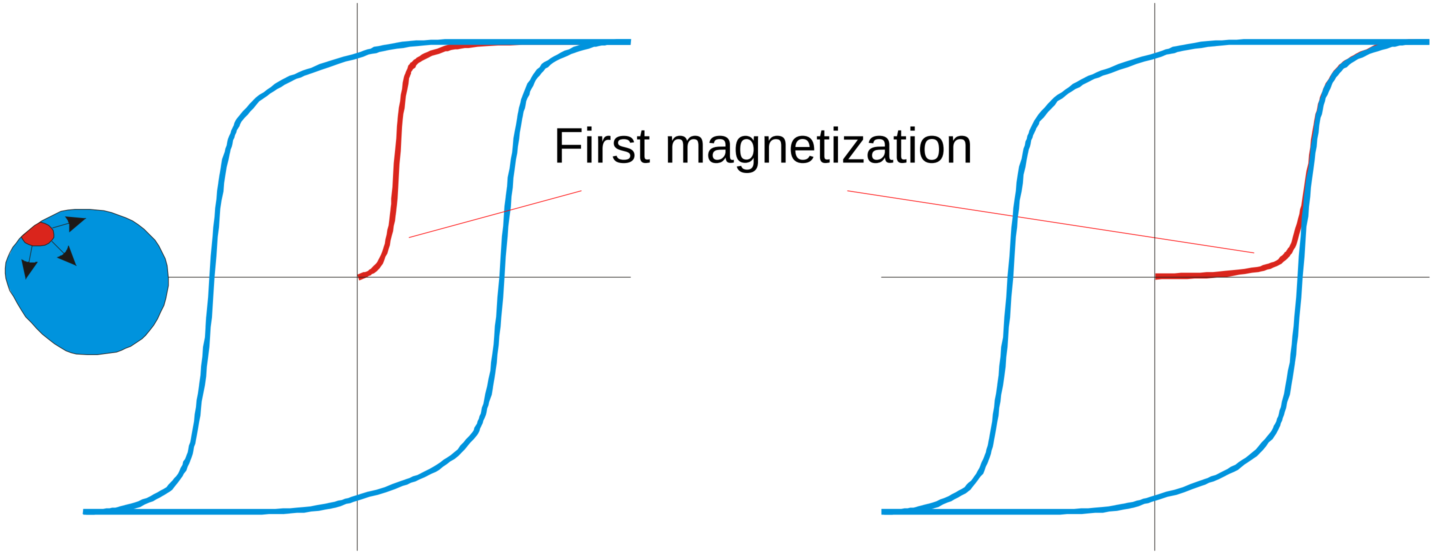


Fig. 1. The nucleation field (dashed) and coercive force (full curve) in terms of the coercive force of perfect material, $HI_s/2K$, as functions of the defect size, d.

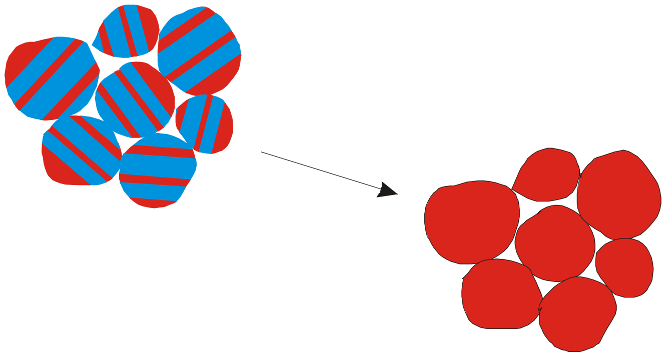
Use first-magnetization curves to determine the type of coercivity

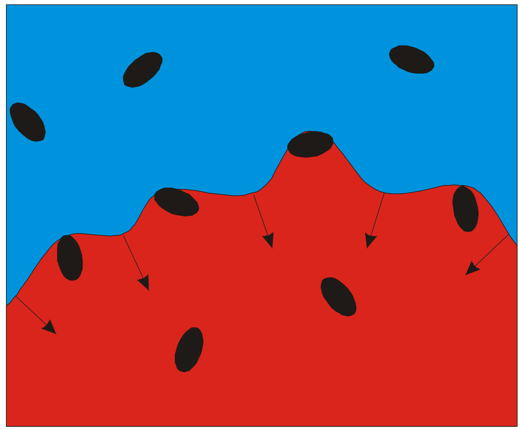


See: E. Burzo

Nucleation-limited
Ex: Sm_2Co_{17}

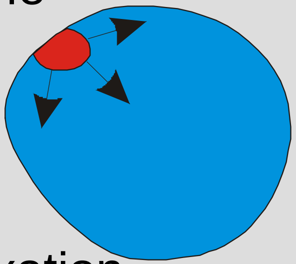
Propagation-limited
Ex: $SmCo_5$





Activation volume

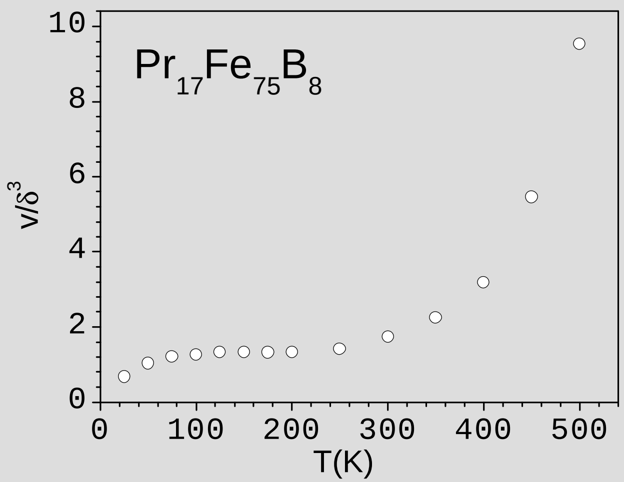
Also called: nucleation volume



Can be used for:

- ⇨ Estimating Hc(T)
- ⇨ Estimating long-time relaxation
- ⇨ Determination of dimensionality

Note: of the order of domain wall width δ



Courtesy D. Givord

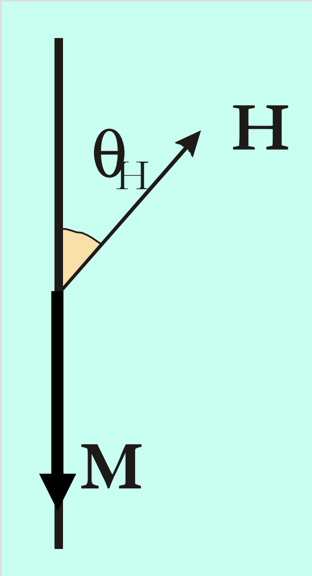
More detailed models:

D. Givord et al., JMMM258, 1 (2003)

$1/\cos\theta_H$ law

E. J. Kondorsky, J. Exp. Theor. Fiz. 10, 420 (1940)

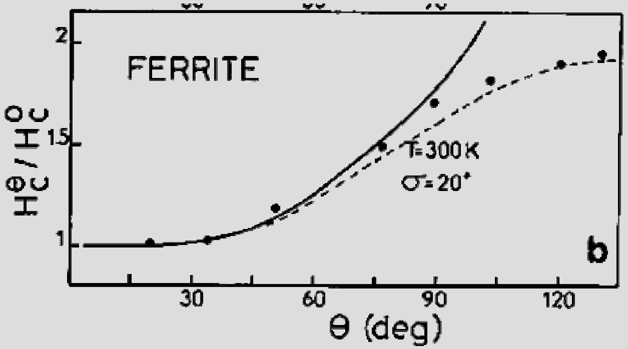
Hypothesis:



- ⇨ Based on nucleation volume
- ⇨ Hc<<Ha

Energy barrier E_0 overcome by gain in Zeeman energy plus thermal energy

$$E_0 = -\mu_0 M_s v_a H \cos(\theta_H) + 25 k_B T$$



D. Givord et al., JMMM72, 247 (1988)

Nucleation of new reversed domains

Fatuzzo/Labrune/Raquet model

$$dN = (N_0 - N)Rdt$$

$$\Rightarrow N = N_0\left[1 - \exp(-Rt)\right]$$

N: number of nucleated centers at time t

N_0: total number of possible nucleation centers

R: rate of nucleation

Radial expansion of existing domains

$$\sigma_n = \sigma - \sigma_c = (v_0^2/T)\left[t_0 + t\right]^2 - \pi r_c^2/T$$

$$A = \int_0^t \left(\frac{dN}{dt}\right)_s (\sigma_n)_{t-s} ds + \frac{\pi r_c^2}{T} N(t)$$

Growth of existing nuclei

New nuclei

R_c: radius of critical nucleus

T: total area of sample

V_0: speed of propagation of domain wall

E. Fatuzzo, Phys. Rev. 127, 1999 (1962)

Model: fraction area not yet reversed

$$B(t) = \exp\Big(-2k^2\big(1 - (Rt + k^{-1}) + \tfrac{1}{2}(Rt + k^{-1})^2 - e^{-Rt}(1 - k^{-1}) - \tfrac{1}{2}k^{-2}(1 - Rt)\big)\Big),$$

$k = v_0 / (R r_c)$

k is a measure of the importance of wall propagation versus nucleation events

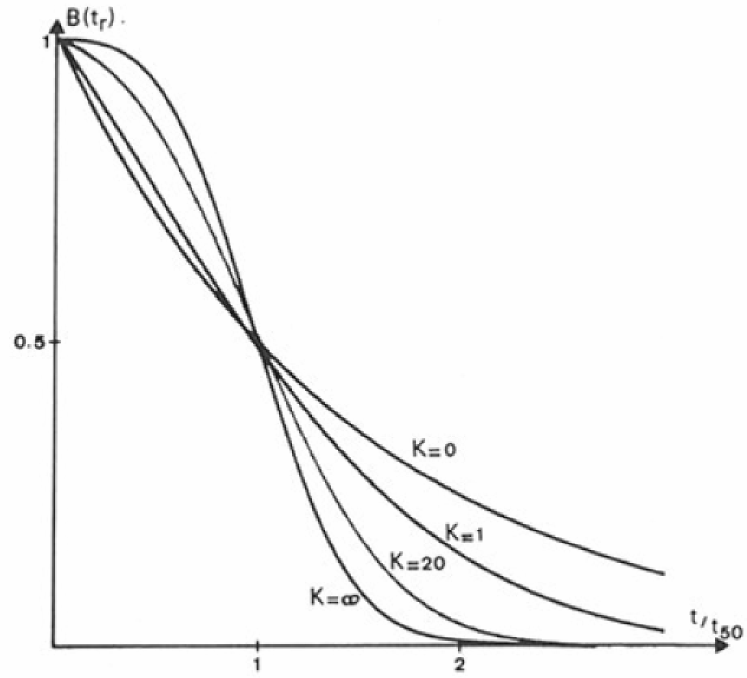


Fig. 6. Theoretical magnetization reversal curves (eq. (6)) for different values of the parameter k.

M. Labrune et al., J. Magn. Magn. Mater. 80, 211 (1989)
E. Fatuzzo, Phys. Rev. 127, 1999 (1962)

Depending on structural defects

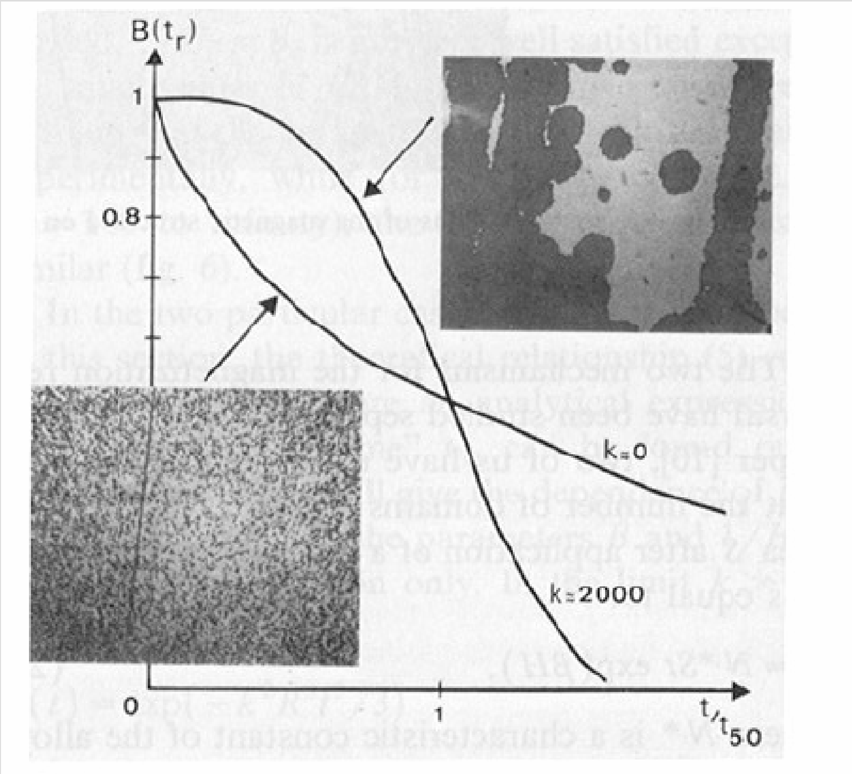
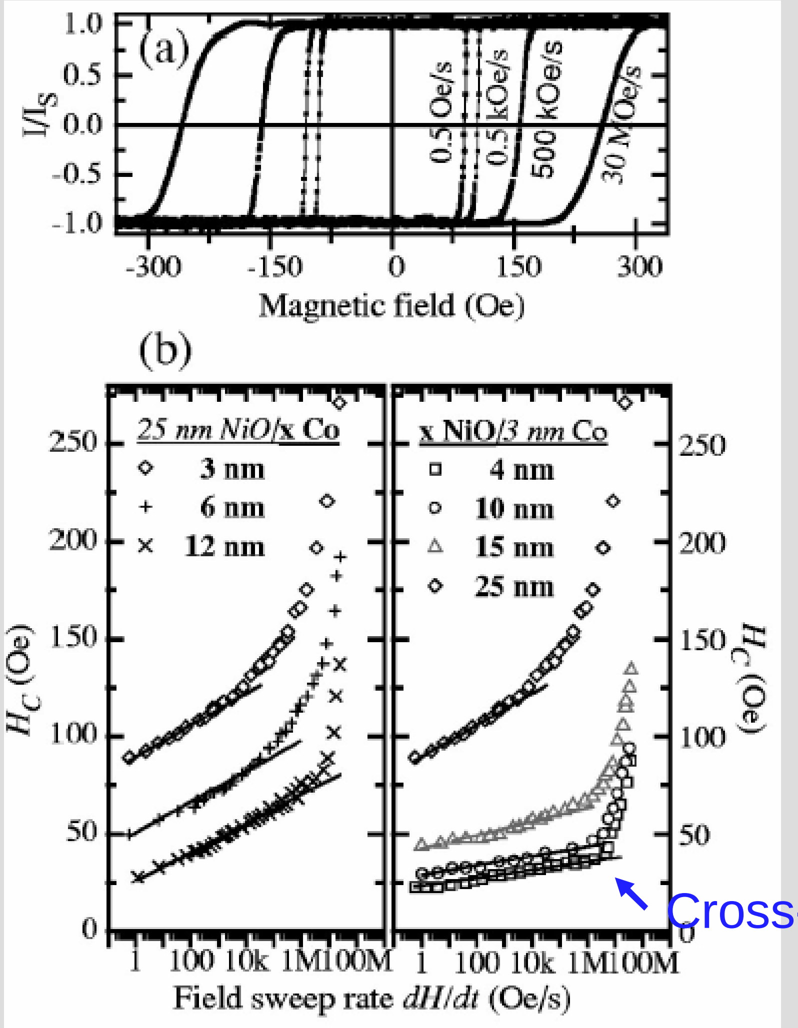


Fig. 4. Magnetization versus reduced time t_R for a GdFe sample ($k \simeq 2000$) and a TbCo one ($k \simeq 0$), corresponding domain structure observed by Kerr effect.

M. Labrune et al., J. Magn. Magn. Mater. 80, 211 (1989)

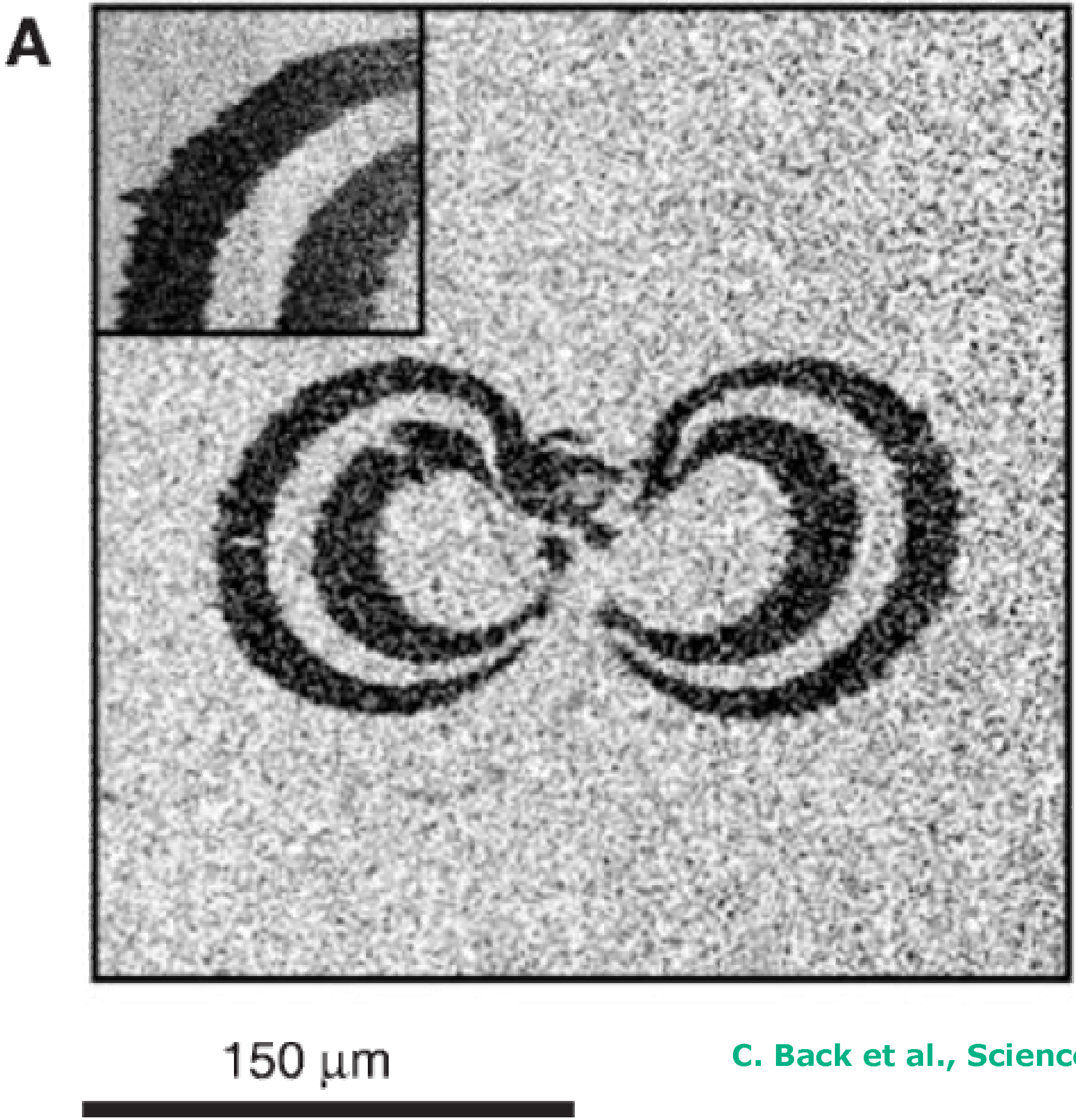
Depending on measurement dynamics



J. Camarero et al., PRB64, 172402 (2001)

Note also for fast propagation of domain walls: breakdown of propagation speed (Walker)

I.3. New ways for magnetization reversal



Electron beam of the SLAC,
pulse width 4.4ps,
sent on a Co film (20nm)
with uniaxial in-plane anisotropy

Magnetic domains imaged
after the impact
using SEMPA

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

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

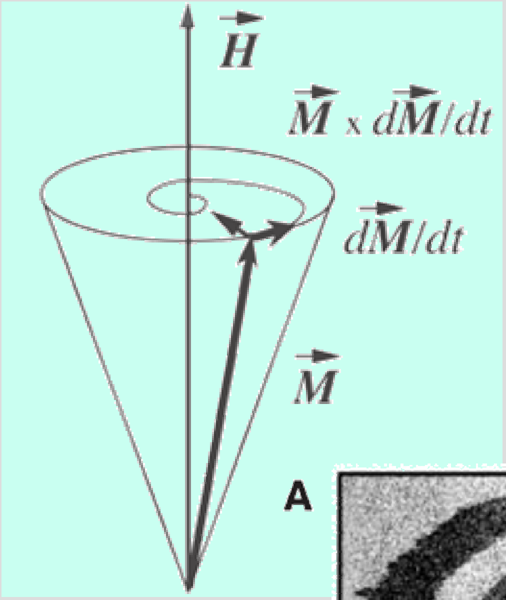
$$\gamma_0 = \mu_0 \gamma \qquad \gamma = \frac{gq}{2m}$$

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

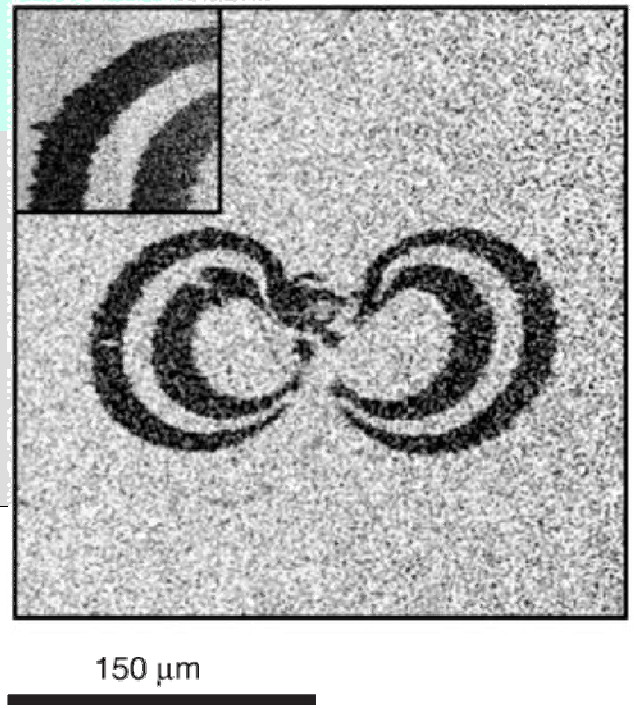
$\mathbf{H}_{eff}$ Effective field (including applied)

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

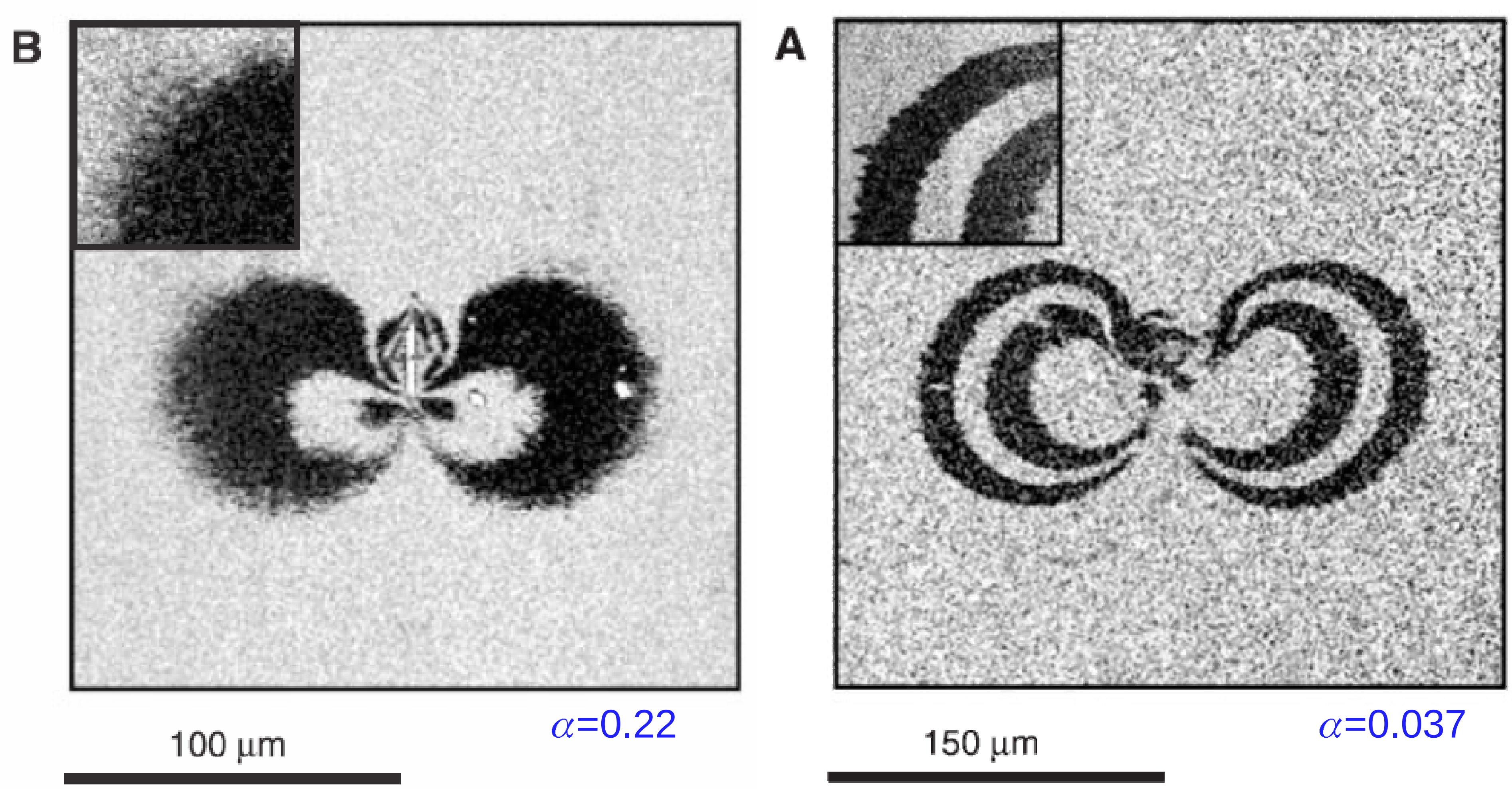
α Damping coefficient ($10^{-3} > 10^{-1}$)



A



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



α=0.22

α=0.037

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

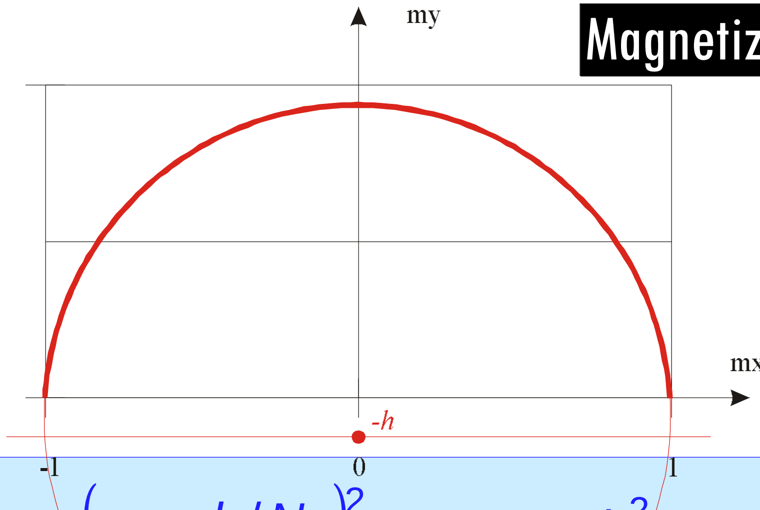
Using (2) ➡ $$m_x^2 = 1 - \frac{2h}{N_z + h_K} m_y - \frac{N_z}{N_z + h_K} m_y^2$$

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

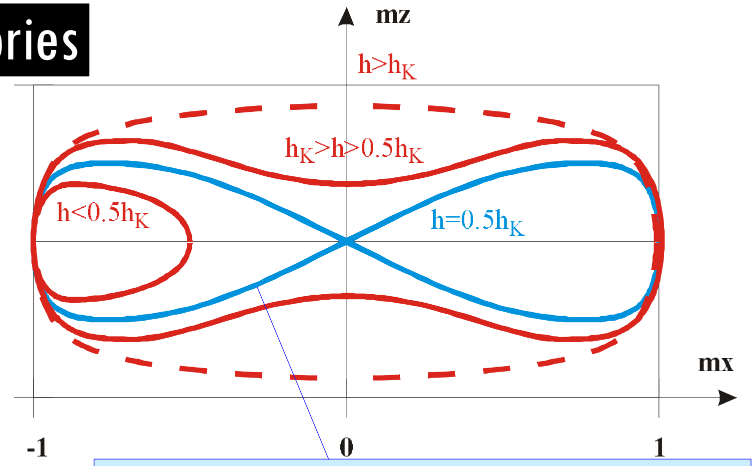
Using (2) ➡ $$m_z^2 = \frac{2h}{N_z + h_K} m_y - \frac{h_K}{N_z + h_K} m_y^2$$

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

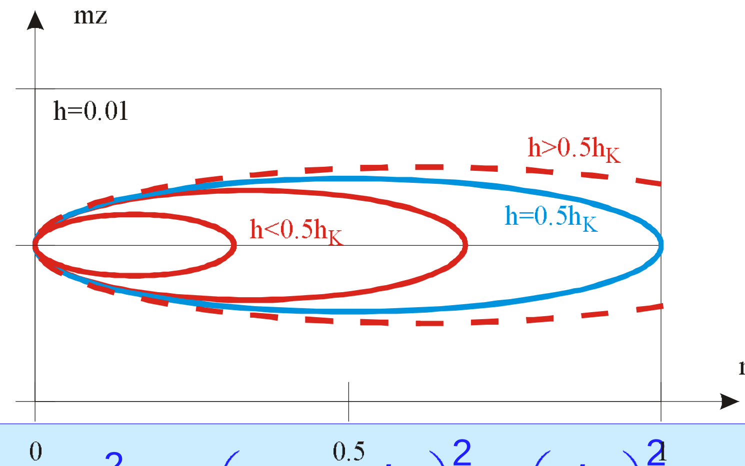
Magnetization trajectories



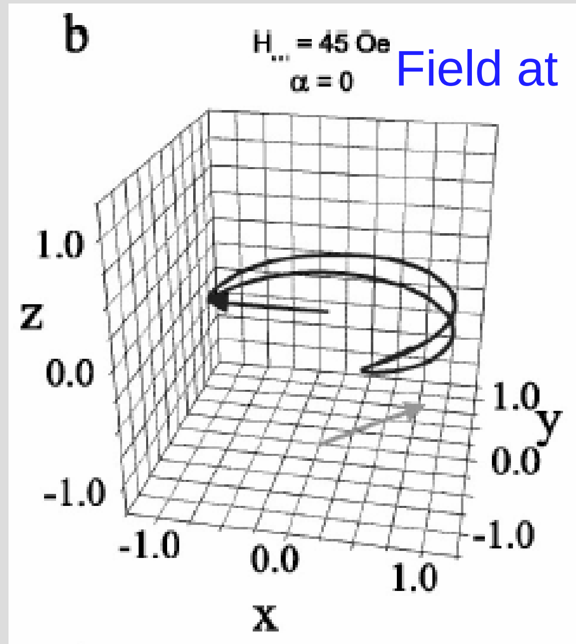
$$m_x^2 + \frac{(m_y + h/N_z)^2}{1+h_K/N_z} = 1 + \frac{h^2}{N_z(N_z+h_K)}$$



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



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



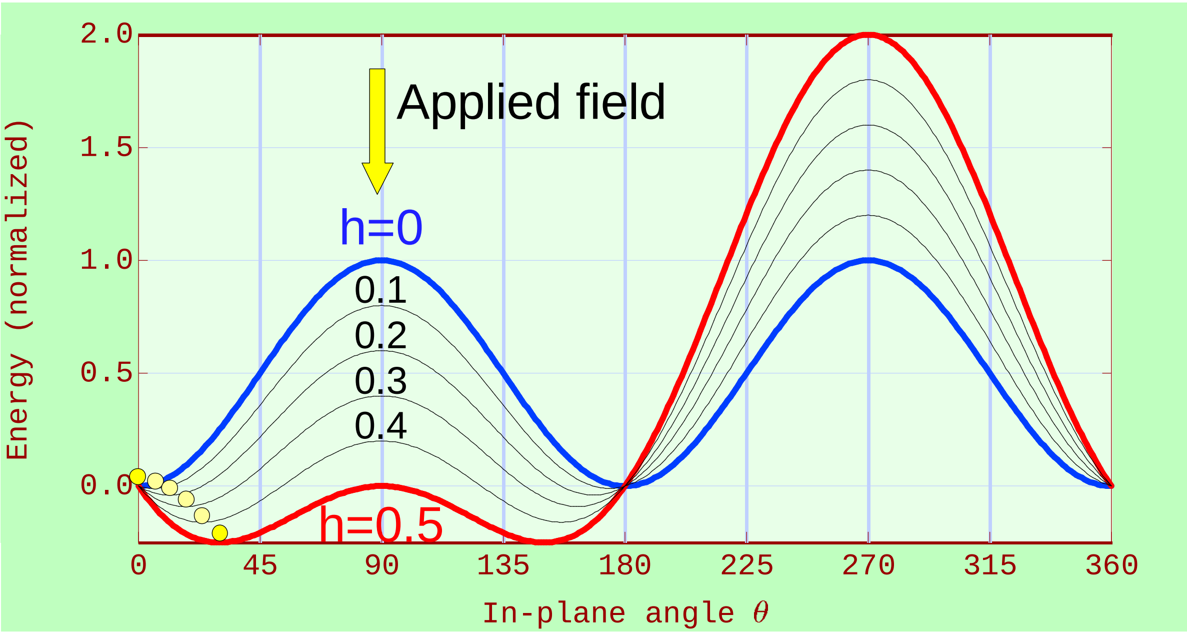
Field at 135°

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

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

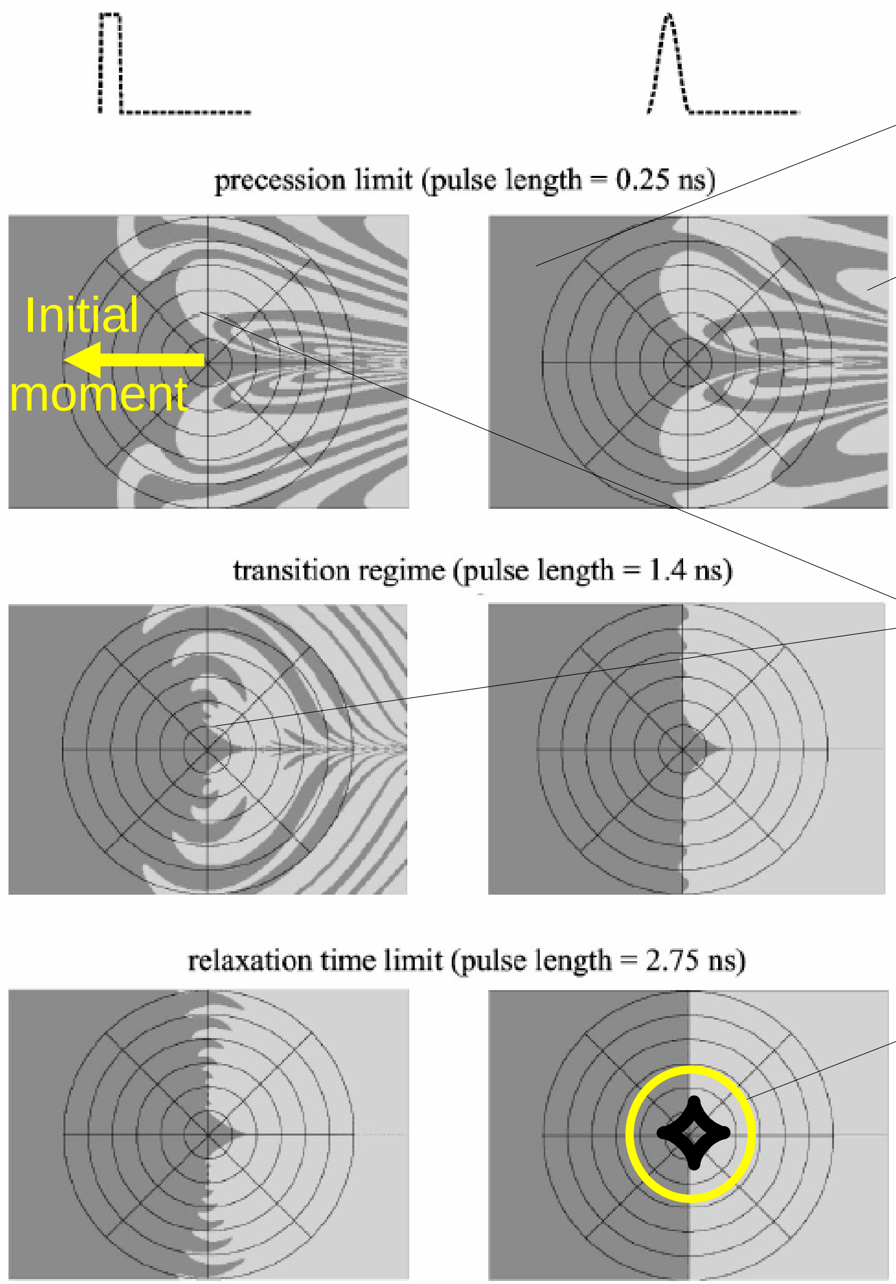
⇒ 25 – 500 ps

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



Non-switched

Switched

Reversal below the quasistatic value h=1 for hy, and even for m.h>0!

Stoner-Wohlfarth astroid

(quasistatic limit)

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

Conclusion on precessional switching

- Most efficient for field applied perpendicular to the easy axis
- Analytical or near-analytical descriptions
- Beyond the simple example given here: field pulse in one or several directions, finite damping, spin-valves etc.

Analytical models

C. Serpico et al., ***Analytical solutions of Landau–Lifshitz equation for precessional switching*****, J. Appl. Phys. 93, 6909 (2003)**

G. Bertotti et al., ***Comparison of analytical solutions of Landau–Lifshitz equation for ''damping'' and ''precessional'' switchings*****, J. APpl. Phys. 93, 6811 (2003)**

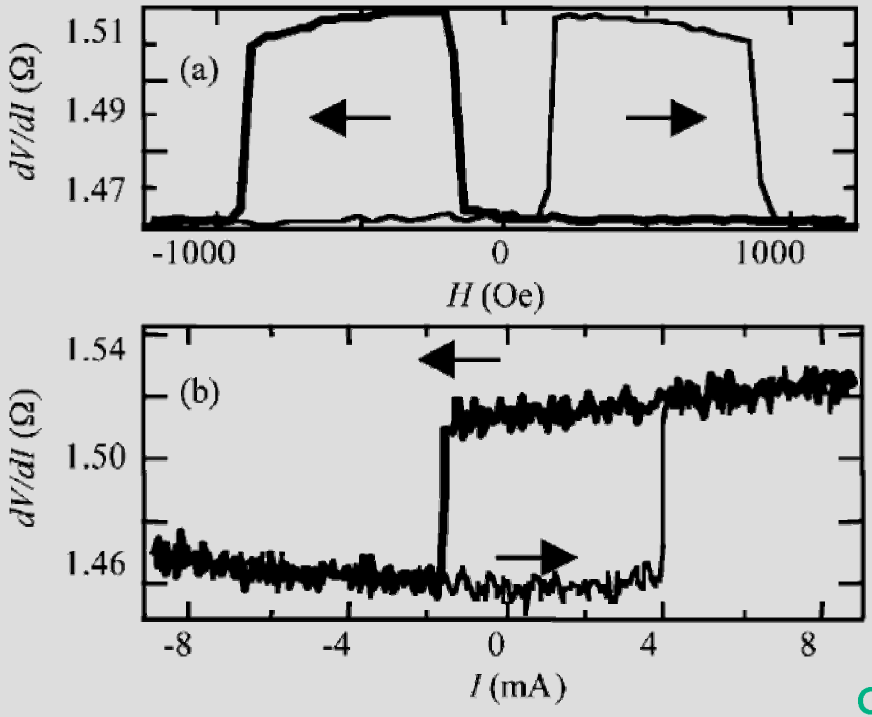
T. Devolder et aL, ***Precessional switching of thin nanomagnets: analytical study*****, Eur. Phys. J. B 36, 57–64 (2003)**

T. Devolder et aL, ***Spectral analysis of the precessional switching of the magnetization in an isotropic thin film*****, Sol. State Com. 129, 97 (2004)**

Basics

Can be viewed as the GMR-reversed effect

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



Conventionnal hysteresis loop

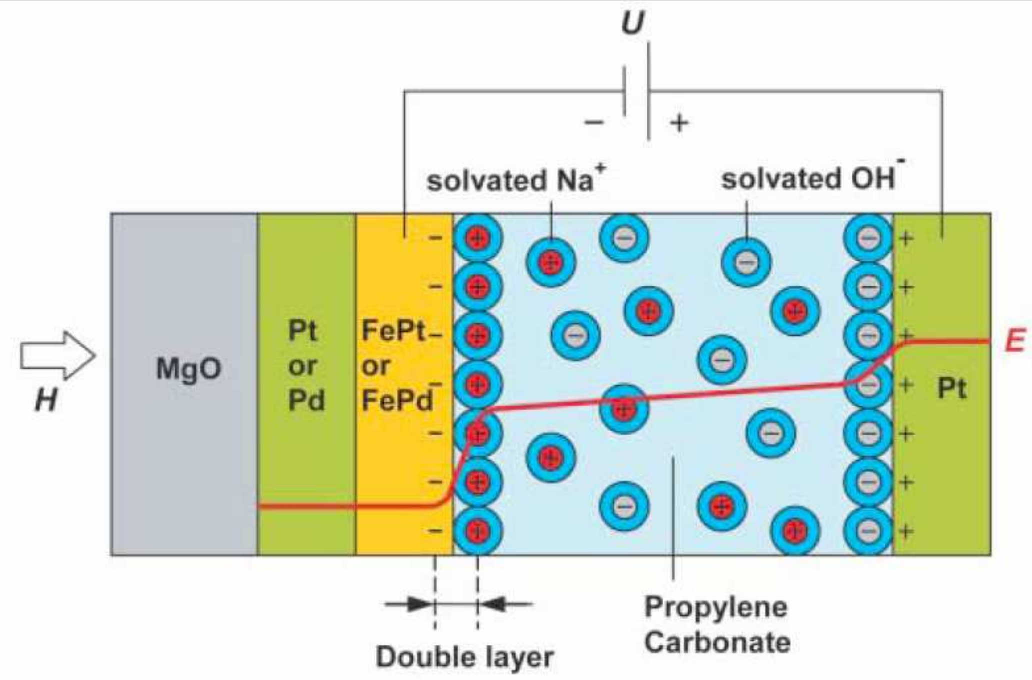
Current-induced magnetization reversal

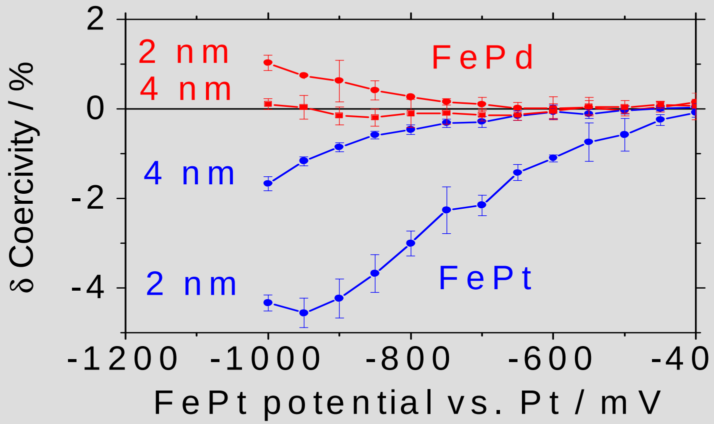
Group Myers et Ralph, Cornell University (2000)

Motivations

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

Electric modification of intrinsic properties





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

See also: magnetic semiconductors, multiferroics etc.

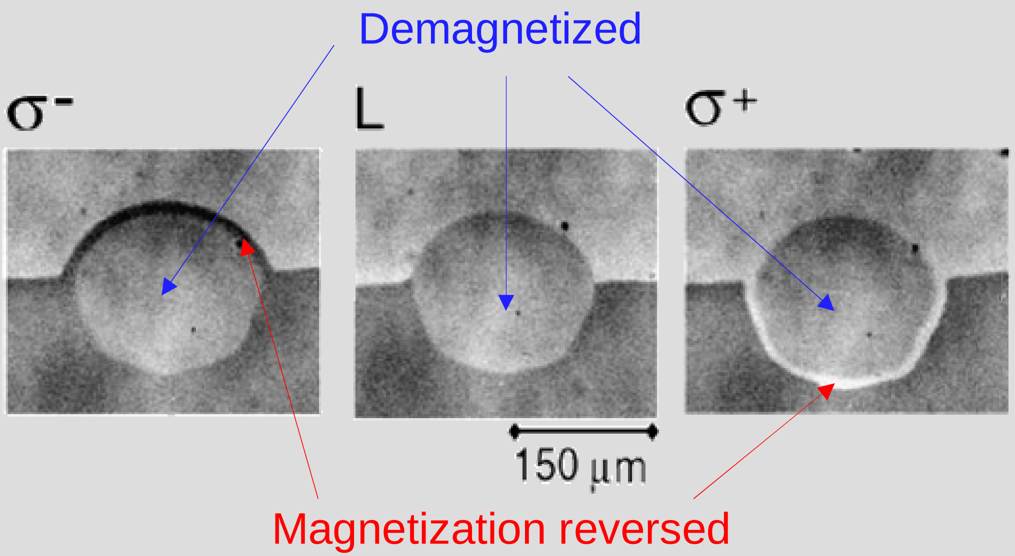
Principle

Combined heating
+ inverse Faraday effect

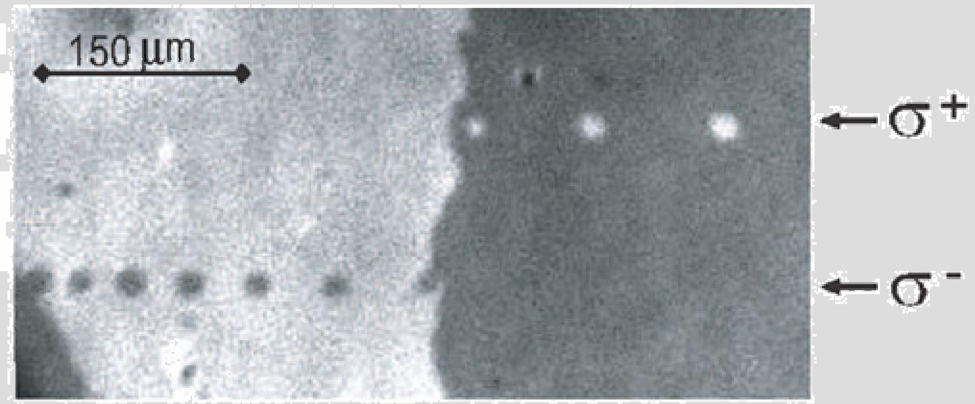
Magneto-optical material. Tc=500K
$Gd_{22}Fe_{74.6}Co_{3.4}$

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

Preliminary: one shot with large power



Local reversal with controlled power



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

SOME READING

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

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

[3] O. Fruchart, *Couches minces et nanostructures magnétiques*, Techniques de l'Ingénieur, E2-150-151 (2007)

[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)

[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).

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