# Magnetization reversal processes

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# Improving the slides

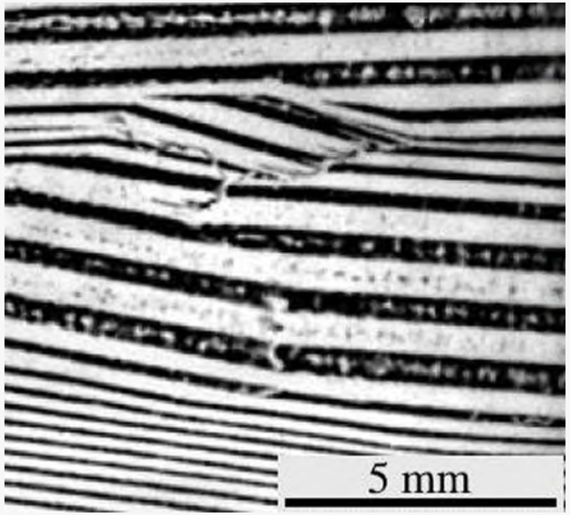
A volunteer to track my mistakes?

(Please)

# Motivation – Domains and domain walls

## Historical background

- **Puzzle from the early days** of magnetism: some materials may be magnetized under applied field, however "loose" their magnetization when the field is removed
- **Postulate from Weiss**: existence of magnetic domains, i.e., large (3D) regions with each uniform magnetization
- **Magnetic domain walls** are the narrow (2D: planes) regions separating neighboring domains

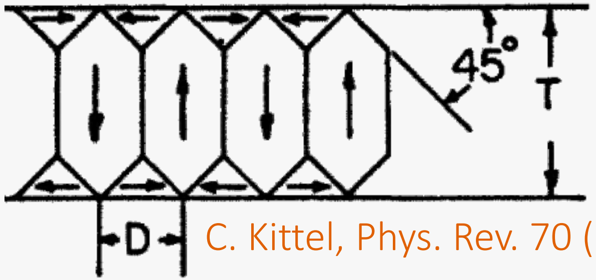



FeSi sheet (transformer)

A. Hubert, magnetic domains

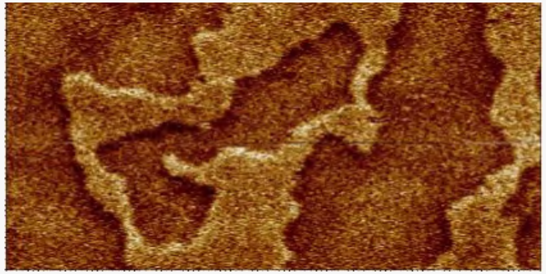
## Origin of domains

- **Minimization of energy:** closure of magnetic flux to decrease dipolar energy, at the expense of energy in the domain walls (exchange, anisotropy…)




C. Kittel, Phys. Rev. 70 (11&12), 965 (1946)

- **Magnetic history:** magnetic domains along various directions may form through the ordering transition or following a partial magnetization process, persisting even though leaving the system not in the ground state



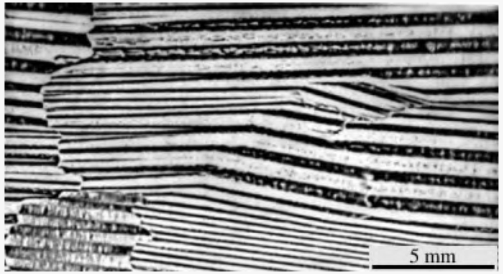
MgO\Co[1nm)\Pt

Magnetic Force Microscopy, 5 x 2.5 µm

# Motivation – Cross-over from domains to single-domain

### Bulk material

Numerous and complex shape of domains

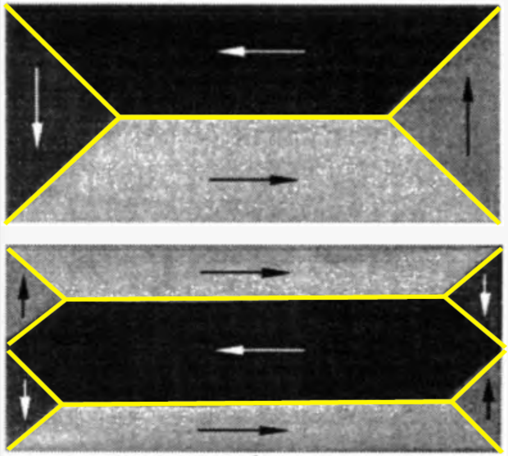



FeSi soft magnetic sheet

A. Hubert, Magnetic domains

### Mesoscopic scale

Small number of domains, simple shape

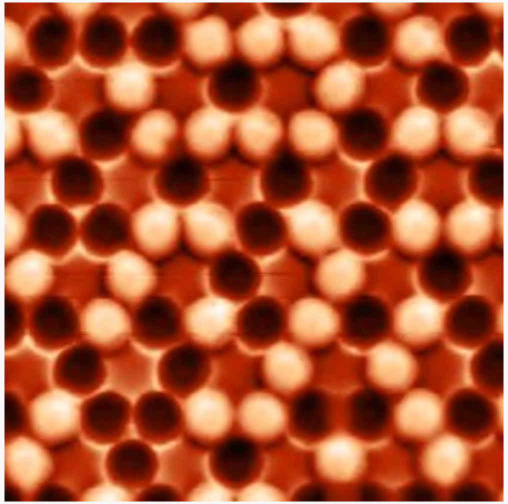


Microfabricated elements
Kerr microscopy

A. Hubert, Magnetic domains

### Nanoscopic scale

Magnetic single domain



Nanofabricated dots
MFM

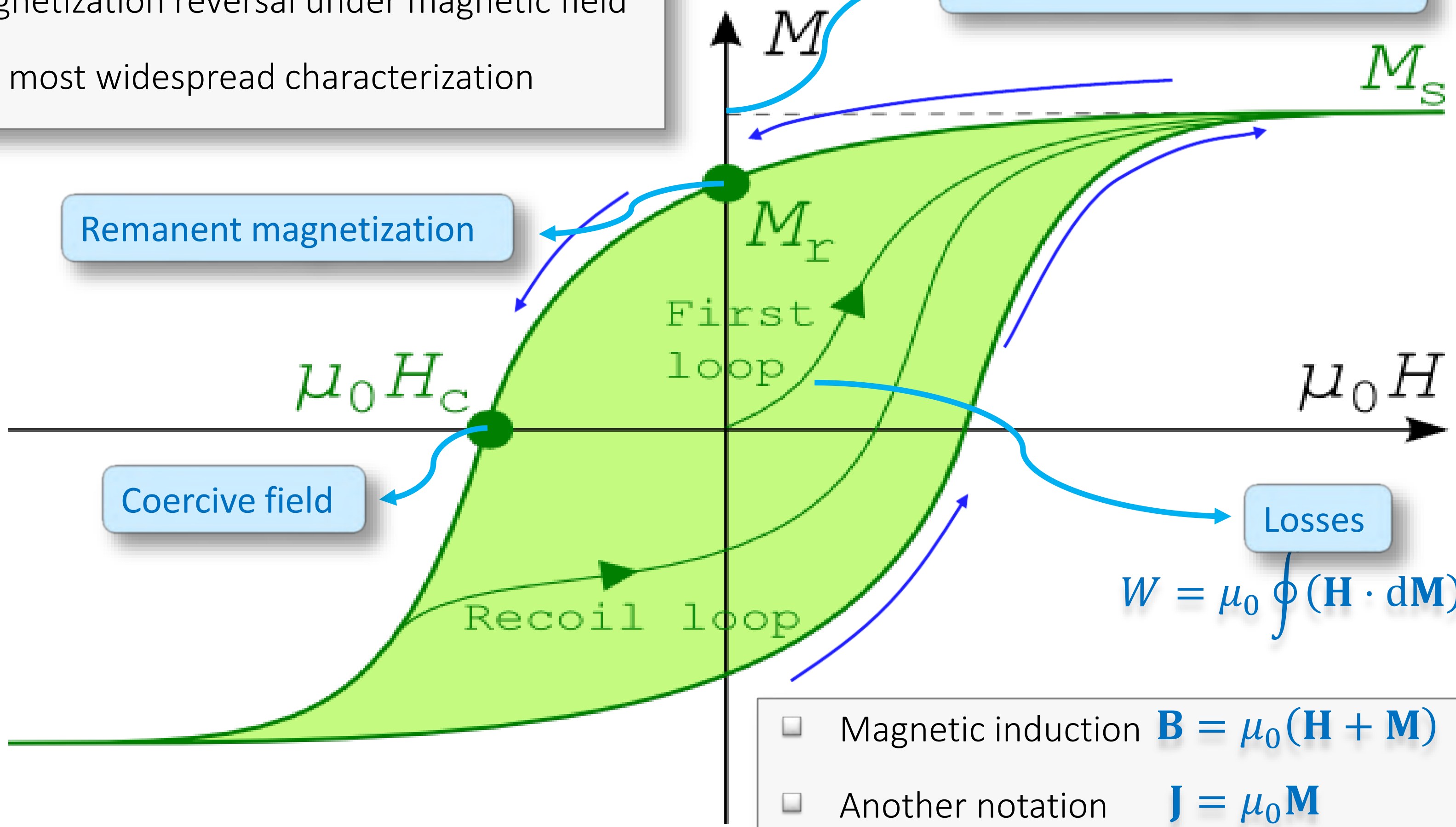
Sample courtesy:
I. Chioar, N.Rougemaille

- Nanomagnetism ≈ Mesomagnetism

### The hysteresis loop

- Magnetization reversal under magnetic field
- The most widespread characterization

Spontaneous ≠ Saturation



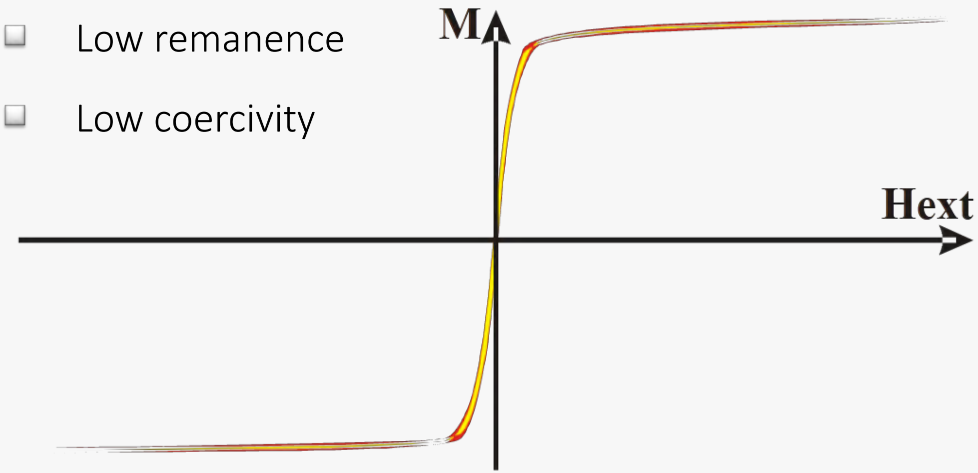

$W = \mu_0 \oint (\mathbf{H} \cdot \mathrm{d}\mathbf{M})$

- Magnetic induction $\mathbf{B} = \mu_0(\mathbf{H} + \mathbf{M})$
- Another notation $\mathbf{J} = \mu_0 \mathbf{M}$

# Motivation – The hysteresis loop

## Soft-magnetic materials

- Low remanence
- Low coercivity

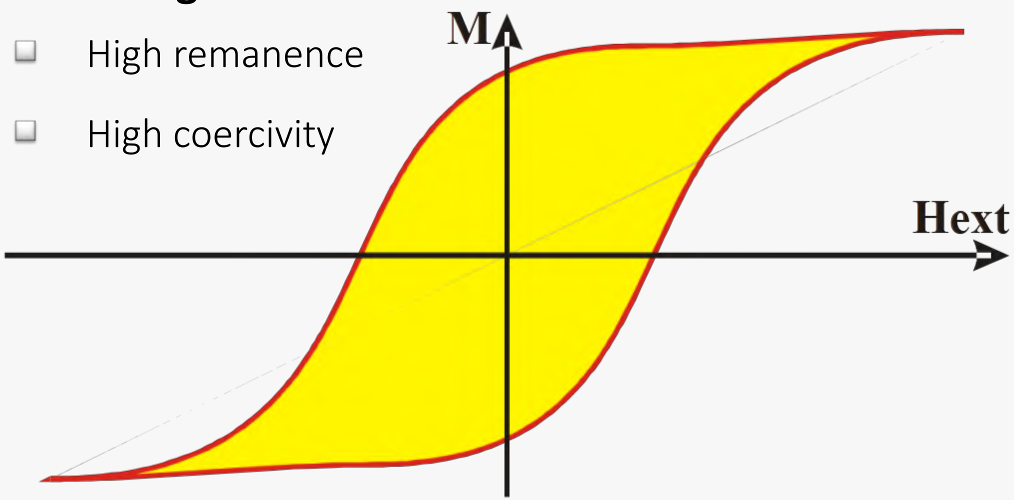



**Applications**

- Transformers
- Flux guides, sensors
- Magnetic shielding

## Hard-magnetic materials

- High remanence
- High coercivity




**Applications**

- Permanent magnets,
- Motors and generators
- Magnetic recording

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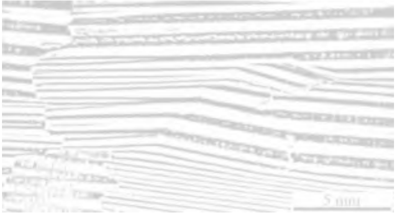
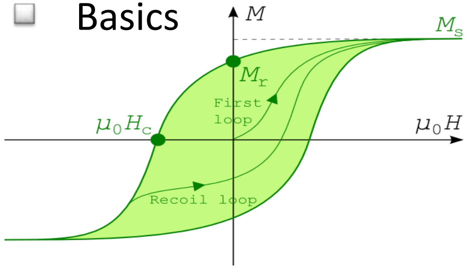
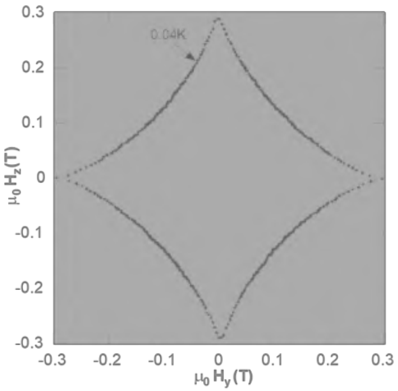
- Motivation



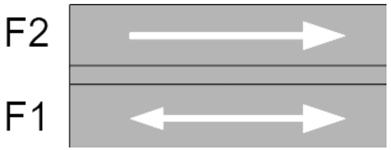
- Basics




- Macrospin switching

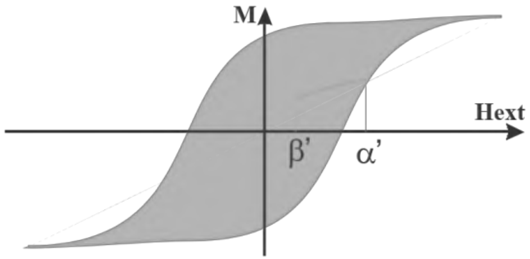



- Coupled systems




- Extended systems

- Learn from hysteresis loops



### Magnetization

Magnetization vector **M**

- Continuous function
- May vary over time and space
- **Modulus is constant and uniform** (hypothesis in micromagnetism)

$$\mathbf{M}(\mathbf{r}) = \begin{pmatrix} M_x \\ M_y \\ M_z \end{pmatrix} = M_s \begin{pmatrix} m_x \\ m_y \\ m_z \end{pmatrix}$$

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

Mean field approach is possible: $M_s = M_s(T)$

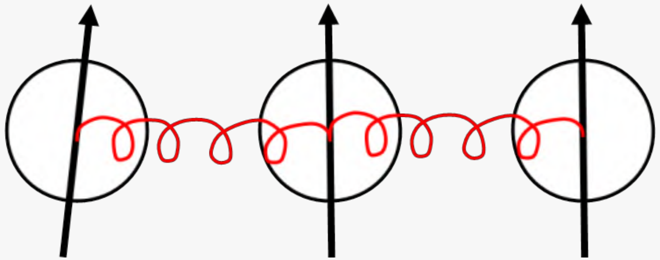
### Exchange interaction

- Atomistic view $\mathcal{E} = -\sum_{i \neq j} J_{i,j} \mathbf{S}_i \cdot \mathbf{S}_j$ (total energy, J)
- Micromagnetic view $\mathbf{S}_i \cdot \mathbf{S}_j = S^2 \cos(\theta_{i,j}) \approx S^2 \left(1 - \frac{\theta_{i,j}^2}{2}\right)$

$$E_{\mathrm{ex}} = A(\nabla \cdot \mathrm{m})^2 = A \sum_{i,j} \left(\frac{\partial m_i}{\partial x_j}\right)^2$$

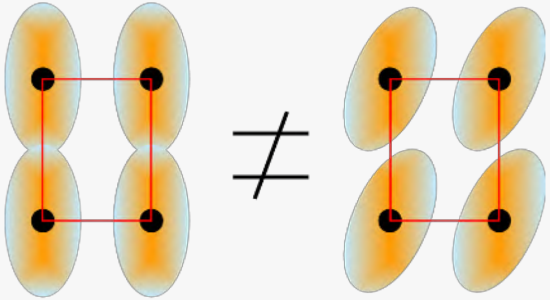
# Basics – The various types of magnetic energy

## Exchange energy



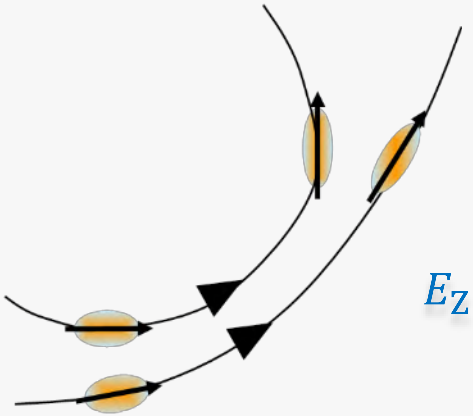
$$E_{\mathrm{ex}} = A(\nabla \cdot \mathrm{m})^2 = A\sum_{i,j}\left(\frac{\partial m_i}{\partial x_j}\right)^2$$

## Magnetocrystalline anisotropy energy



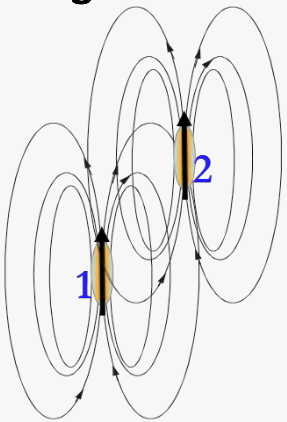
$$E_{\mathrm{mc}} = K\ f(\theta, \varphi)$$

## Zeeman energy (→ enthalpy)



$$E_{\mathrm{Z}} = -\mu_0 \mathbf{M}.\mathbf{H}$$

## Magnetostatic energy




$$E_{\mathrm{d}} = -\frac{1}{2}\mu_0 \mathbf{M} \cdot \mathbf{H}_{\mathrm{d}}$$

## The dipolar exchange length

When: anisotropy and exchange compete

$$E = A\left(\frac{\partial m_i}{\partial x_j}\right)^2 + K_\mathrm{d}\sin^2\theta$$

Exchange: $\mathrm{J/m}$

Dipolar: $\mathrm{J/m^3}$

$$K_\mathrm{d} = \frac{1}{2}\mu_0 M_\mathrm{s}^2$$

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

$$\Delta_\mathrm{d} \simeq 3 - 10\ \mathrm{nm}$$

Critical single-domain size, relevant for small particles made of soft magnetic materials

Often called: exchange length

## The anisotropy exchange length

When: anisotropy and exchange compete

$$E = A\left(\frac{\partial m_i}{\partial x_j}\right)^2 + K\sin^2\theta$$

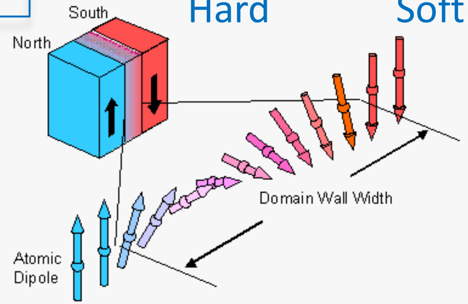
Exchange: $\mathrm{J/m}$

Anisotropy: $\mathrm{J/m^3}$

$$\Delta_\mathrm{u} = \sqrt{A/K}$$

$$\Delta_\mathrm{u} \simeq 1\ \mathrm{nm} \rightarrow 100\ \mathrm{nm}$$

Hard → Soft



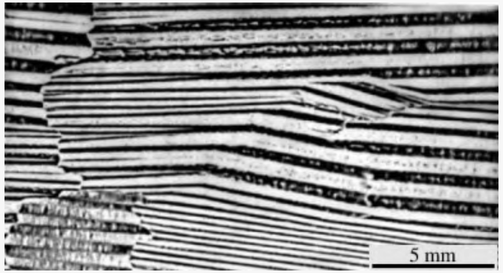

Sometimes called: Bloch parameter, or wall width

**Note:** Other length scales can be defined, e.g. with magnetic field

# Basics – Understand the smallest/simplest to the largest

## Bulk material

Numerous and complex shape of domains

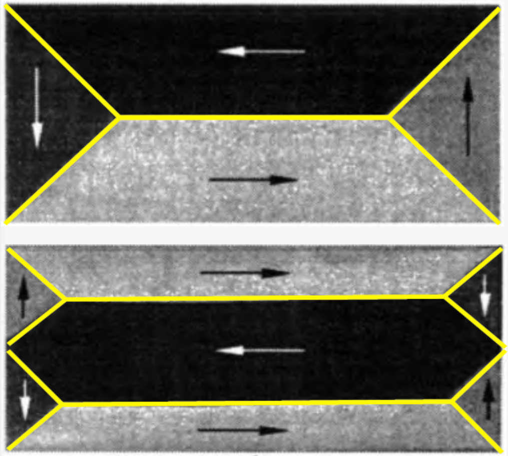



FeSi soft magnetic sheet

A. Hubert, Magnetic domains

## Mesoscopic scale

Small number of domains, simple shape



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Kerr microscopy

A. Hubert, Magnetic domains

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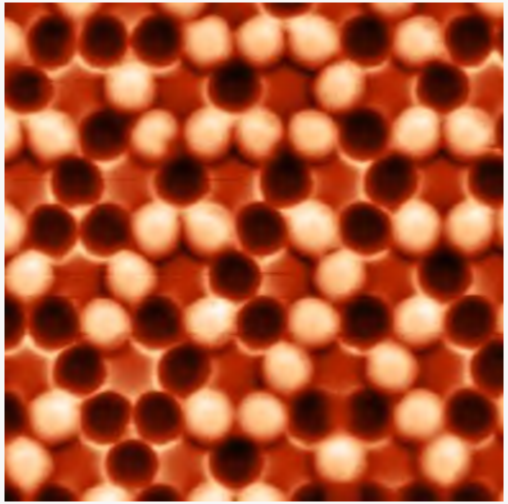
Magnetic single domain



Nanofabricated dots
MFM

Sample courtesy:
I. Chioar, N.Rougemaille

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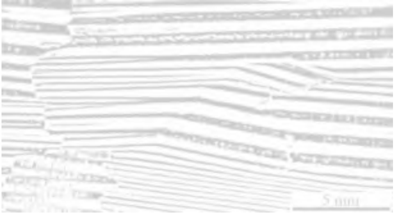

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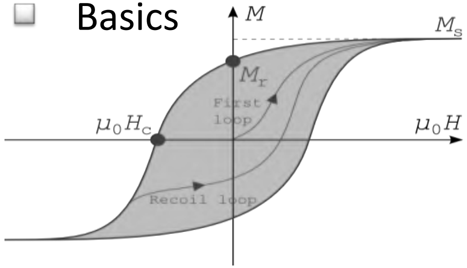


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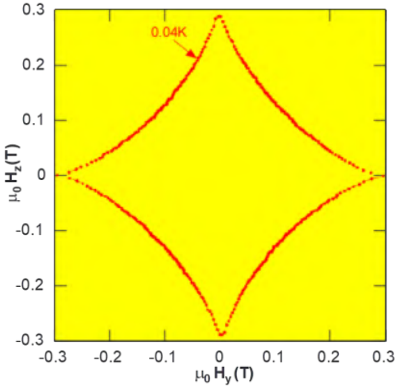


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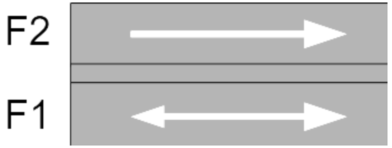
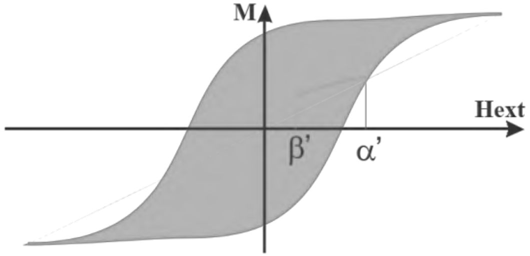



- Extended systems

- Learn from hysteresis loops



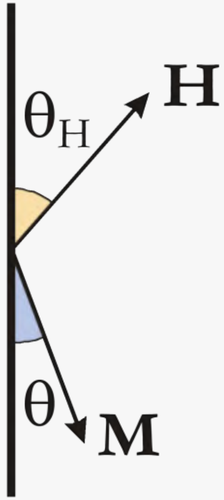
**Framework: uniform magnetization**

- Drastic, unsuitable in most cases
- Remember: demagnetization field may not be uniform

$$\mathcal{E} = E\mathcal{V}$$

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

- Anisotropy: $K_{\mathrm{eff}} = K_{\mathrm{mc}} + (\Delta N)K_{\mathrm{d}}$




**Names used**

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

**Dimensionless units**

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

$$e = \mathcal{E}/(K\mathcal{V})$$

$$h = H/H_{\mathrm{a}}$$

$$H_{\mathrm{a}} = 2K/(\mu_0 M_s)$$


L. Néel, Compte rendu Acad. Sciences 224, 1550 (1947)

E. C. Stoner and E. P. Wohlfarth,
Phil. Trans. Royal. Soc. London A240, 599 (1948)
Reprint: IEEE Trans. Magn. 27(4), 3469 (1991)

Example: $\theta_H = \pi$ → $e = \sin^2\theta + 2h\cos\theta$

**Equilibrium positions**

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

$\cos\theta_\mathrm{m} = h$

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

**Stability**

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

$\partial_{\theta\theta} e(0) = 2(1-h)$

$\partial_{\theta\theta} e(\theta_\mathrm{m}) = 2(h^2-1)$

$\partial_{\theta\theta} e(\pi) = 2(1+h)$

**Switching field**

- Vanishing of local minimum
- Is abrupt

$h_\mathrm{sw} = 1$

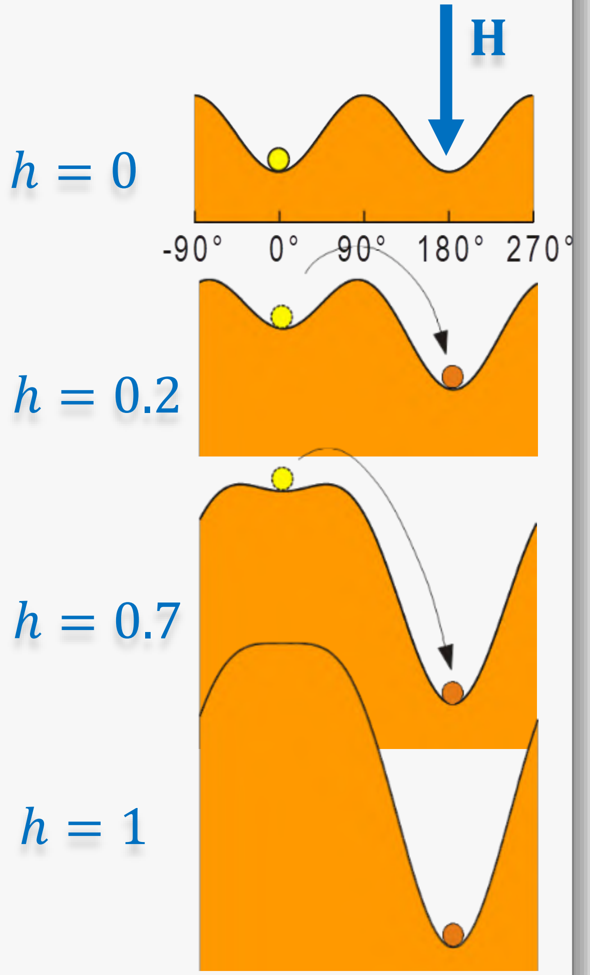
→ $H = H_\mathrm{a} = 2K/(\mu_0 M_\mathrm{s})$

**Energy barrier**

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

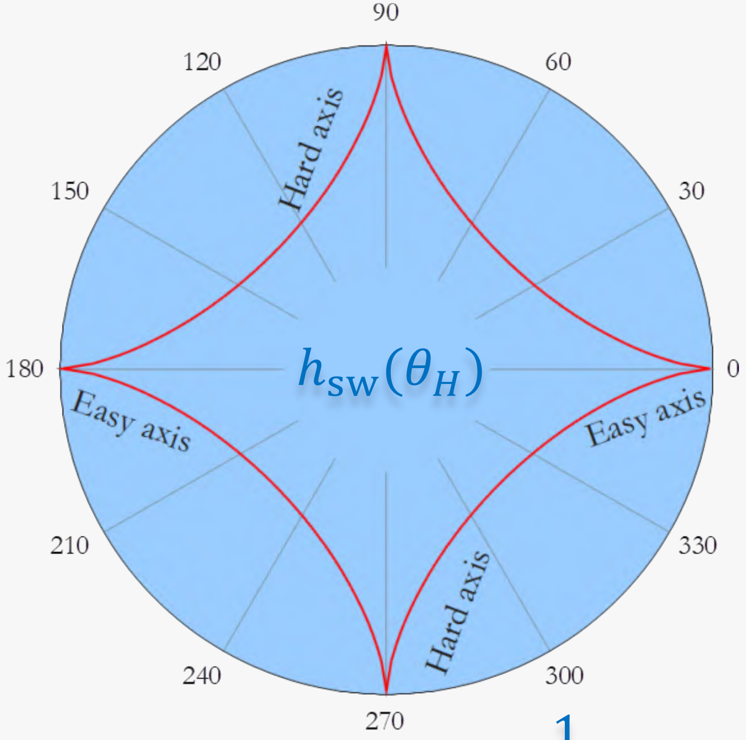
$\Delta e \sim (1-h)^{1.5}$ In general (breaking of symmetry)

**Energy landscape**



# Macrospins – The Stoner-Wohlfarth model

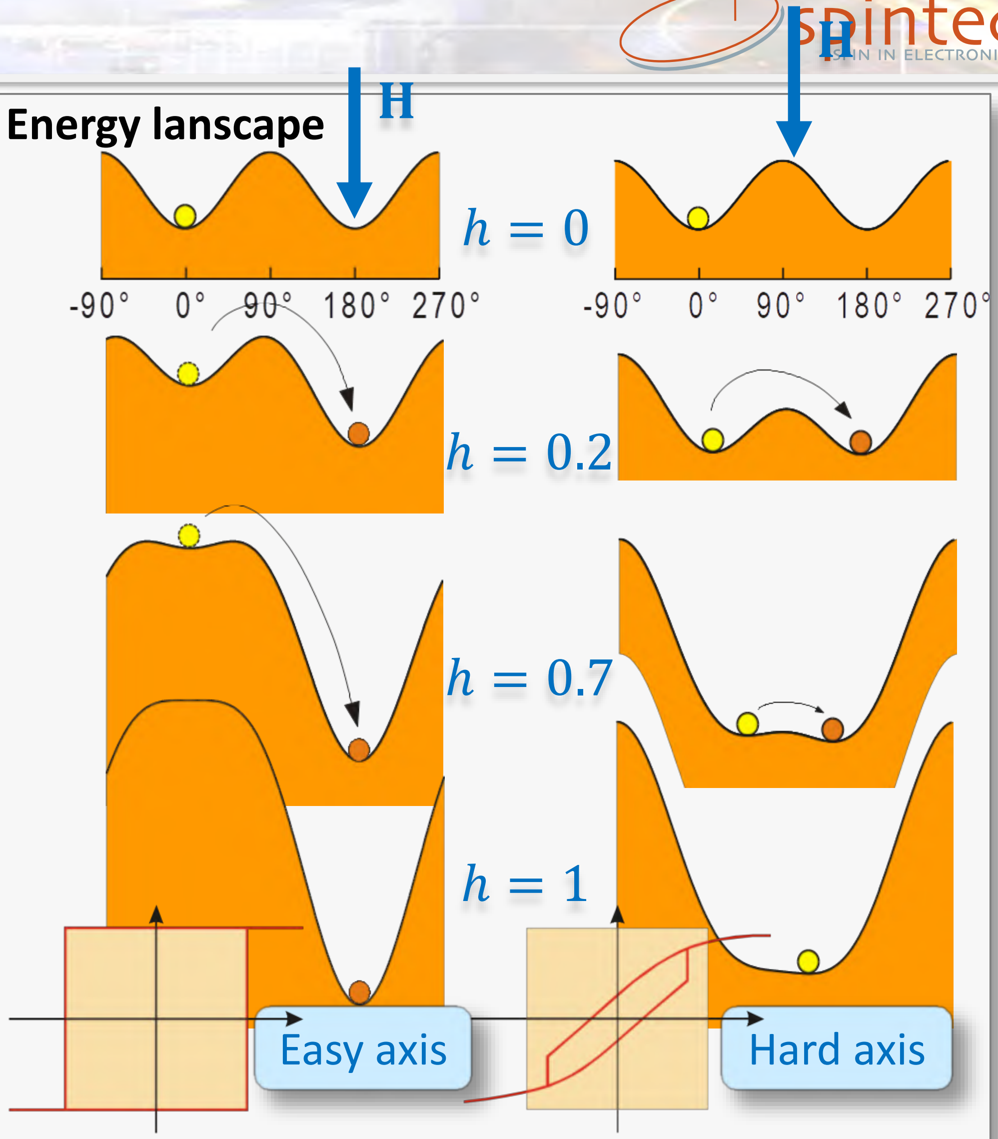
## Stoner-Wohlfarth astroid: switching field




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

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

## Energy lanscape



# Macrospins – Switching vs coercive field

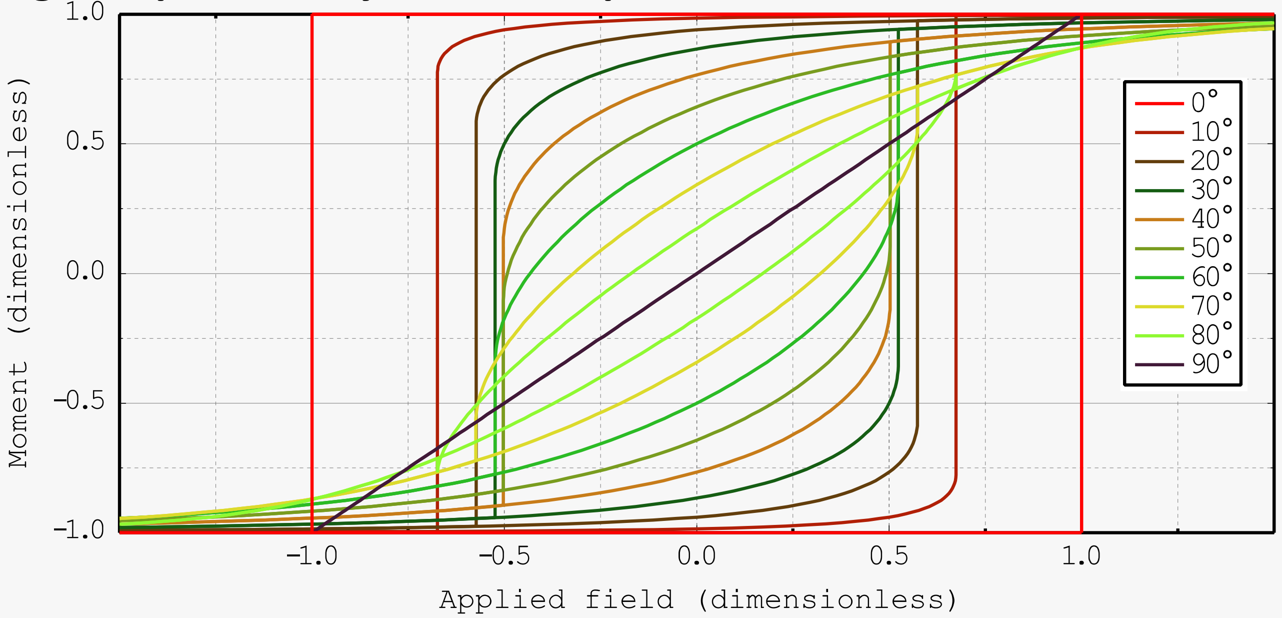
### Switching field $H_{sw}$

- A value of field at which an irreversible (abrupt) jump of magnetization angle occurs.
- Can be measured only in single particles.

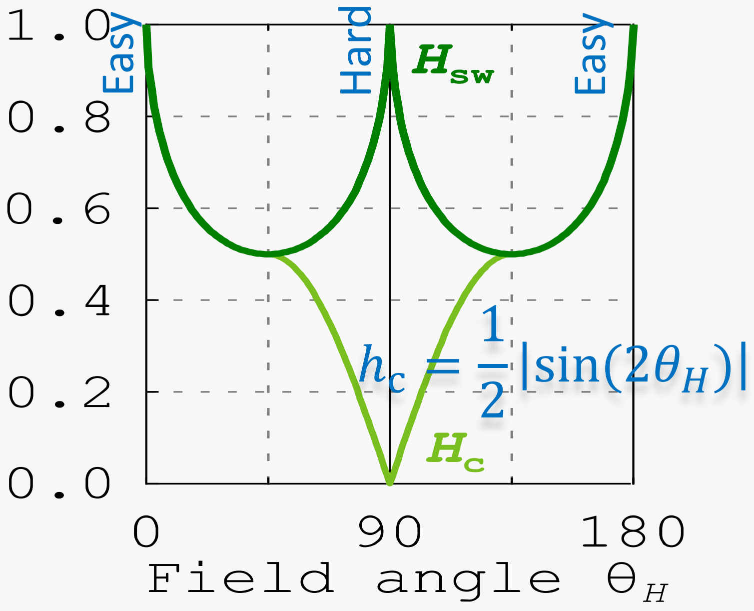
### Coercive field $H_c$

- The field at which $\mathbf{H} \cdot \mathbf{M} = 0$
- Measurable in materials (large number of 'particles').
- May or may not be a measure of the mean switching field at the microscopic level

### Angle-dependent hysteresis loops

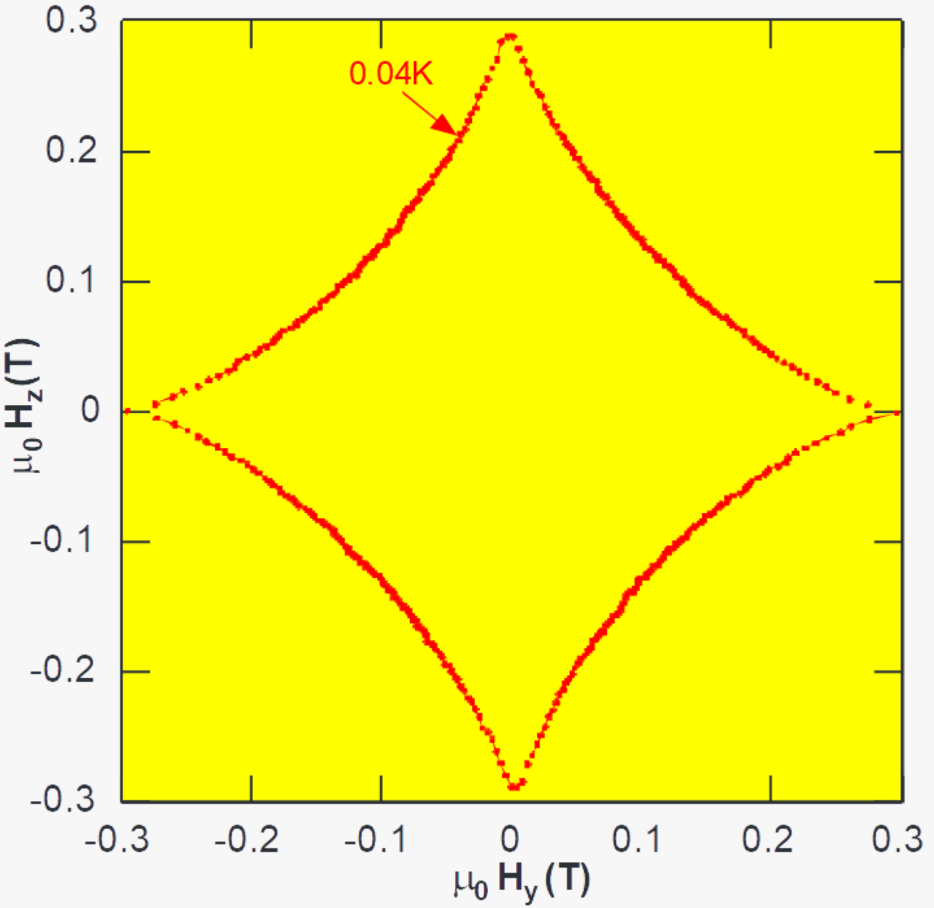



### Switching versus coercive field

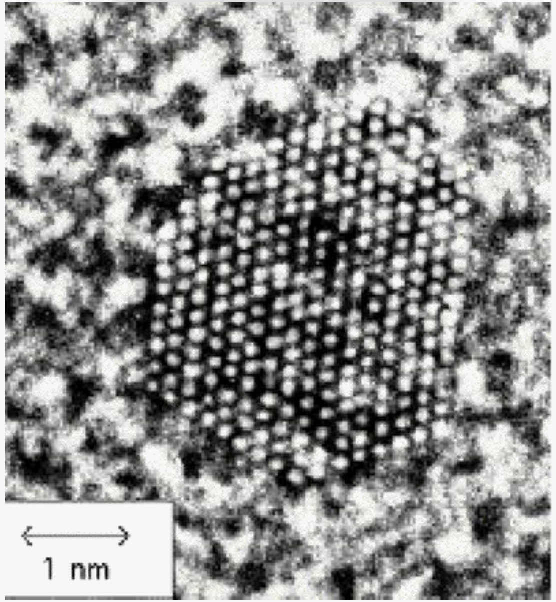


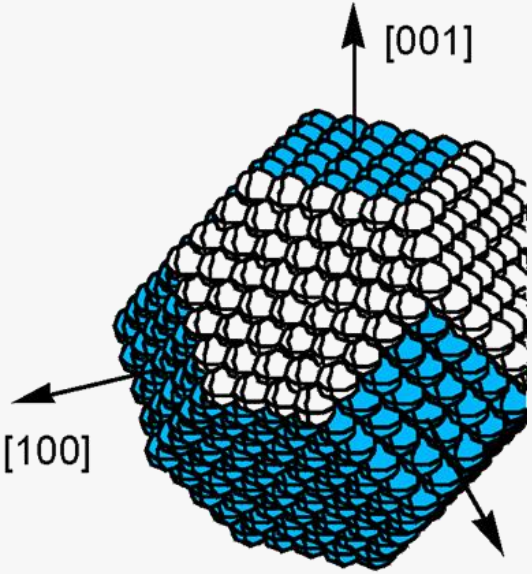
# Macrospins – Experiments

## First experimental evidence




Co cluster

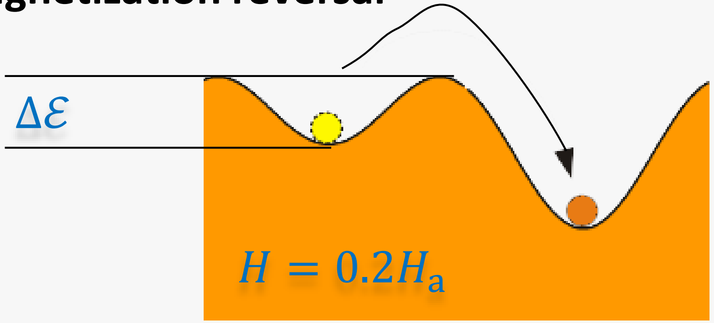



W. Wernsdorfer et al., Phys. Rev. Lett. 78, 1791 (1997)

# Macrospins – The blocking temperature

## Energy barrier preventing magnetization reversal




$$\Delta\mathcal{E} = K\mathcal{V}\left(1 - \frac{H}{H_a}\right)^2$$

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)

## Thermal activation

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

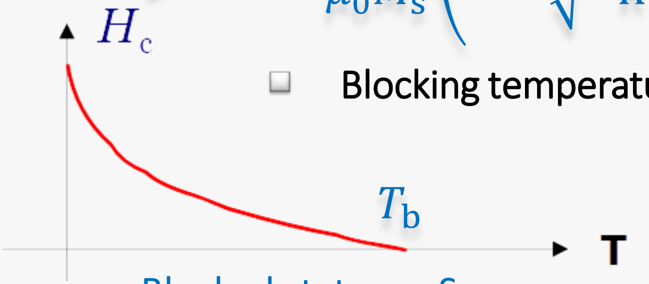
- **Waiting time** (Arrhenius law) $\tau = \tau_0 \exp\left(\frac{\Delta\mathcal{E}}{k_B T}\right)$

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

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

  ➔ $H_c = \frac{2K}{\mu_0 M_s}\left(1 - \sqrt{\frac{25 k_B T}{K\mathcal{V}}}\right)$

- Blocking temperature: $T_b \approx \frac{K\mathcal{V}}{25 k_B}$




Blocked state Superparamagnetic state

- Coercivity and remanence are lost at small size
- Incentive to enhance magnetic anisotropy

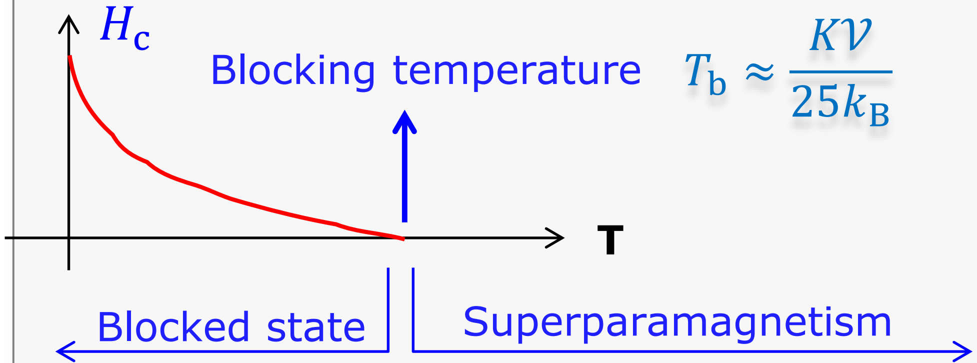
**The case of magnetic recording or memory**

Stability factor

$\tau \approx 10^9\ \mathrm{s}$ ➔ $\Delta = \Delta\mathcal{E}/k_B T \approx 40 - 60$

**Superparamagnetism**

Thermally-induced loss of all coercivity

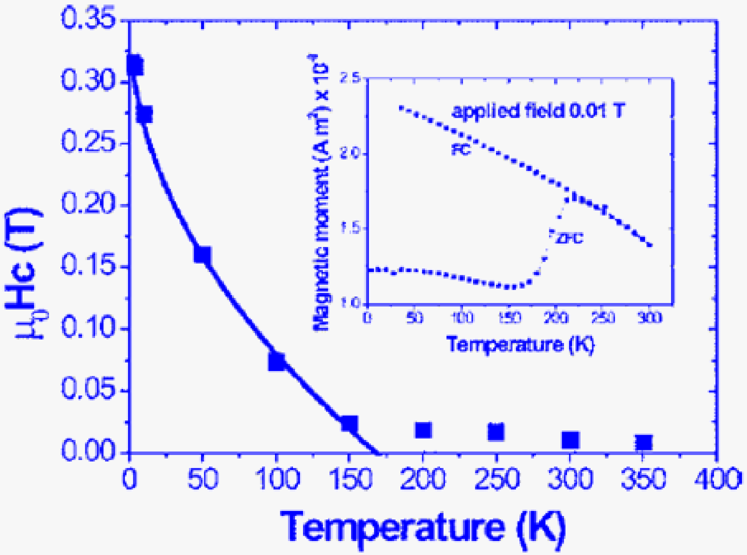



Blocking temperature $T_b \approx \frac{KV}{25 k_B}$

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

Exemple

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



spintec
SPIN IN ELECTRONICS

## Superparamagnetism – Formalism

- Energy

$$\mathcal{E} = KVf(\theta,\phi) - \mu_0\,\boldsymbol{\mu}\cdot\mathbf{H}$$

- Partition function

$$Z = \sum \exp(-\beta\mathcal{E})$$

- Average moment

$$\langle\mu\rangle = \frac{1}{\beta\mu_0 Z}\frac{\partial Z}{\partial H}$$

## Isotropic case

$$Z = \int_{-\mathcal{M}}^{\mathcal{M}} \exp(\beta\mu_0\mu H)\,\mathrm{d}\mu$$

$$\Rightarrow \langle\mu\rangle = \mathcal{M}\left[\coth\left(x - \frac{1}{x}\right)\right]$$

Langevin function

Consider total moment, not with spin ½

$$x = \beta\mu_0\mathcal{M}H$$

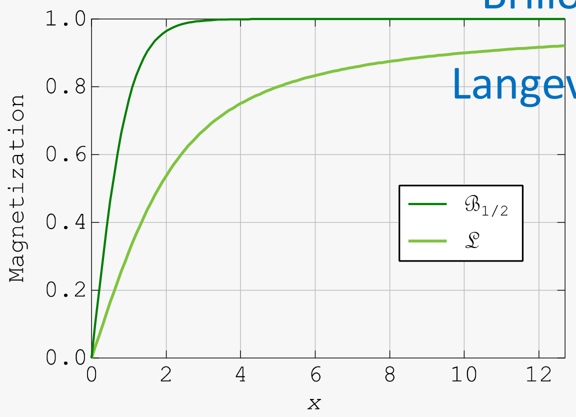
## Infinite anisotropy

$$Z = \exp(\beta\mu_0\mathcal{M}H) + \exp(-\beta\mu_0\mathcal{M}H)$$

$$\Rightarrow \langle\mu\rangle = \mathcal{M}\,\mathrm{th}(x)$$

Brillouin ½ function

## Langevin versus Brillouin




- Fit M(H) to extract moment (and hence volume) of nanoparticles
- Beware of anisotropy strength and distribution in fits !

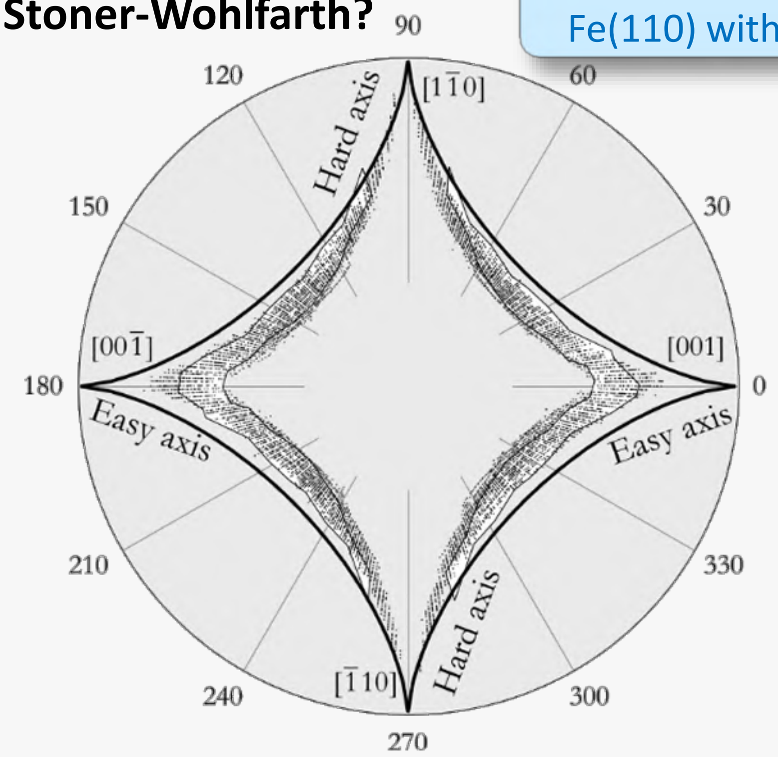
REVIEW : S. Bedanta & W. Kleemann, Supermagnetism, J. Phys. D: Appl. Phys., 013001 (2009)

# Macrospins – Ground-state macrospin does not imply coherent reversal

spintec SPIN IN ELECTRONICS

## Stoner-Wohlfarth?

1nm-thick 200nm dots Fe(110) with IP magn.

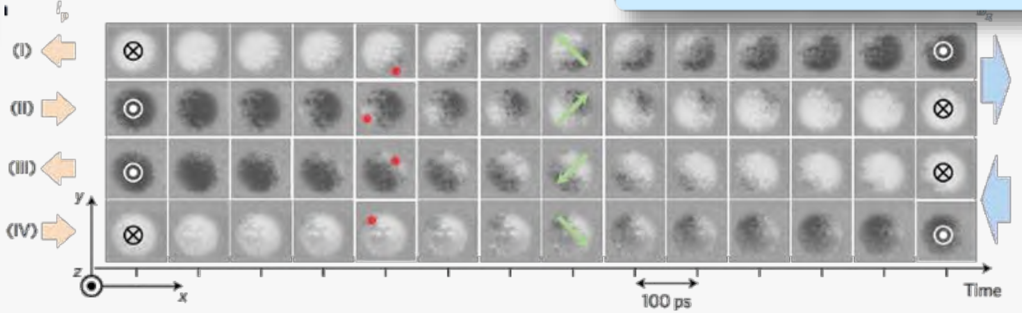



- Flavor of Stoner-Wohlfarth asteroid
- Temperature- and time-dependent measurements reveals incoherent reversal: $v_n \ll V$

O. Fruchart et al., Phys. Rev. Lett. 82, 1305 (1999)

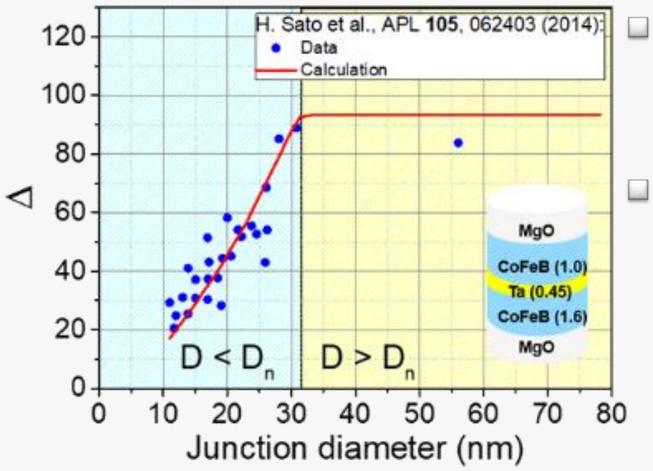
## Time-resolved measurements

500nm disks Co 1nm-thick




M. Baumgartner et al., Nat. Nanotech. 12, 980 (2017)

## Stability of Magnetic Tunnel Junctions



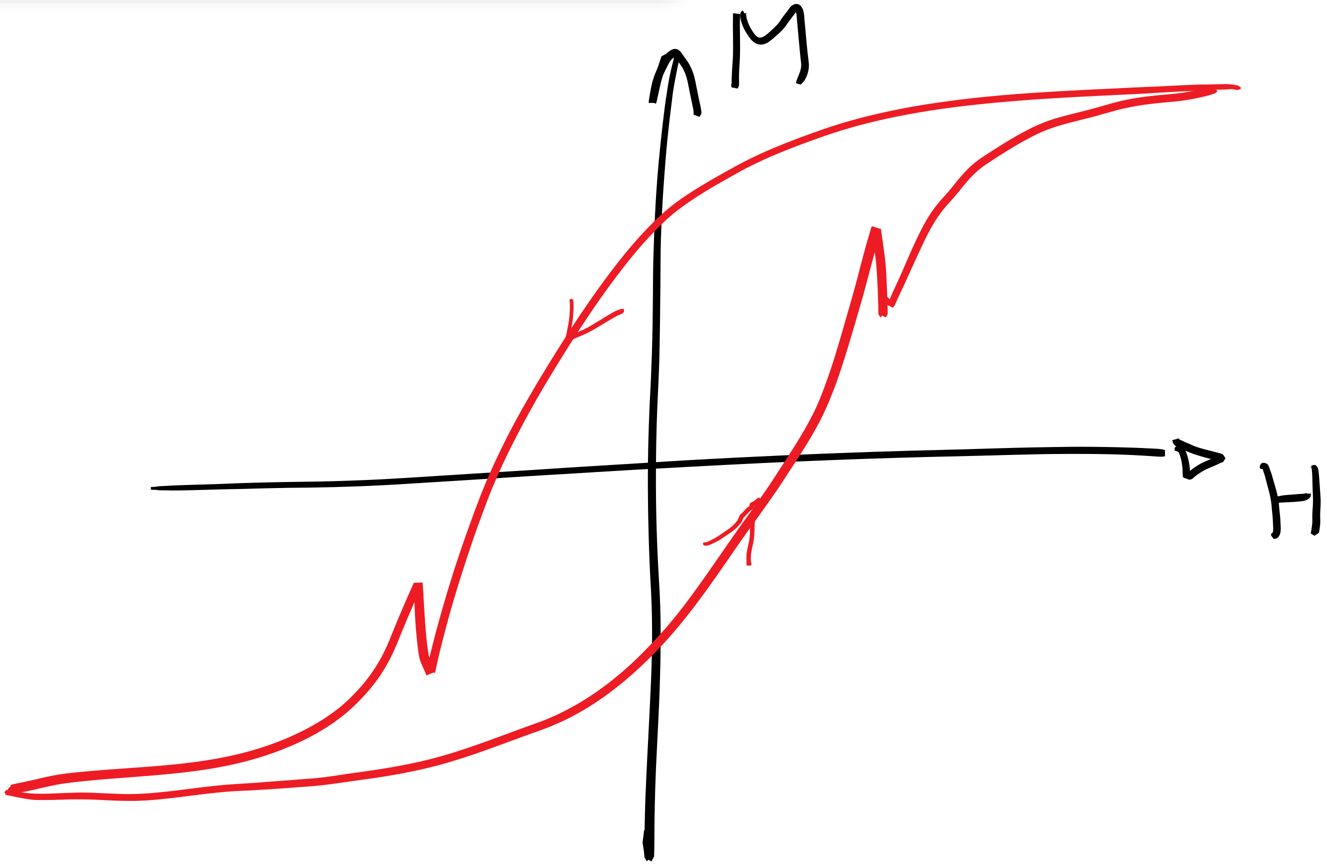

- Large diameter: activation volume related to domain-wall nucleation
- Small diameter: scales with cell volume

→ Decrease of stability at very small size

H. Sato et al., Appl. Phys. Lett. 105, 062403 (2014)

## Quizz #2

Is such a hysteresis loop possible?



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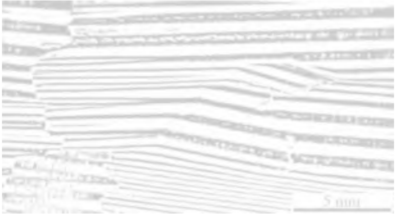
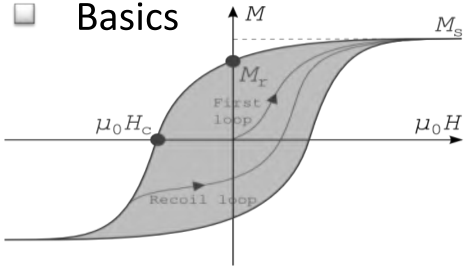
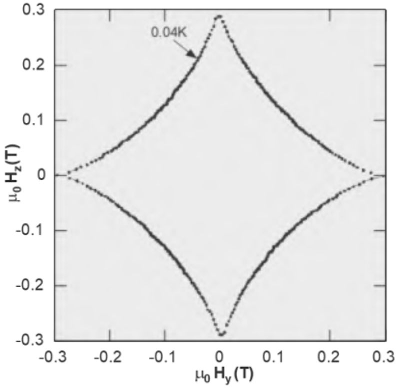
- Motivation



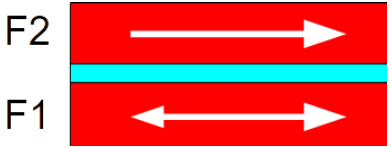
- Basics




- Macrospin switching

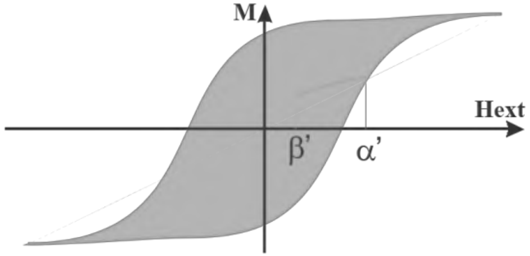



- Coupled systems




- Extended systems

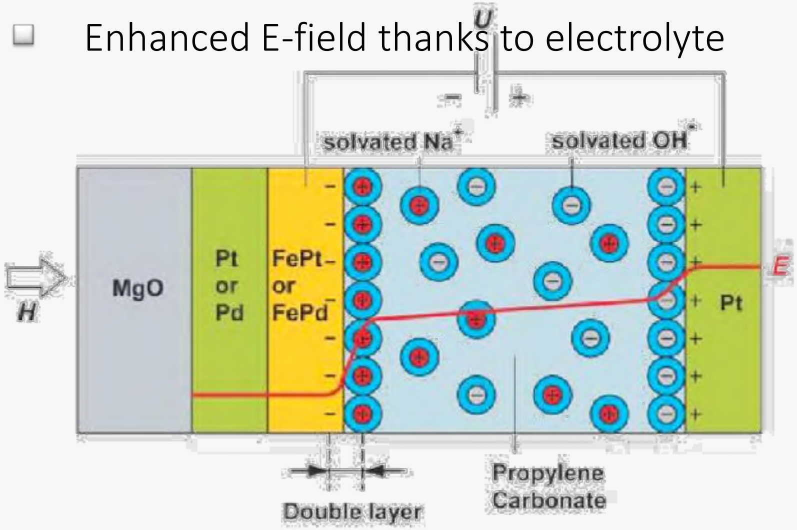
- Learn from hysteresis loops



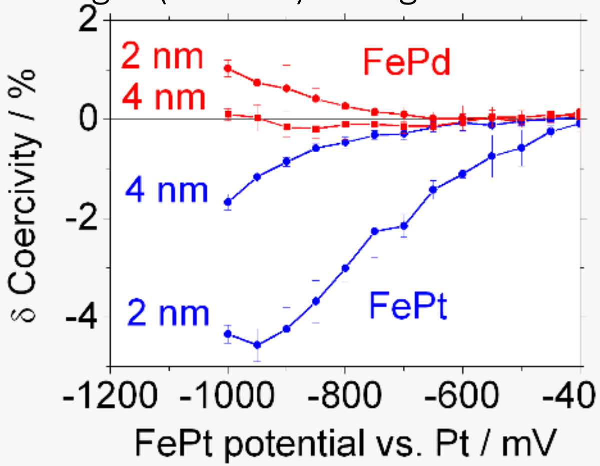
# Coupled systems – Voltage control of magnetization in metals

## Seminal report

- Enhanced E-field thanks to electrolyte




- Slight (relative) change of coercivity




- Effect not expected for metals, due to short screening length
- Relative change of coercivity is weak as coercivity is large

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

## Developments

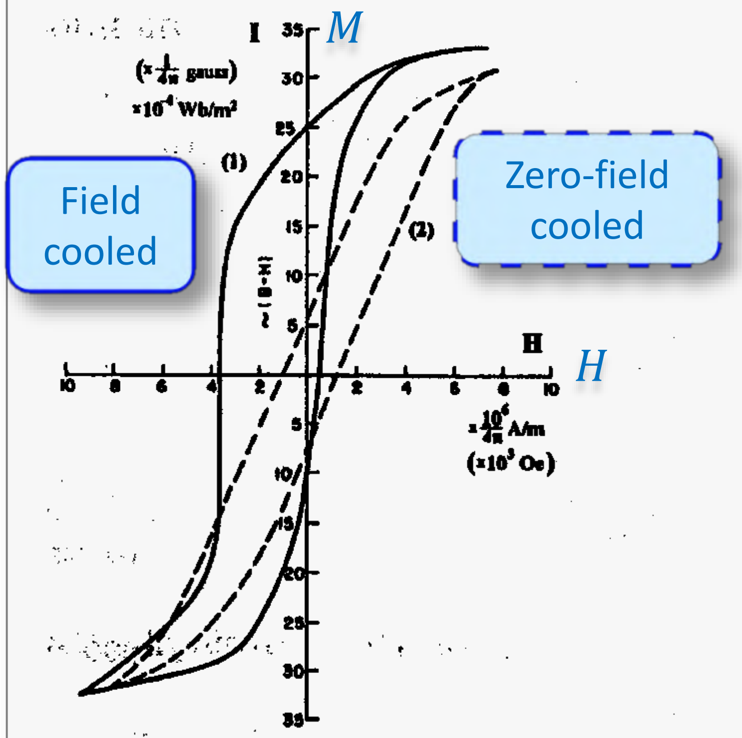
- Precessional switching with pulse of E-field
  Y. Shiota et al., Nature Mater.11, 39 (2012)
- Ferromagnetic resonance with ac E-field
  T. Nozaki et al., Nature Phys. 8, 491 (2012)
- Inversion of sign of DMI and skyrmions chirality
  C.E. Fillion, Nat. Comm. 13, 5257 (2022)

**Motivations for technology**

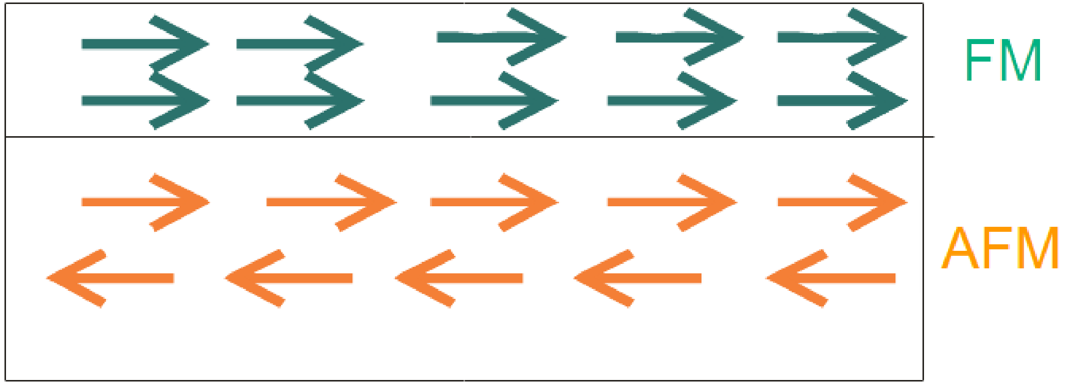
- Drastically reduce Joule heating (only capacitance current)
- Gateable functionality

# Coupled systems – Exchange bias

## Seminal invertigation




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




- Field-shift of hysteresis loop
- Increase of coercivity
- Crucial to design reference layer in memories

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)

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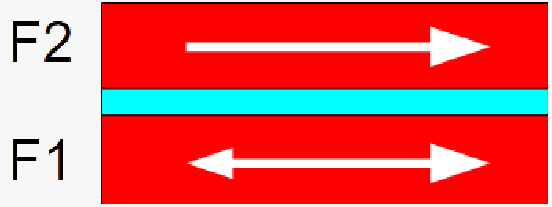
## RKKY Synthetic Ferrimagnets (SyF) – Basics




- Crude phenomenology

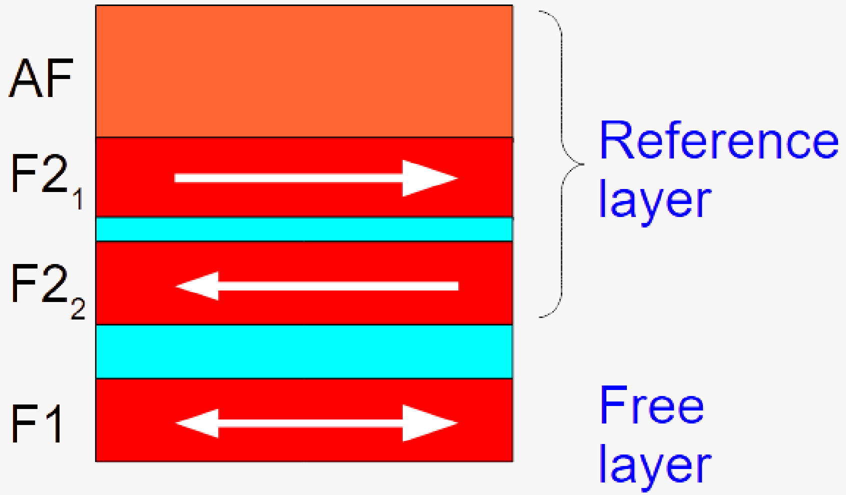
$$M = \frac{|e_1 M_1 - e_2 M_2|}{e_1 + e_2} \qquad K = \frac{e_1 K_1 + e_2 K_2}{e_1 + e_2}$$

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

- Enhances coercivity
- Reduces cross-talk in dense arrays

## Spin valves

- "Free" and reference layers




B. Diény et al., J. Magn. Magn. Mater. 93, 101 (1991)

- Spin-valves are key elements in magneto-resistive devices (sensors, memories)
- Control Ru thickness within the Angström !

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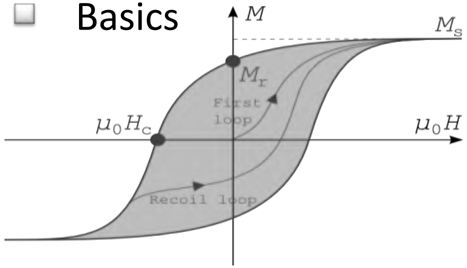
- Motivation

- Basics

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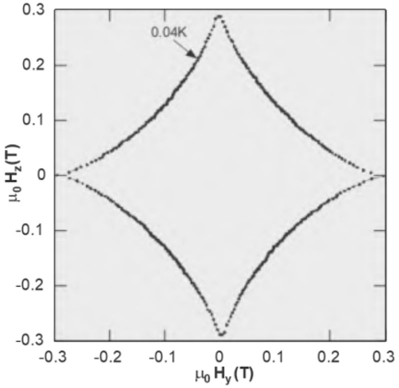


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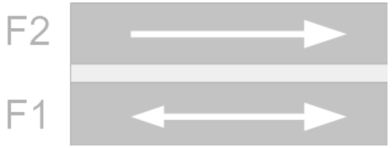
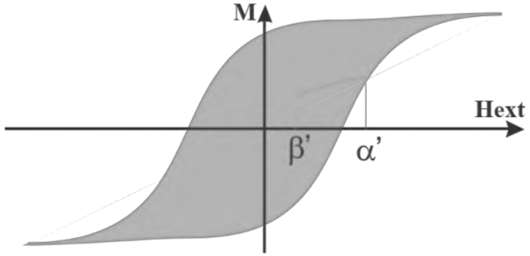



- Extended systems

- Learn from hysteresis loops



# Extended systems – Historical background

**Brown paradox**

In most (extended systems): $H_c \ll \frac{2K}{\mu_0 M_s}$

→

**(Micromagnetic) modeling**

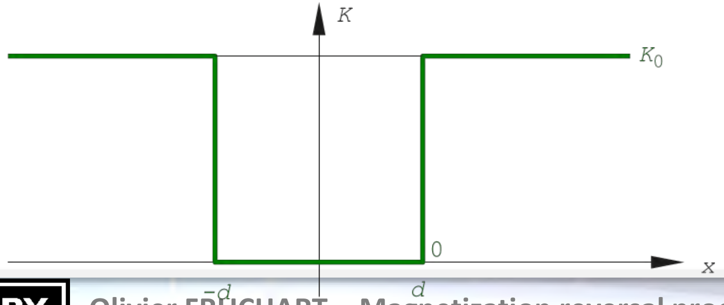
Exhibit analytic, nevertheless realistic models for magnetization reversal

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.



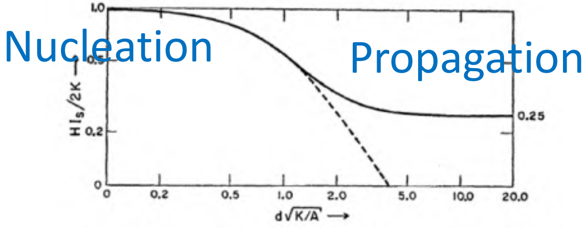




FIG. 1. The nucleation field (dashed) and coercive force (full curve) in terms of the coercive force of perfect material, $HI_s/2K$, as functions of the defect size, $d$.

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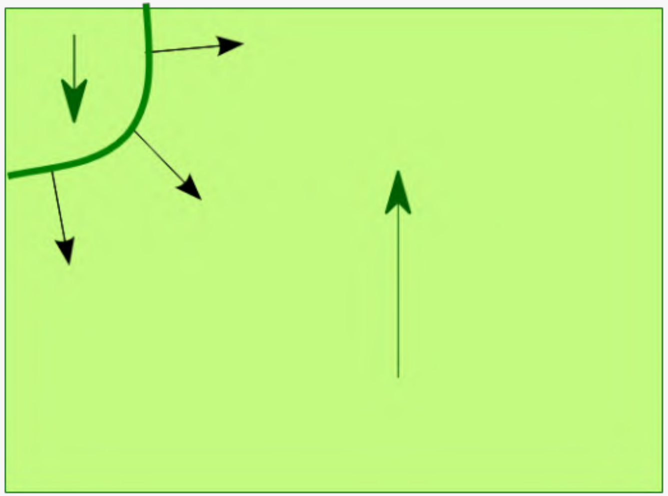
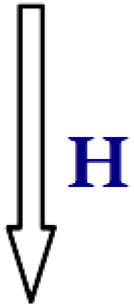
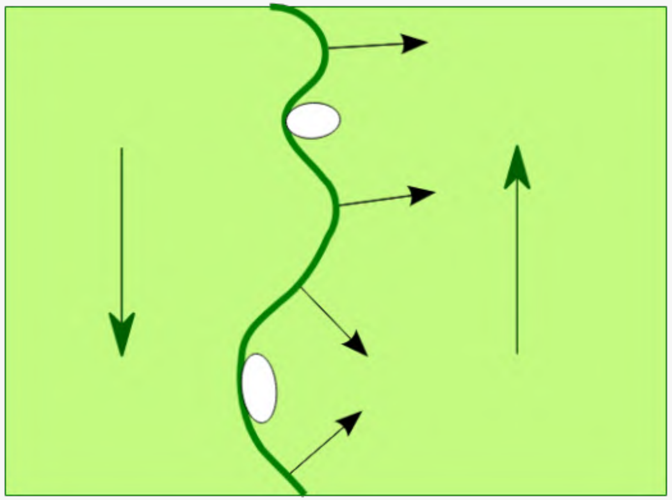
### Coercivity determined by nucleation



- Concept of nucleation volume
- Physics has some similarity with that of the Stoner-Wohlfarth model for small particles



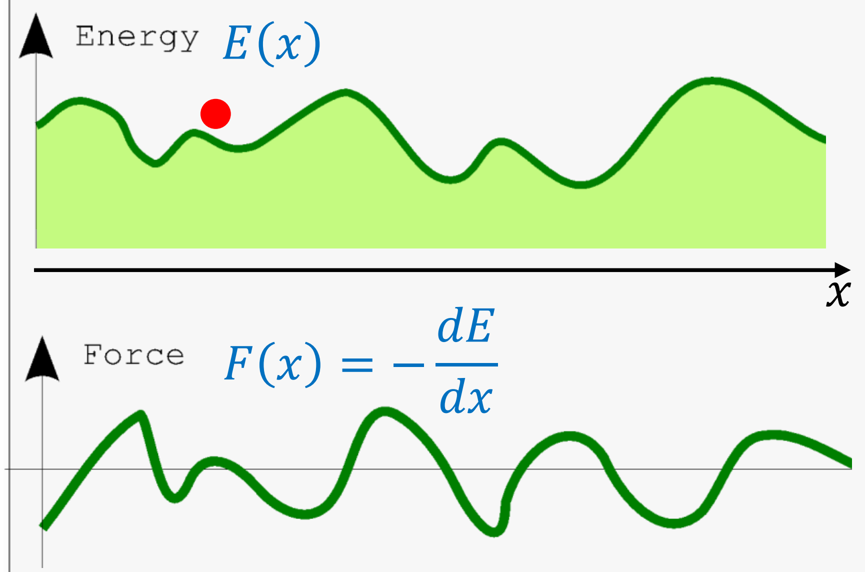

### Coercivity determined by propagation



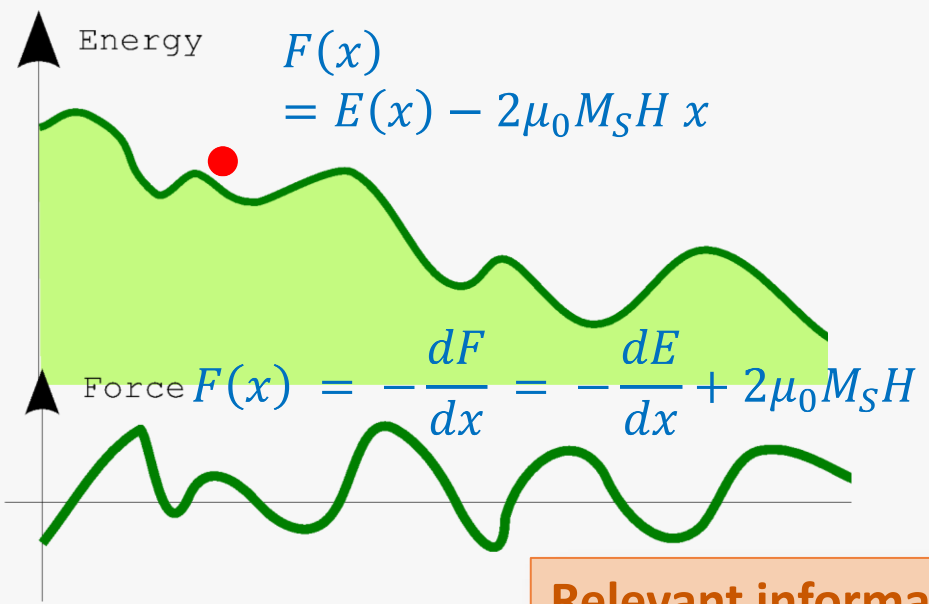
- Physics of surface/string in heterogeneous landscape
- Modeling necessary

Example : domain wall to be moved along a 1d system

### Without applied field




### With applied field



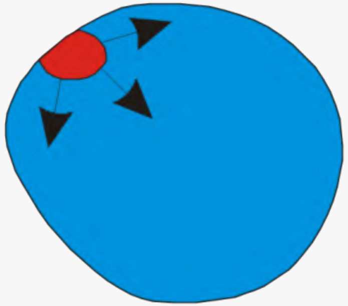

E. Kondorski, On the nature of coercive force and irreversible changes in magnetisation, Phys. Z. Sowjetunion 11, 597 (1937)

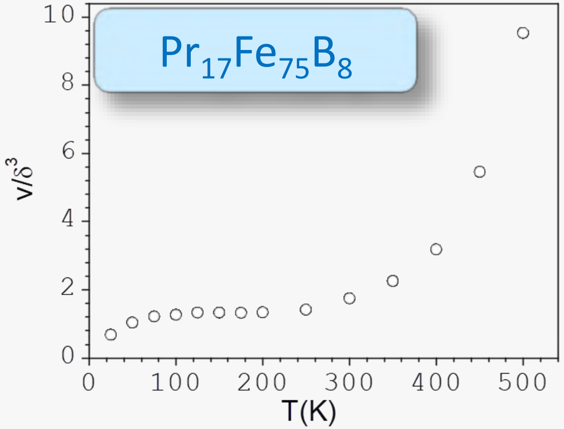
**Relevant information**

- ☐ Microstructure
- ☐ Chemical composition
- ☐ Crystal structure

### Activation volume

- Also called: nucleation volume
- Should be considered if system is larger than the characteristic length scale
- Use for: estimate $H_c(T)$, long-time relaxation, dimensionality
- Size similar to wall width $\delta$






Courtesy D. Givord

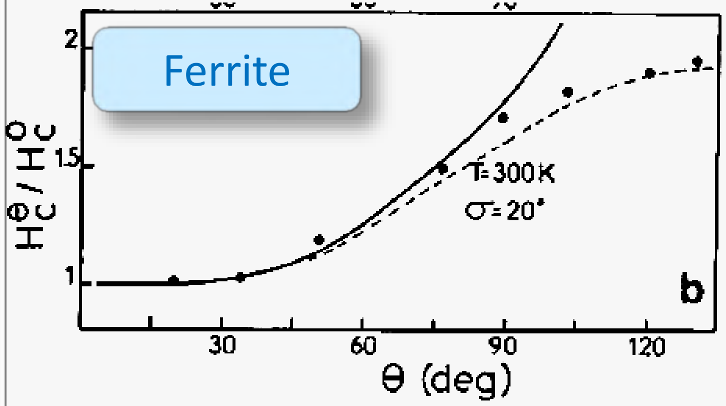
REVIEW: D. Givord et al., JMMM258, 1 (2003)

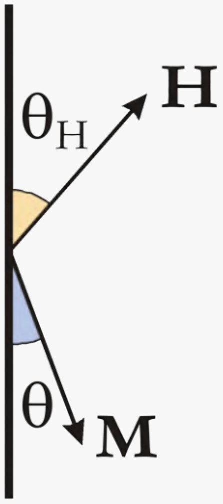
### 1/cos(ϑ) law, Becker-Kondorski model

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

- Assumes:
  coercivity << anisotropy field
- Energy barriers overcome by Zeeman + thermal energy

$$\Delta E = -\mu_0 M_s H v_a \cos\theta_H + 25 k_B T$$




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

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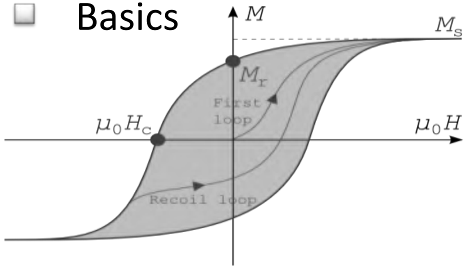


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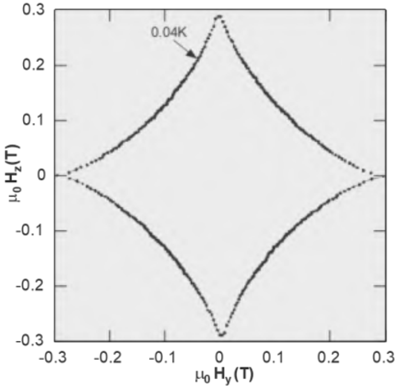


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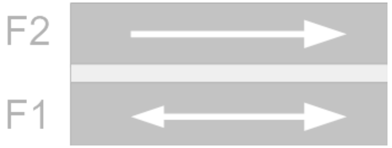
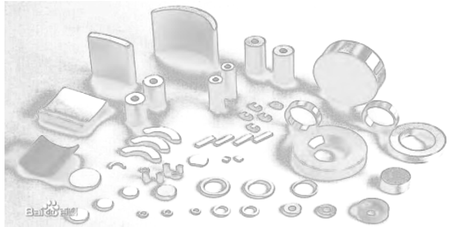
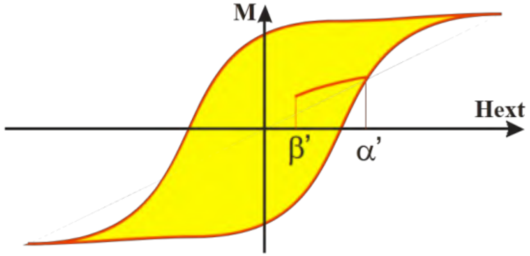


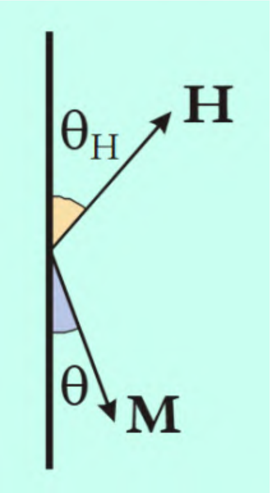

- Extended systems



- Learn from hysteresis loops



## Magnetization loop of a macrospin along hard axis




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

Dipolar energy:

$$H = h.H_a$$
$$H_a = 2K / \mu_0 M_s$$
$$K = N_i K_d$$

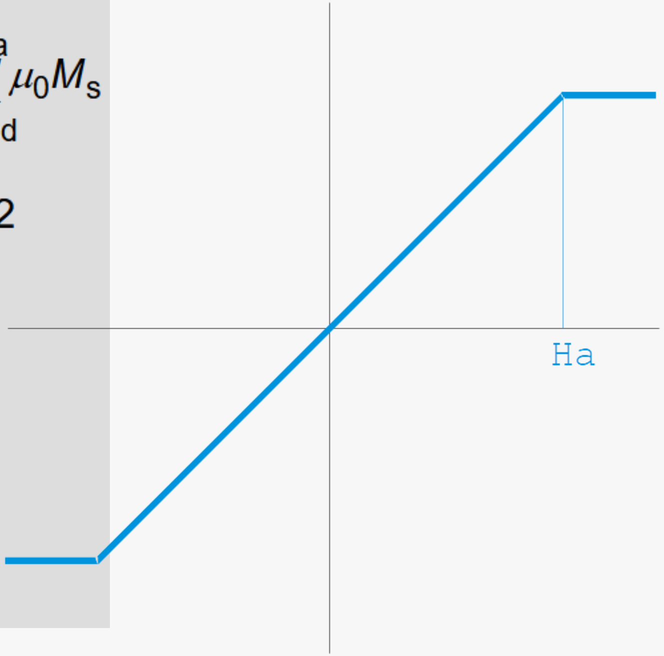
Hard axis: $\theta_H = \pi / 2$

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

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

Equilibrium position

$$h = \sin\theta = \cos(\theta - \theta_H) = \mathbf{m}.\mathbf{u}_h$$




- Reversible loop. Saturation field informs about anisotropy field
- Note: here the specific case of uniaxial second-order anisotropy

# Learn from hysteresis loops – Extract anisotropy

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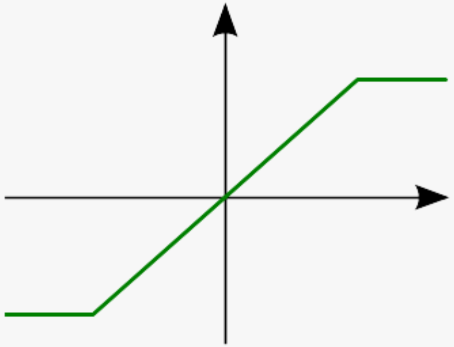
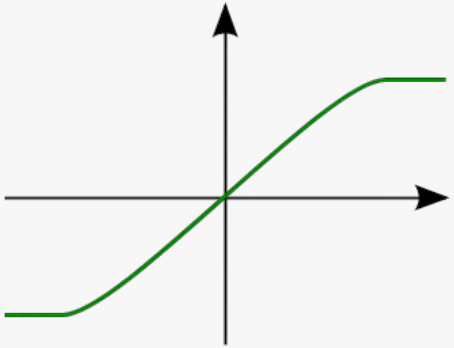
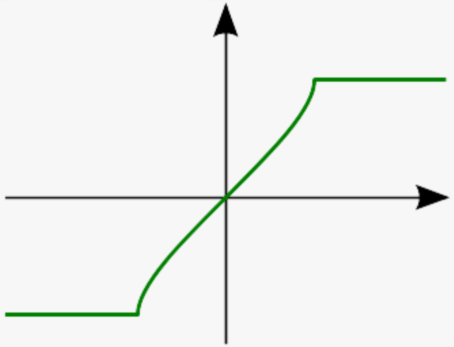
**Higher-order anisotropy** Example: second- and forth-order anisotropy $E_{\mathrm{mc}} = K_1 \sin^2\theta + K_2 \sin^4\theta$



$K_2 = 0$



$K_2 > 0$

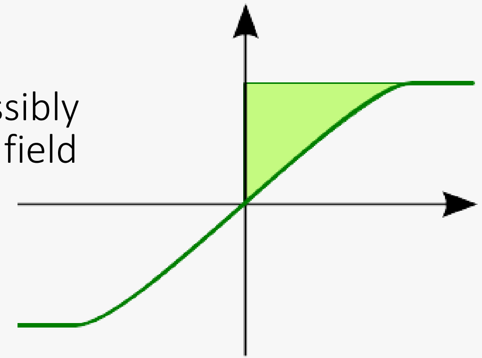


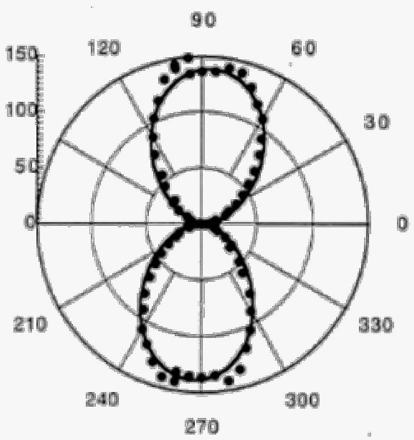
$K_2 < 0$

**Means of analysis**

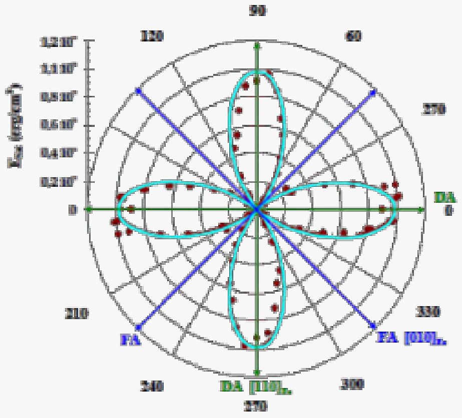
- Area above curve
- Initial susceptibility, possibly under a transverse bias field

D. Berling, J. Magn. Magn. Mater. 297, 118 (2006)






Uniaxial




Biaxial

# Learn from hysteresis loops – Configurational anisotropy

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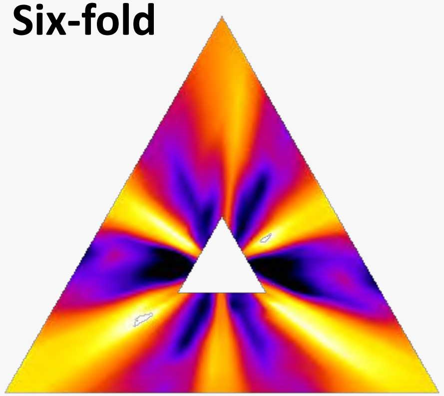
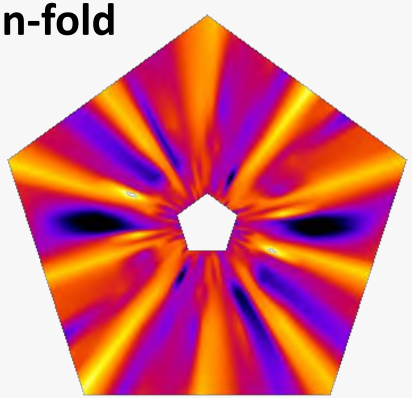
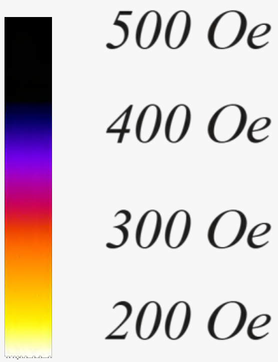
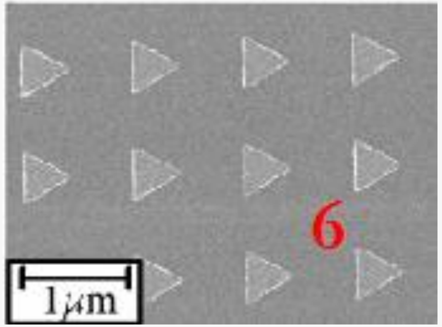
**Six-fold**

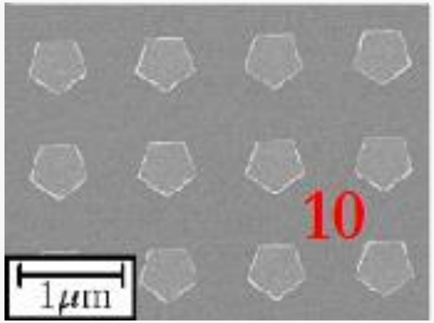


**Ten-fold**






R.P. Cowburn, J.Phys.D:Appl.Phys.33, R1–R16 (2000)

- Results from the interplay of demagnetizing energy and exchange energy
- Is not captured by the demagnetizing tensor, which is of second order

# Learn from hysteresis loops – Consider internal field

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## Case of soft-magnetic material

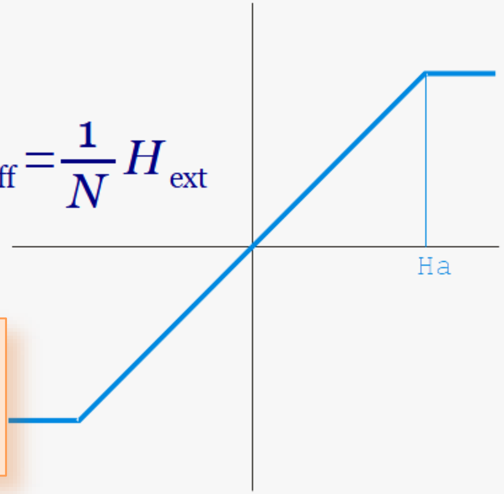
Hypothesis

- Demagnetizing field is homogeneous.
- Domains can be created, yielding a uniform and effective magnetization $M_{eff}$

Energy $$E_{tot} = \frac{1}{2}\mu_0 N M_{eff}^2 - \mu_0 M_{eff} H_{ext}$$

Minimization $$\frac{\partial E_{tot}}{\partial M_{eff}} = \mu_0 N M_{eff} - \mu_0 H_{ext}$$

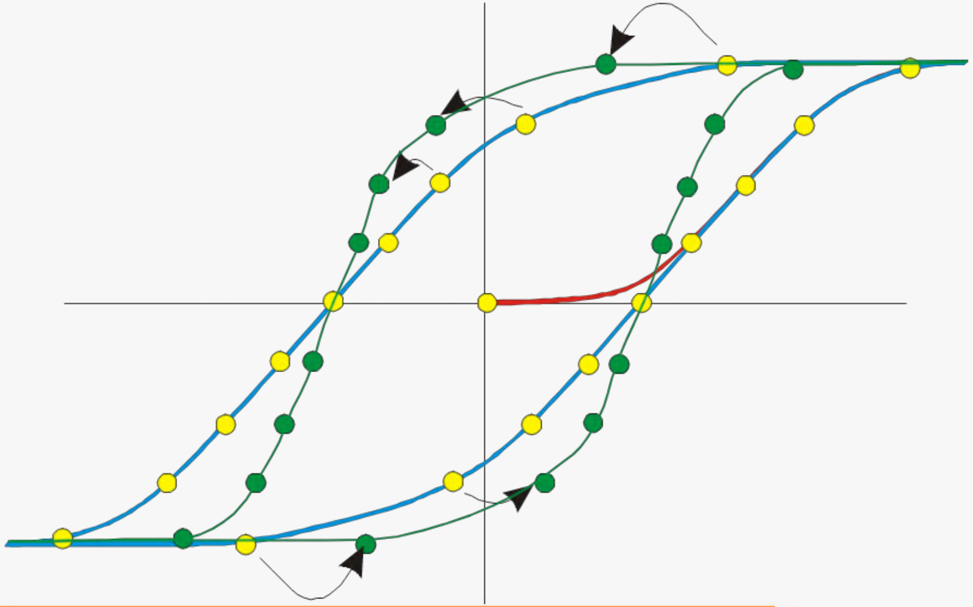
$$M_{eff} = \frac{1}{N} H_{ext}$$




- Saturation field related to demagnetizing coefficient

## Arbitrary (unknown) situation

- Measure a hysteresis loop $M_1(H_a)$
- Estimate internal field during loop $H_d = -N_i M_1(H_a)$
- Plot loop versus internal field $H_a + H_d)$

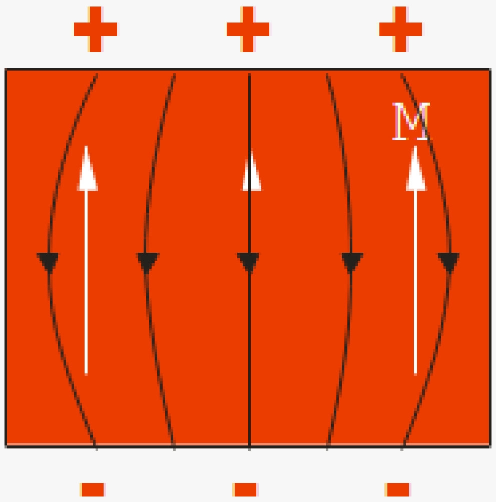


- In an approximation: remain cautious

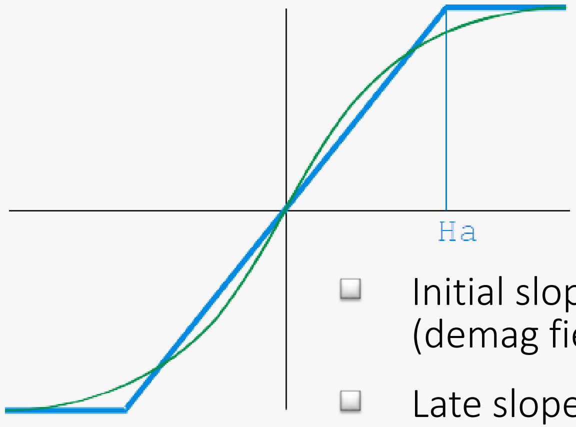
# Learn from hysteresis loops – Consider internal field

## Deviations for non-ellipsoidal or non-thin-film shapes

- Demagnetizing field is not homogeneous in magnitude nor direction




## Resulting hysteresis loops




- Initial slope higher than 1/N (demag field smaller than average)
- Late slope smaller than 1/N (demag field larger than average)

- Demagnetizing energy (area above loop) is identical $E_d = \int_0^{M_s} \mu_0 H_{ext} \mathrm{d}M = \frac{1}{2}\mu_0 N M_s^2$

- In a non-ellipsoidal sample (or cylinder, slab) the loop is overcompensated at low magnetization and undercompensated at high field, even for soft magnetic materials.

# Learn from hysteresis loops – (BH)max

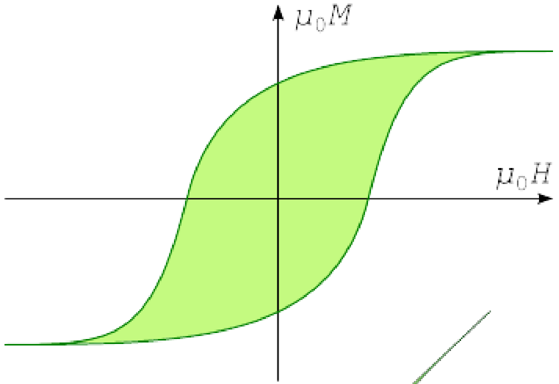
## (De)magnetization energy

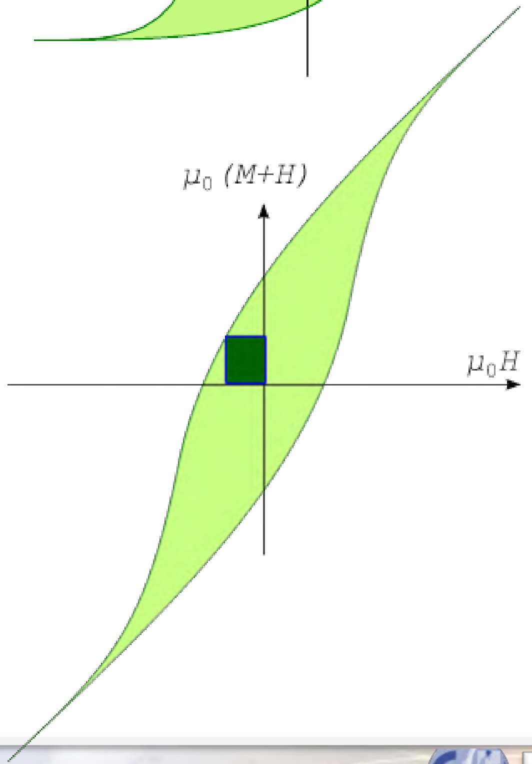
$$\mathcal{E} = -\frac{1}{2}\mu_0 \iiint_{\text{sample}} \mathbf{M}.\mathbf{H}_\text{d}.\text{d}V = \frac{1}{2}\mu_0 \iiint_{\text{space}} \mathbf{H}_\text{d}^2.\text{d}V$$

$$-\frac{1}{2}\mu_0 \iiint_{\text{sample}} (\mathbf{M}+\mathbf{H}_\text{d}).\mathbf{H}_\text{d}.\text{d}V = -\frac{1}{2}\mu_0 \iiint_{\text{sample}} \mathbf{B}.\mathbf{H}_\text{d}.\text{d}V$$

$$= \frac{1}{2}\mu_0 \iiint_{\text{space}\setminus\text{sample}} \mathbf{H}_\text{d}^2.\text{d}V$$

Energy available outside the sample, usefull for devices

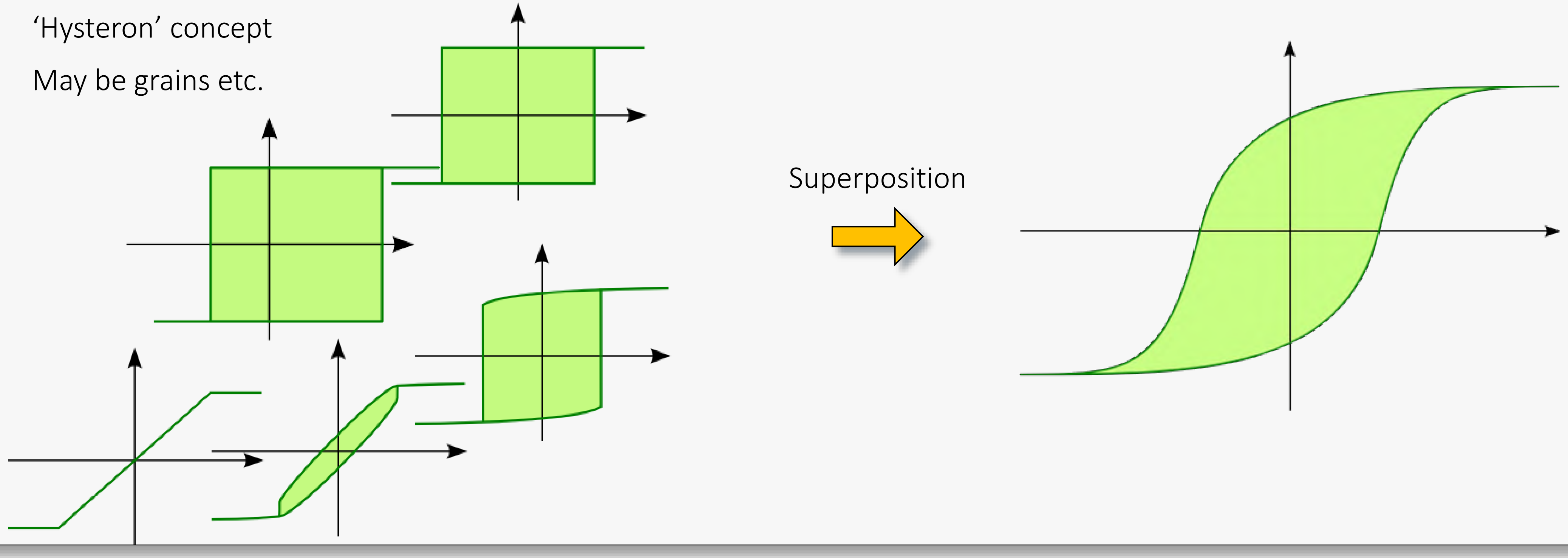



- Must be computed versus the internal field (remove demag field)
- Is an intrinsic quantity of a hard-magnetic material

## Individual constituents of a large magnetic body

- ‘Hysteron’ concept
- May be grains etc.




**How to understand the physics of such loops when measured ?**

- Distribution of coercive fields ?
- Dipolar interactions ?
- Individual loops are slanted ?

# Learn from hysteresis loops – Distributions: isolated grains

**Textbook case**

- Uniaxial anisotropy, second order : $E_{\mathrm{mc}} = K_1 \sin^2\theta$
- Fully remanent grains

**3D distribution** $(\theta, \varphi)$

- Remanence : $m_{\mathrm{r}}^{3\mathrm{D}} = 1/2$
- Measured anisotropy : $\left\langle K^{3\mathrm{D}} \right\rangle = 2\mathrm{K}/3$

**2D distribution** $(\varphi)$

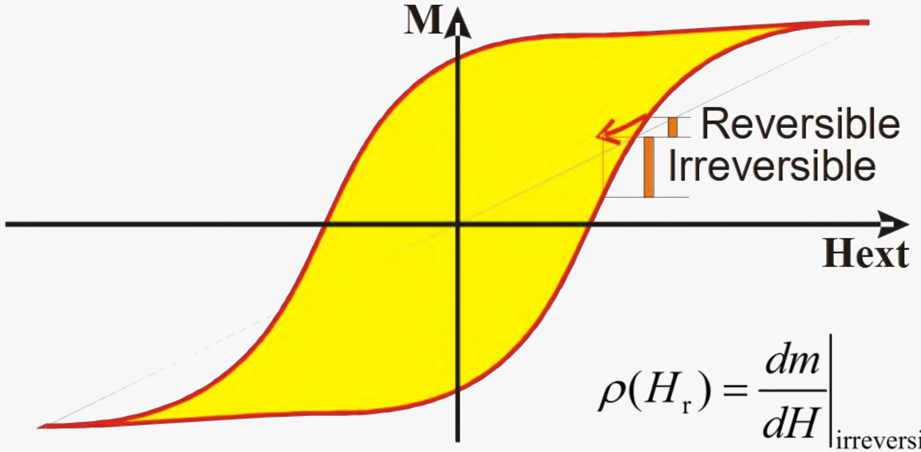
- Remanence : $m_{\mathrm{r}}^{3\mathrm{D}} = 2/\pi$
- Measured anisotropy : $\left\langle K^{3\mathrm{D}} \right\rangle = K/2$

**Use of the measurement of these quantities**

- Distribution -> Estimate K
- Interactions: decrease of increase remanence

# Learn from hysteresis loops – Recoil loops

## Reversible versus irreversible contributions




$$\rho(H_r) = \left.\frac{dm}{dH}\right|_{\text{irreversible}}$$

- Determine distribution of 'individual' switching fields
- Possible use: investigate Hc(T) at a given stage of the reversal and learn about nucleation volumes etc.

## Henkel plots

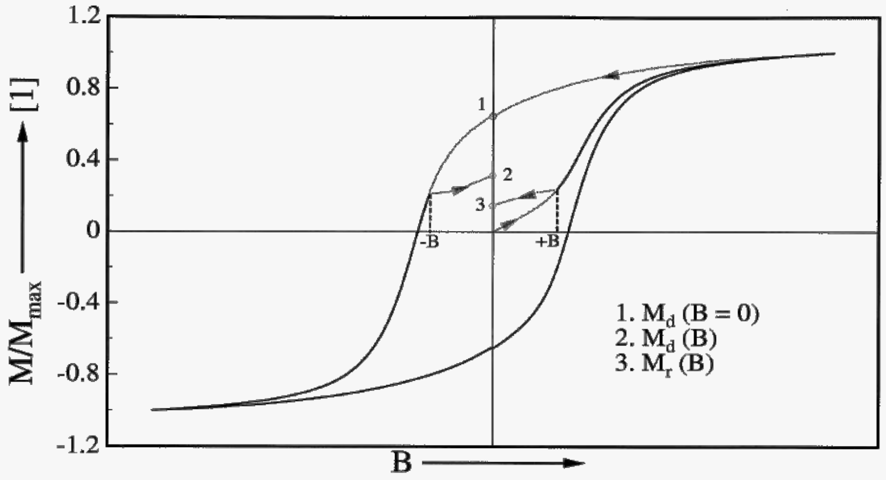



Fig. 1. Explanation of how to measure the two different remanent magnetisations $M_r$ and $M_d$.

- Estimation of interactions (e.g. dipolar)

$$\Delta M_H(x) = M_d(x) - [1 - 2M_r(x)]$$

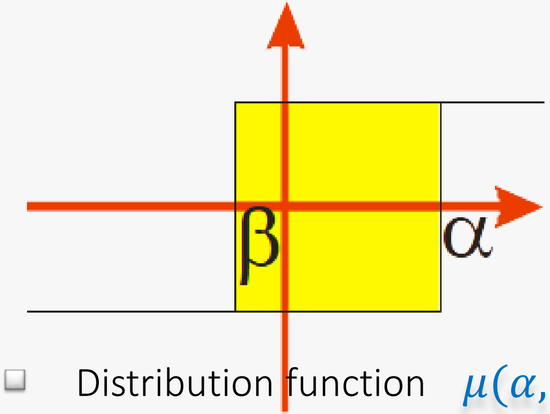
O. Henkel, Phys. Stat. Sol. 7, 919 (1964)

S. Thamm et al., JMMM184, 245 (1998)

## Background: Preisach model

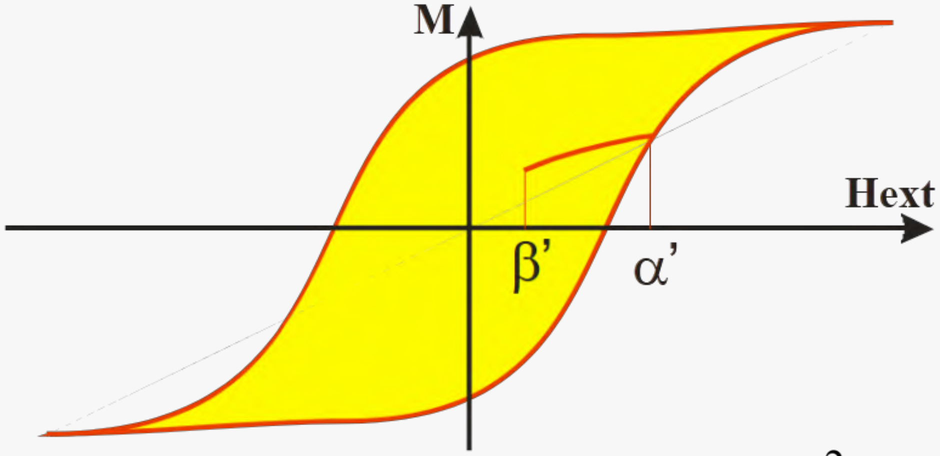
G. Biorci et al., Il Nuov. Cim. VII, 829 (1958)

I. D. Mayergoyz, Mathematical models of hysteresis, Springer (1991)




- Distribution function $\mu(\alpha,\beta)$
- Mimics intra-body interactions
- No true link with physics constituents

## Experimental determination



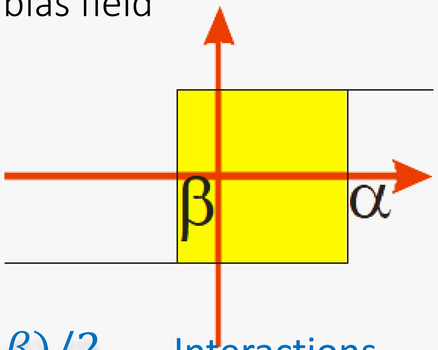

$$\mu(\alpha',\beta') = \frac{1}{2}\frac{\partial^2 f_{\alpha',\beta'}}{\partial\alpha'\partial\beta'}$$

- Long experiments (1D set of hysteresis curves)
- Better suited to bulk materials with strong interactions

## Concept

- Recent 'rediscovery' or 're-interpretation : the FORC diagrams:
- First-Order Reversal Curves

→ Outline distribution of switching field and bias field

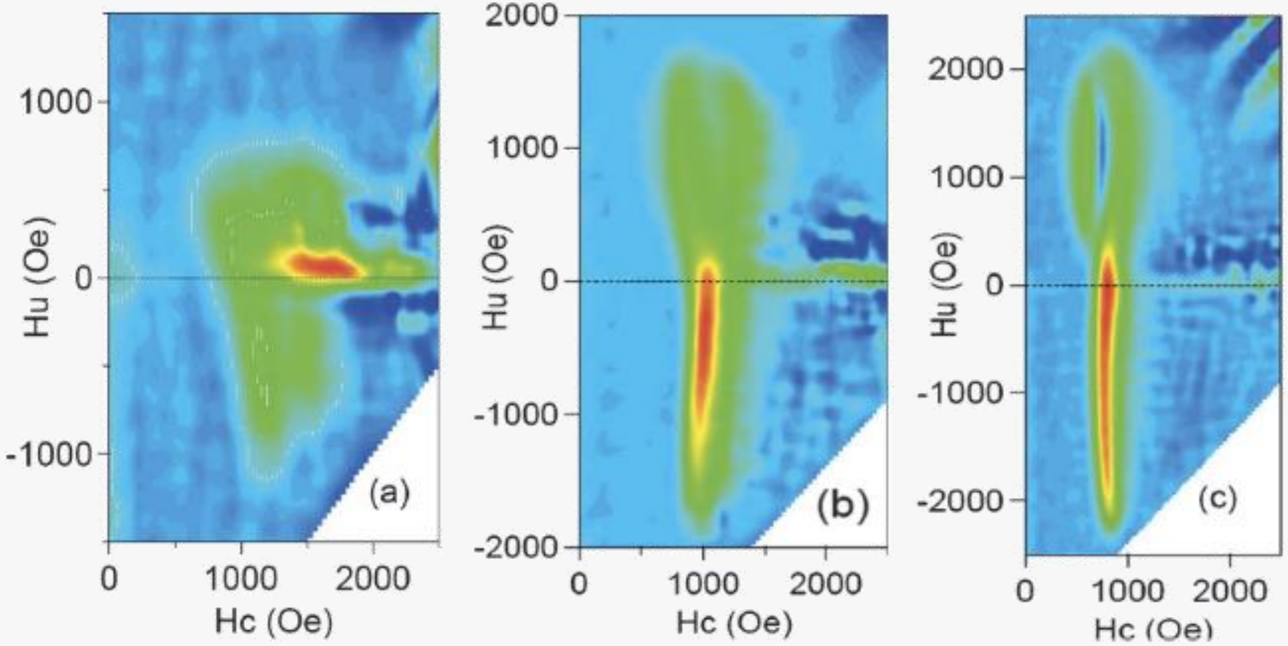



$H_i = (\alpha + \beta)/2$ Interactions

$H_c = (\alpha - \beta)/2$ Coercivity

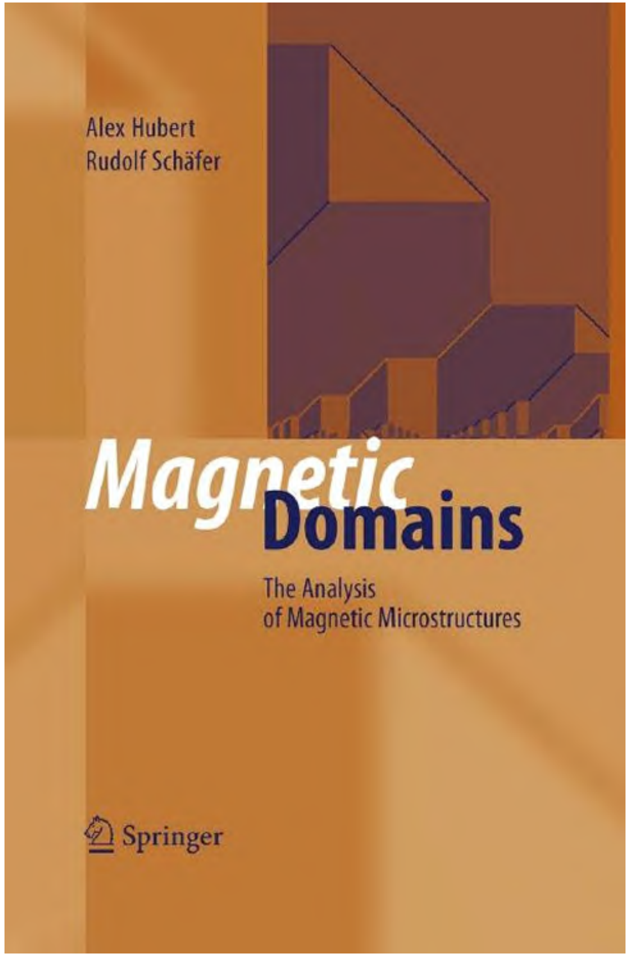
C. Pike et al., J. Appl. Phys. 85, 6668 (1999)

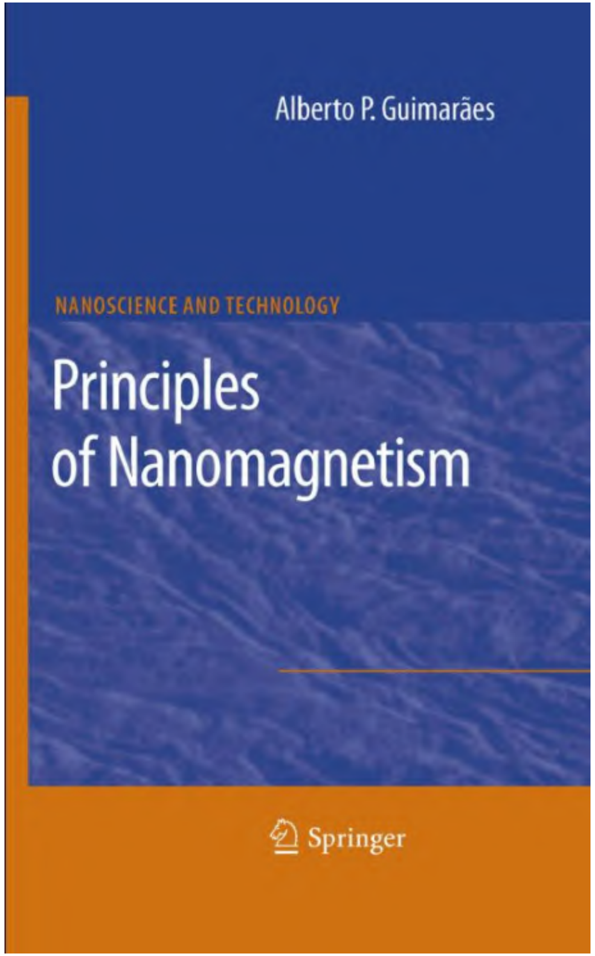
## Example Dense array of permalloy nanowires with increasing diameter

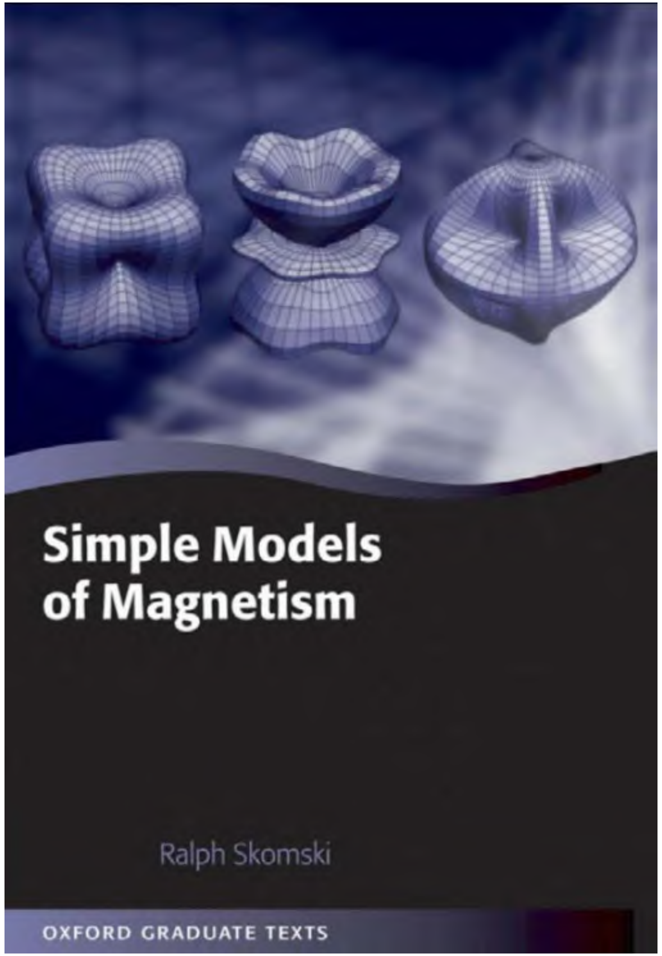



M. S. Salem et al., J. Mater. Chem. 22, 8549 (2012)

# Books (nanomagnetism)



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More extensive slides on: http://magnetism.eu/esm/repository-authors.html#F

2019, 2013, 2009, 2007

Lecture notes from undergraduate lectures, plus various slides on magnetization reversal:
http://fruchart.eu/olivier/slides/

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

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# Thank you for your attention !

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