Patterned magnetic structures

from fundamental micromagnetism to micron-scale applications

Micromagnetism =

Continous media theory describing the magnetization distribution inside samples

- Classical theory
- Atomic structure of matter is ignored
- Analytical as well as numerical approach

Magnetic domains, A. Hubert and R. Schäfer, Springer Verlag, 1998.

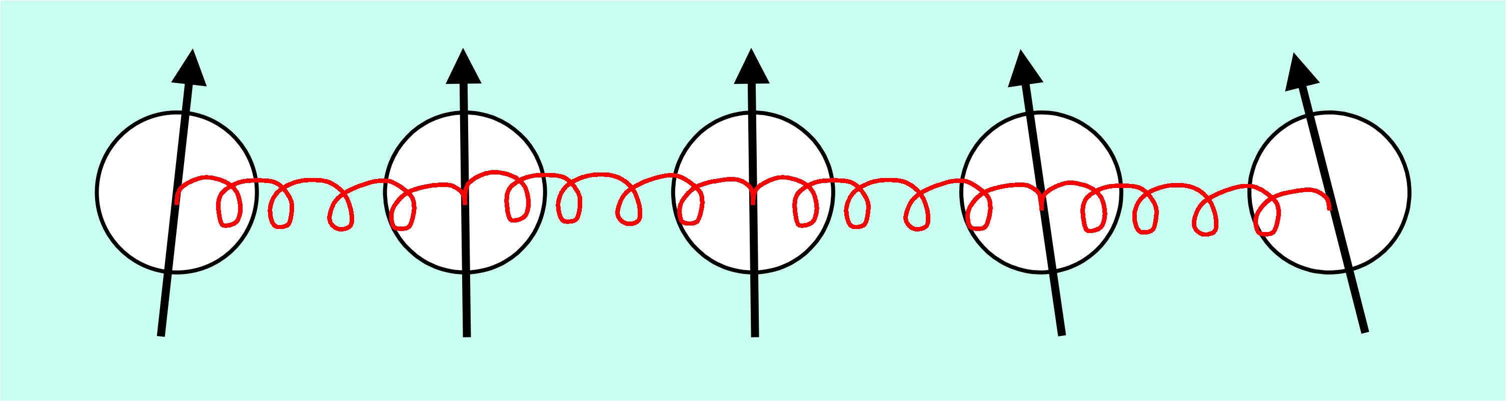
Practical although rigourous approach to micromagnetism. More imaging.

An introduction to the theory of ferromagnetism, A. Aharoni, Clarendon Press, 2001.

A more mathematical approach. More historical (math.) concepts.

Exchange energy

Ferromagnetic order comes from quantum mechanics



Pauli exclusion principle
+
Electrostatic forces

⇒ **Spins do not ignore each other**

Exchange energy

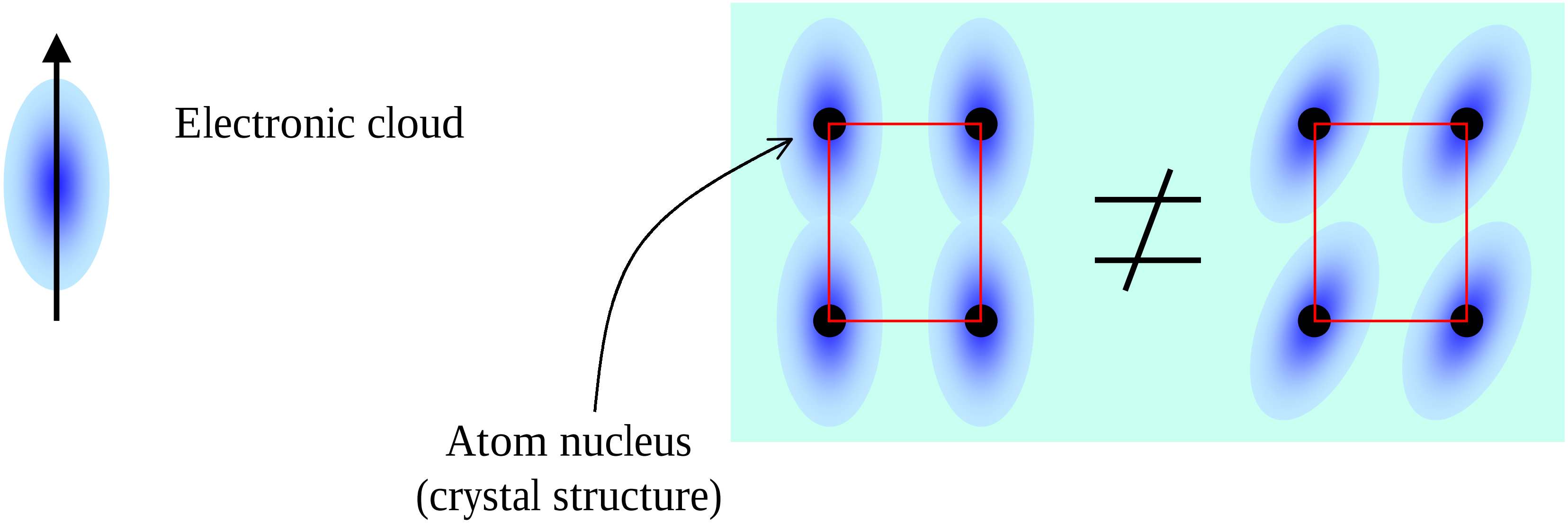
$$e_{\mathrm{ex}} = -J_{1,2}\,\vec{\mathbf{S}}_1 . \vec{\mathbf{S}}_2$$

For ferromagnetic substances : parallel alignement is favored

Magnetic moment, M(T), etc.

$$e_{\mathrm{ex}} \approx A(\nabla\theta)^2 = A(\partial\theta/\partial x)^2$$ for 1D situation

Magnetocrystalline anisotropy energy



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

Series development on an angular basis:

Anisotropy energy **Normalized magnetization components**

$$e_{\mathrm{mc}} = K_2 m_z^2 + K_4 m_z^4 + \ldots \quad \text{Uniaxial}$$

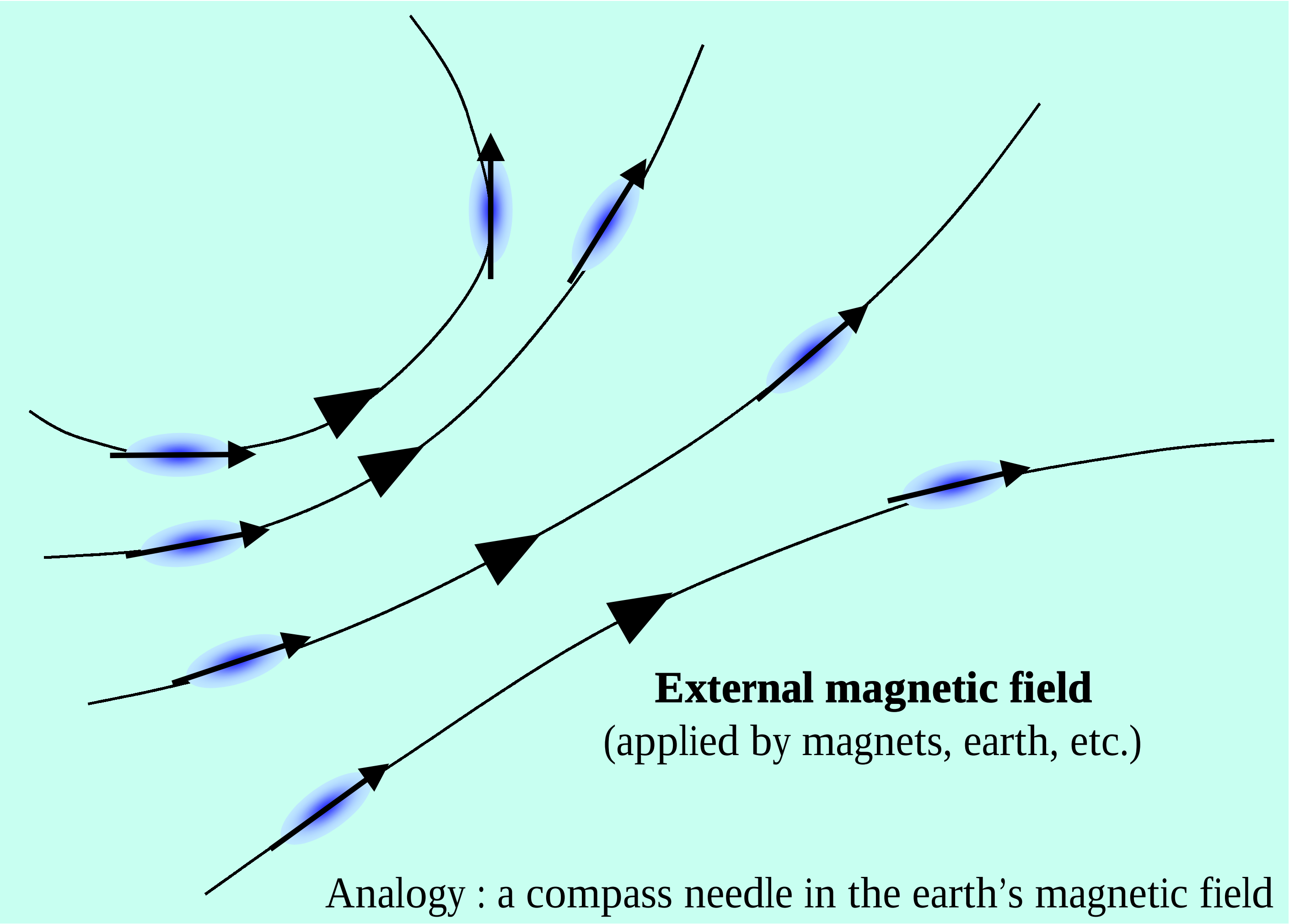
$$e_{\mathrm{mc}} = K_4 (m_x^2 m_y^2 + m_y^2 m_z^2 + m_z^2 m_x^2) + \ldots \quad \text{Cubic}$$

...

Alignement of magnetization is favored along given axes of the crystal

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

Zeeman energy



Zeeman energy

$$e_Z = -\mu_0 \overrightarrow{\mathbf{M}}_S . \overrightarrow{\mathbf{H}}$$

Alignement of magnetization is favored parallel to the external field

Dipolar energy

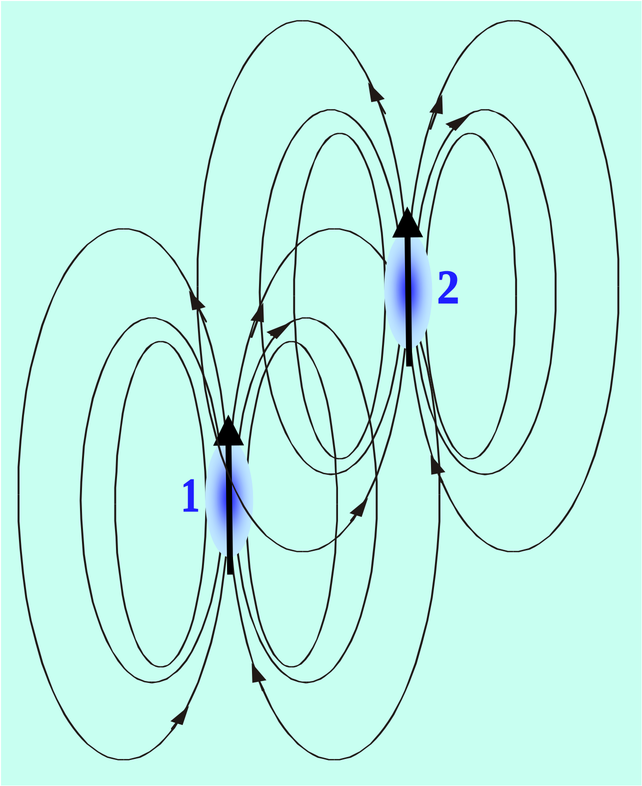
Magnetic moments (spin or orbital) are assimilated to microscopic currents
↳ they create long-range dipolar fields **H**
↳ What is the effect of these fields ?

The dipolar energy is the Zeeman energy of the sample in the dipolar field H_d created by all its spins

Mutual energy should be counted only once !

$$E_{1,2} = -\mu_0 \vec{\mu}_1 . \vec{\mathbf{H}}_2 = -\mu_0 \vec{\mu}_2 . \vec{\mathbf{H}}_1$$

$$= -\frac{1}{2}\mu_0 \left(\vec{\mu}_1 . \vec{\mathbf{H}}_2 + \vec{\mu}_2 . \vec{\mathbf{H}}_1 \right)$$



Local dipolar energy

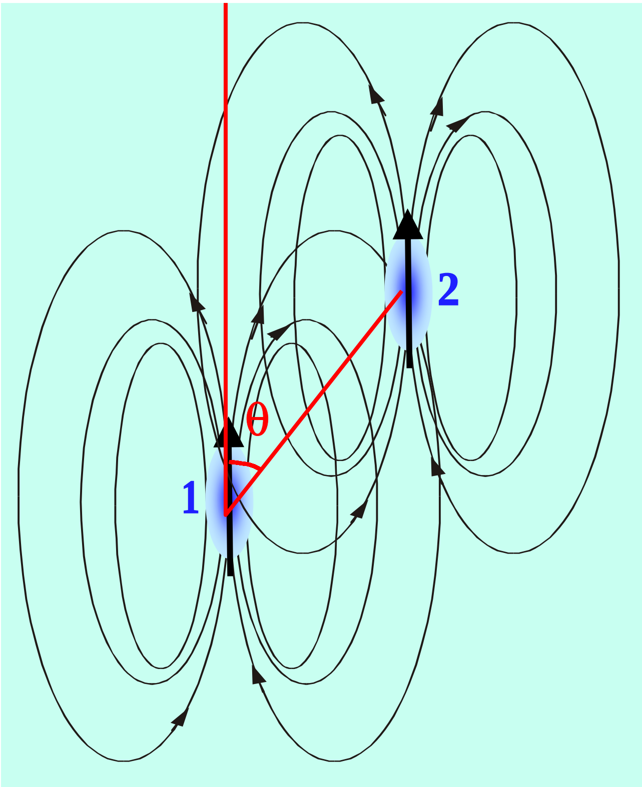
$$e_d = -\frac{1}{2}\mu_0 \vec{\mathbf{M}}_S . \vec{\mathbf{H}}_d$$

(per unit volume)

Cone of alignment

Mutual energy of two magnetic dipoles :

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

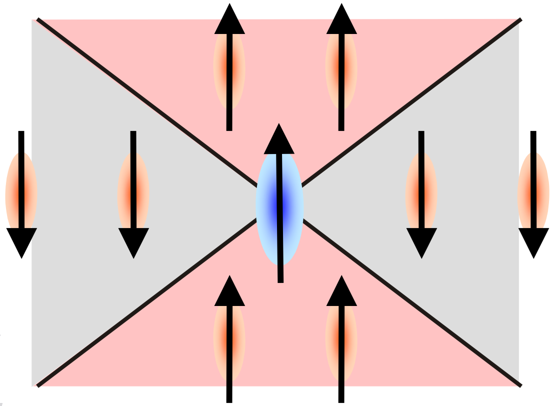


Let us assume two magnetic dipoles with vertical direction, either 'up' or 'down' :

$$E_{1,2}(\theta) = \frac{\mu_0}{4\pi r^3}\mu_1\mu_2\left[1-3\cos^2\theta\right] \qquad \cos^2(\theta_C) = 1/3$$

Parallel alignment is favored for $\theta < \theta_C \approx 54.74°$

Antiparallel alignment is favored for $\theta > \theta_C \approx 54.74°$

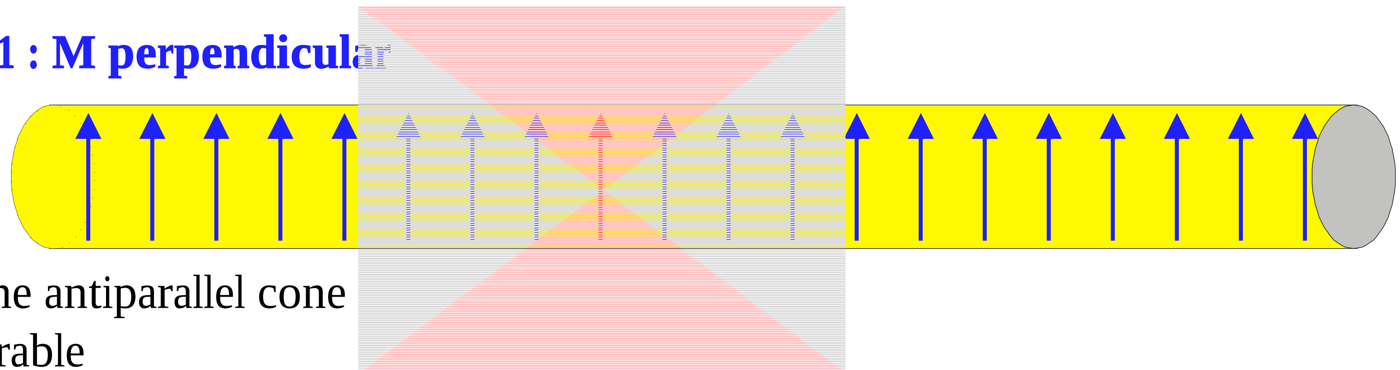


$1/r^3$ decay:
the dipolar interaction is long ranged

Cone of alignment

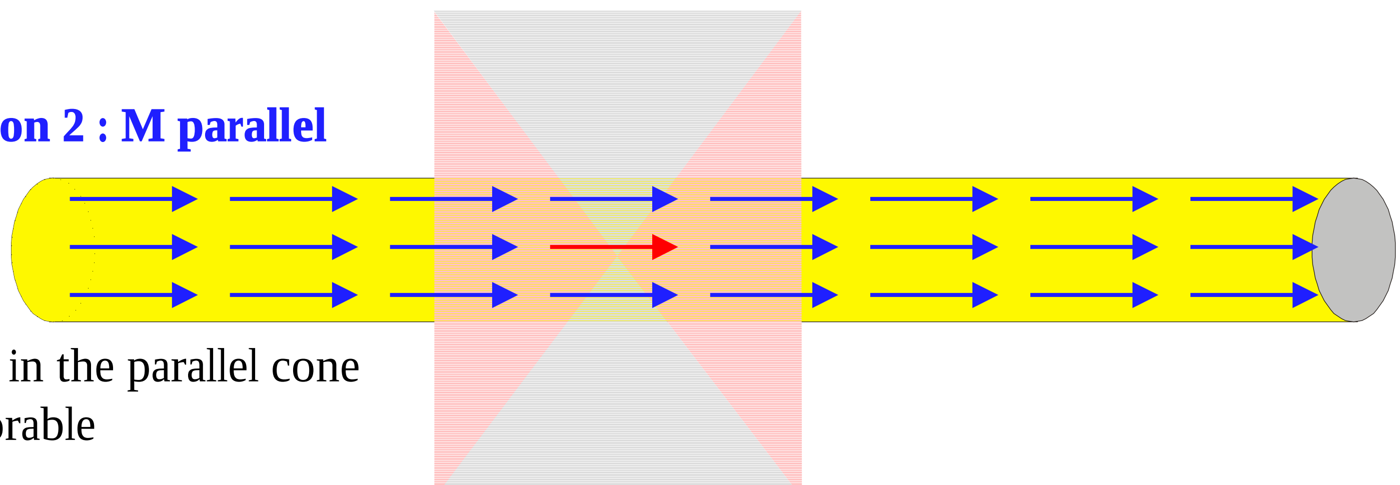
How to use the ‘cone of alignment’ to predict the effect of dipolar fields ?

Situation 1 : M perpendicular



Most of the spins are in the antiparallel cone
↪ not favorable

Situation 2 : M parallel



Most of the spins are in the parallel cone
↪ favorable

The favored magnetization direction is along the long axis of the sample

Electrostatics / Magnetostatics parallel

Maxwell's equations : Electrostatics 'Electric charge'

$$div\vec{\mathbf{E}} = \frac{\varrho}{\varepsilon_0} \Rightarrow \vec{\mathbf{E}}(M) = \iiint \frac{\varrho(P)d^3P}{4\pi\varepsilon_0}\frac{\vec{\mathbf{u}}_{PM}}{PM^2}$$

Magnetostatics

$$div\vec{\mathbf{B}} = 0$$

$$\frac{\vec{\mathbf{B}}}{\mu_0} = \vec{\mathbf{H}} + \vec{\mathbf{M}}$$

$$\Rightarrow \mathrm{div}\vec{\mathbf{H}} = -\mathrm{div}\vec{\mathbf{M}} \Rightarrow \vec{\mathbf{H}}(M) = -\iiint \frac{\mathrm{div}[\vec{\mathbf{M}}(P)]d^3P}{4\pi}\frac{\vec{\mathbf{u}}_{PM}}{PM^2}$$

'Magnetic charge'

For a finite size sample:

after integration over the entire space, a new term arises due to the magnetization discontinuity at the sample's surface:

'Volume charges' 'Surface charges'

$$\vec{\mathbf{H}}_{\mathrm{d}}(M) = -\iiint_{\text{sample}} \frac{\mathrm{div}[\vec{\mathbf{M}}(P)]d^3P}{4\pi}\frac{\vec{\mathbf{u}}_{PM}}{PM^2} + \iint_{\text{sample's surface}} \frac{\vec{\mathbf{M}}(P).\vec{\mathbf{n}}}{4\pi PM^2}dS$$

with : $\mathrm{div}\vec{\mathbf{M}} = \frac{\partial M_x}{\partial x} + \frac{\partial M_y}{\partial y} + \frac{\partial M_z}{\partial z}$

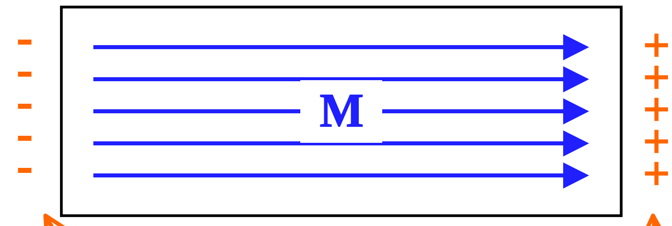
Local dipolar energy

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

The dipolar field coming from a sample can be calculated from these 'magnetic charges'

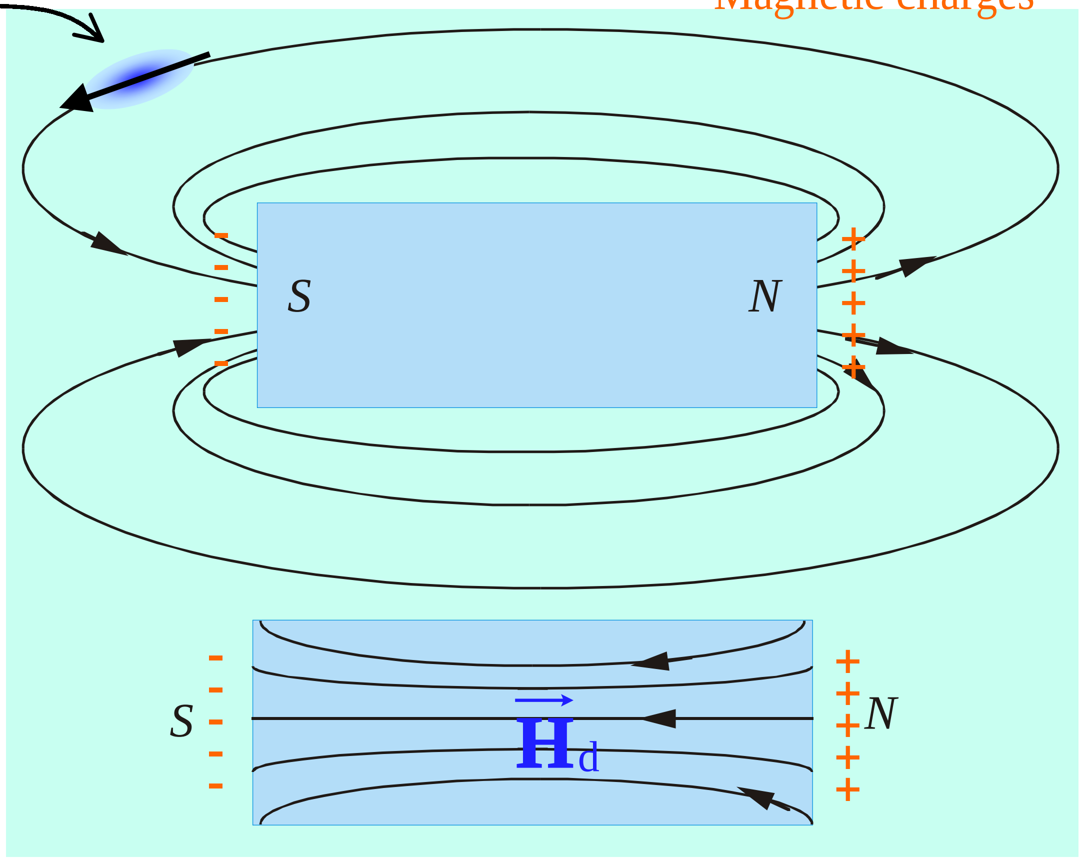
Example

Let us assume a uniformly magnetized prism body :



Magnetic charges

Note: a free dipole aligns itself parallel to the stray field **H** of the magnet



Stray field =

Field created outside the sample

Long-range : dipole-like

Demagnetizing field =

Field created inside the sample

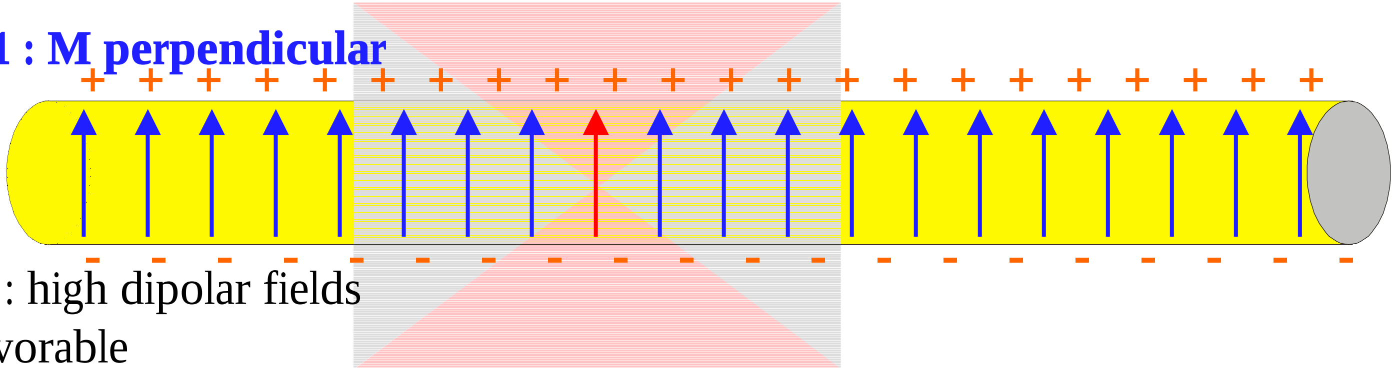
(acting from the sample on itself)

(Images from A. Thiaville – CNRS/Orsay)

Demagnetizing fields

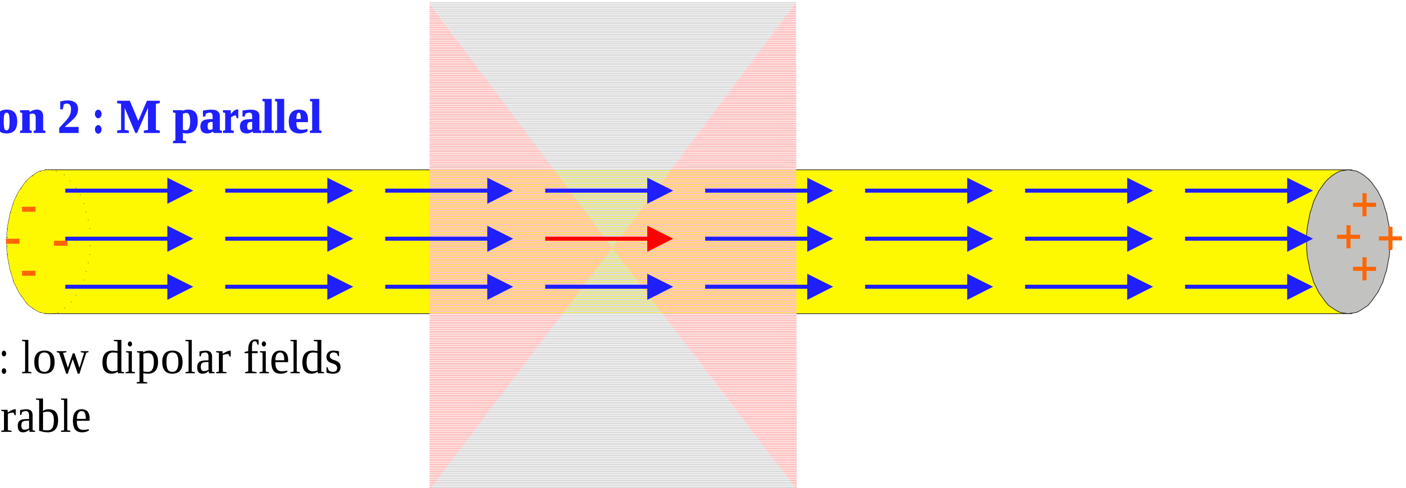
How to use the 'surface charges' model to predict the effect of dipolar fields ?

Situation 1 : M perpendicular



Many surface charges : high dipolar fields
↪ not favorable

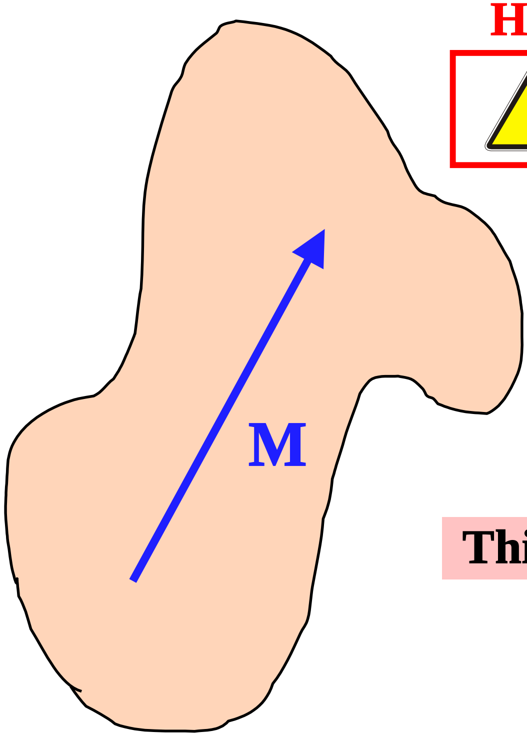
Situation 2 : M parallel



Few surface charges : low dipolar fields
↪ favorable

The favored magnetization direction is along the long axis of the sample

« Shape anisotropy »



Hypothesis : **Uniformly magnetized body with arbitrary shape**

See validity for real samples, later in the course

It can be shown that :

$$e_{\mathrm{d}} = \frac{1}{2}\mu_0\left(N_x M_x^2 + N_y M_y^2 + N_z M_z^2\right)$$

With : $N_x + N_y + N_z = 1, \quad N_i \geq 0$

This is the 'Shape anisotropy energy'

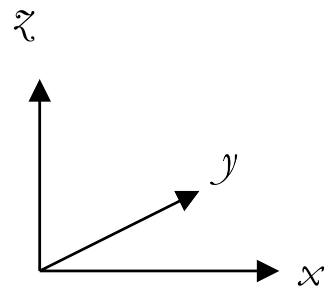
(see analogy with magnetocrystalline…)

Notes and consequences :

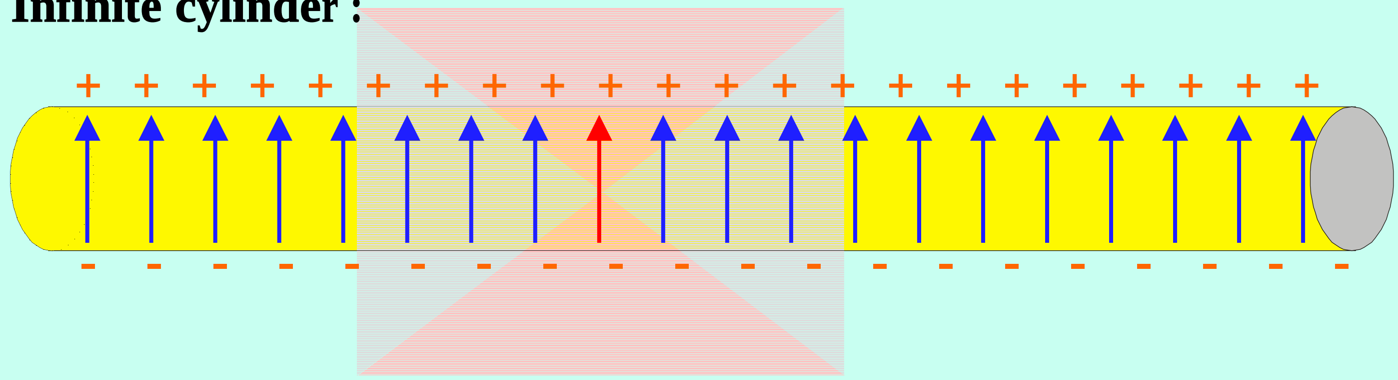
- $e_{\mathrm{d}}^{\max} = \max \frac{1}{V}\iiint_{\text{sample}} e_{\mathrm{d}}.d\tau = \frac{1}{2}\mu_0 M_{\mathrm{S}}^2$
- **The 'shape' energy is uniaxial**
- **N_i is higher along short sample directions**
- **Effective anisotropy energy:** $K_{\mathrm{eff}} = K_{\mathrm{mc}} + K_{\mathrm{d}}$

- **Even if M is assumed to be uniform in the system, $\mathbf{H}_{\mathrm{d}}$ is in general not uniform, except for special shapes.**

see examples



Infinite cylinder :

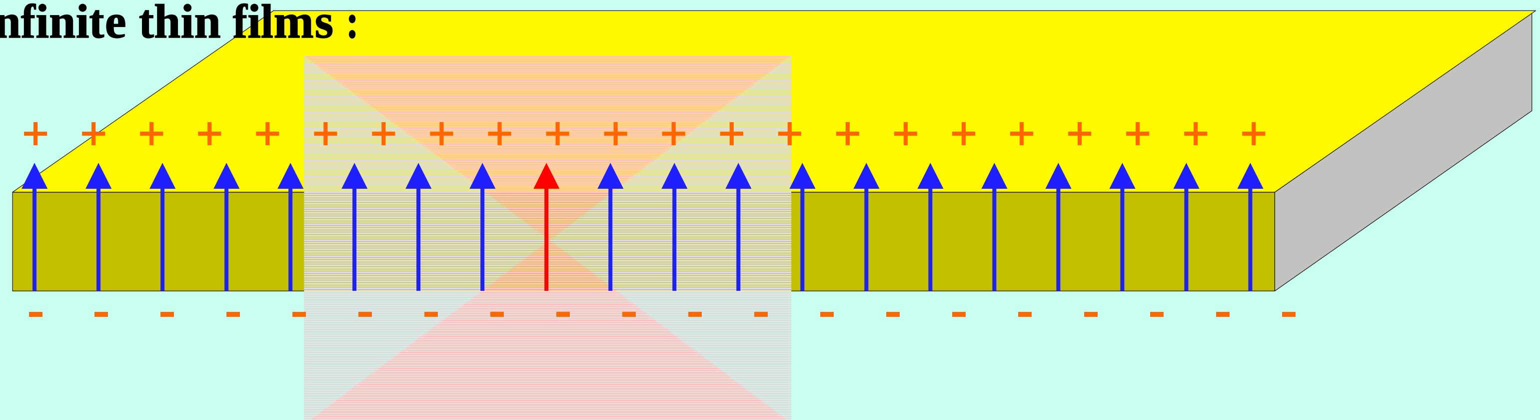


$$e_d^x = 0 \qquad e_d^y = e_d^z = 0.5\left(\frac{1}{2}\mu_0 M_S^2\right)$$

Infinite thin films :

$$e_d^x = e_d^y = 0$$

$$e_d^z = \frac{1}{2}\mu_0 M_S^2$$



In thin films (or portions of thin films)
the magnetization usually lies in the plane of the film

« Shape anisotropy »

General micromagnetic equations

Must be minimized locally (Lagrange minimization)

$$e(\mathbf{r}) = e_{\mathrm{ex}}(\mathbf{r}) + e_{\mathrm{mc}}(\mathbf{r}) + e_{\mathrm{Z}}(\mathbf{r}) + e_{\mathrm{d}}(\mathbf{r})$$

Any spin interacts with all other spins in the sample:
dipolar term is **non-linear** and **non-local**.

No general solution.

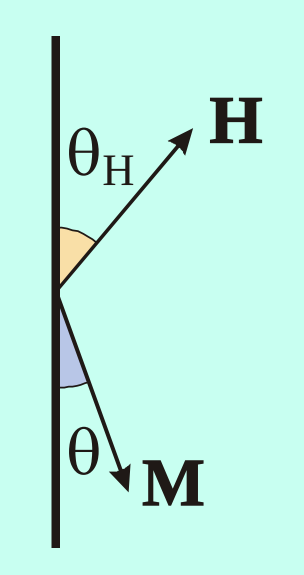
- **Only extremely simple problems can be solved analytically** (historical approach)
- Since about 10 years: 'small-scale' problems (<1µm) have become tractable with computers → **Numerical micromagnetics**

Coherent reversal

Question to answer:

What happens to a piece of ferromagnet when
an external field is applied antiparallel to its magnetization ?

(The sample is fixed in position and orientation
in the external field : different from a compass needle)



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

(Extremely strong !)

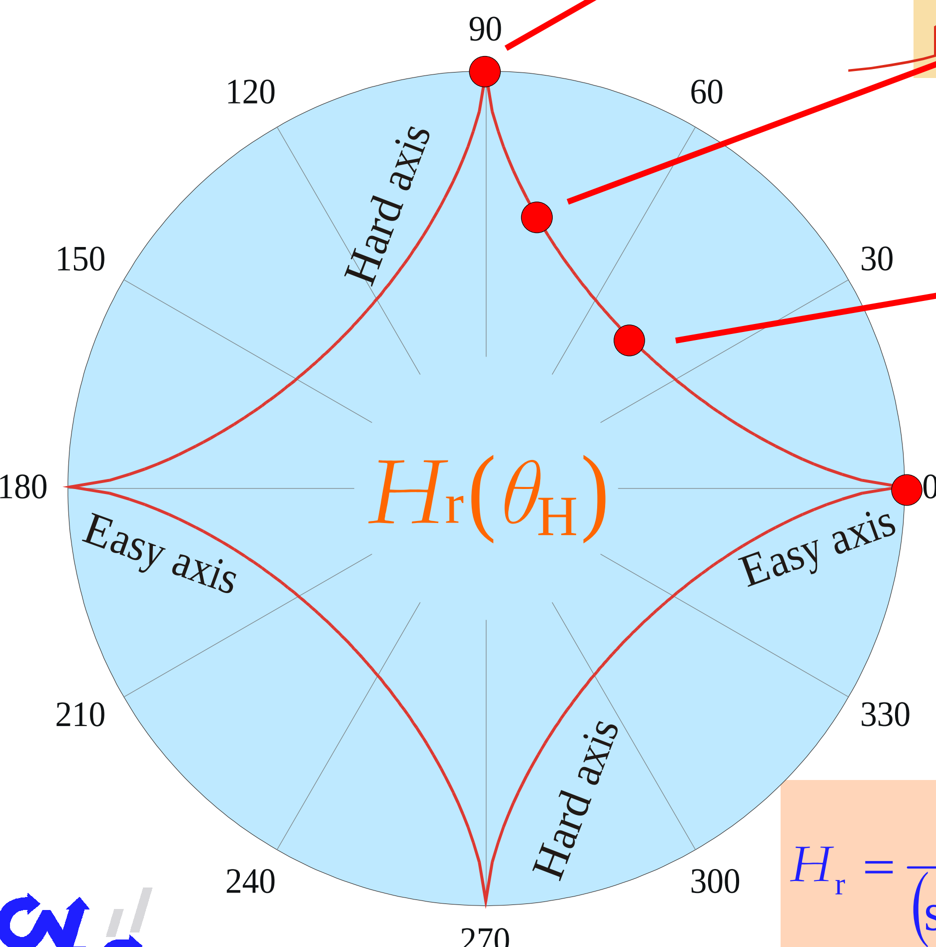
$$E_{\mathrm{tot}} = V\left[K_{\mathrm{eff}} \sin^2\theta - \mu_0 M_{\mathrm{S}} H_{\mathrm{ext}} \cos(\theta - \theta_{\mathrm{H}})\right]$$

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

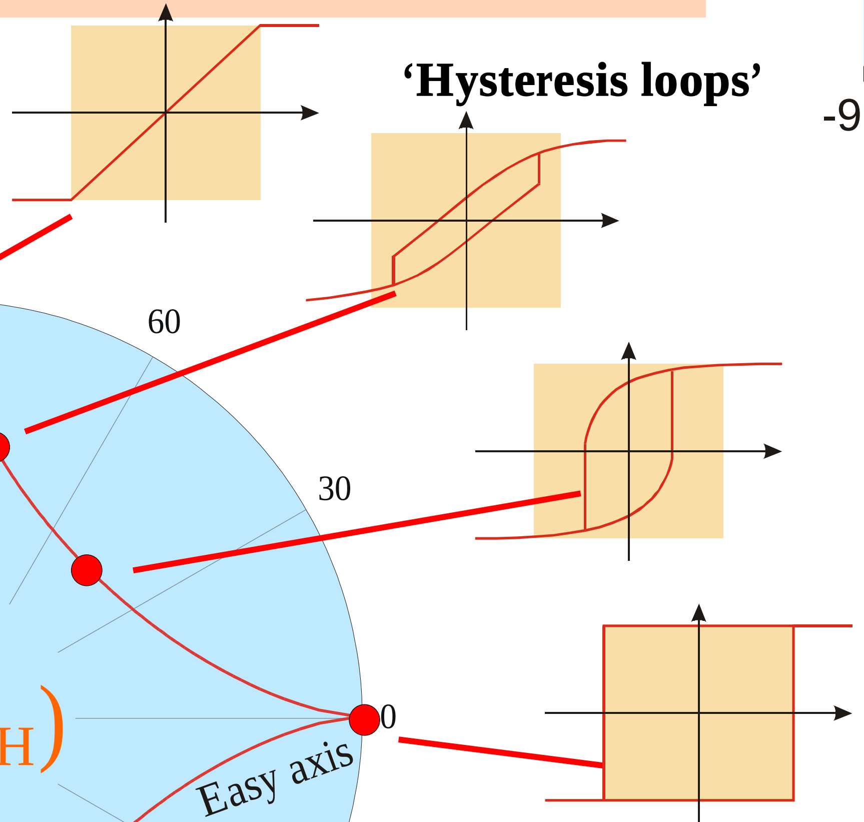
L. Néel, Compte rendu Acad. Sciences **224**, 1550 (1947)
E. C. Stoner and E. P. Wohlfarth,
Phil. Trans. Royal. Soc. London **A240**, 599 (1948)
IEEE Trans. Magn. **27**(4), 3469 (1991) : reprint

$$E_{\mathrm{tot}} = V\left[K_{\mathrm{eff}} \sin^2\theta - \mu_0 M_{\mathrm{S}} H_{\mathrm{ext}} \cos(\theta-\theta_{\mathrm{H}})\right]$$

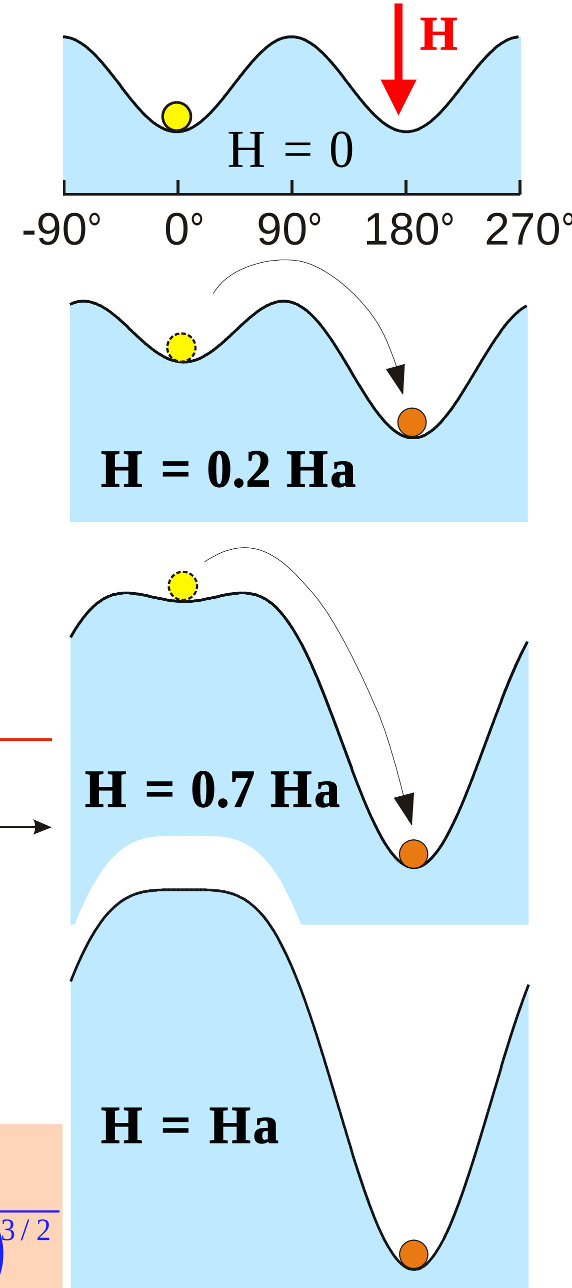
Predicted switching field:
Stoner-Wohlfarth 'astroïd'



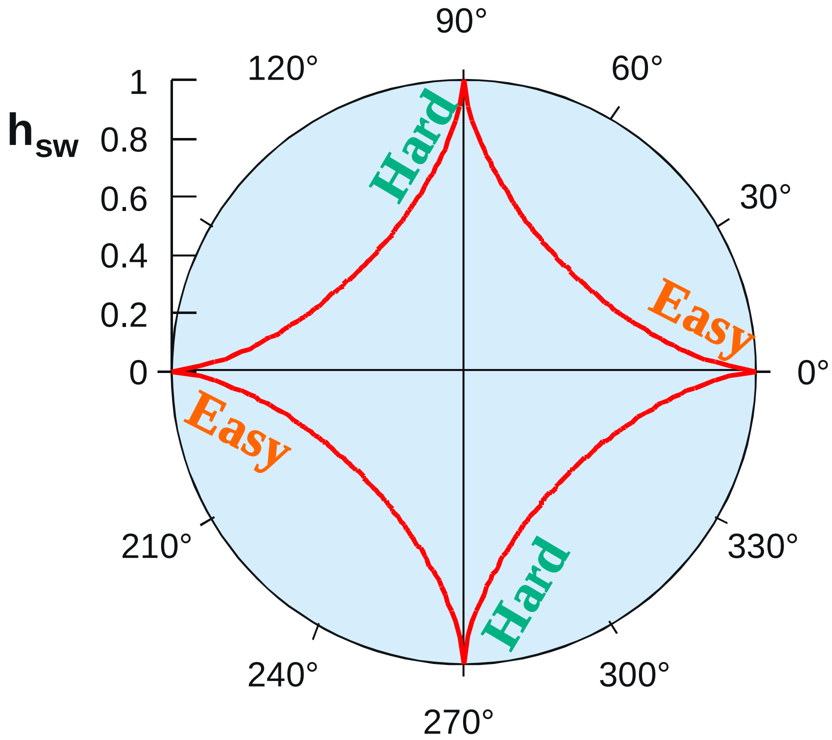
'Hysteresis loops'



$$H_{\mathrm{r}} = \frac{1}{\left(\sin^{2/3}\theta_{\mathrm{H}} + \cos^{2/3}\theta_{\mathrm{H}}\right)^{3/2}}$$

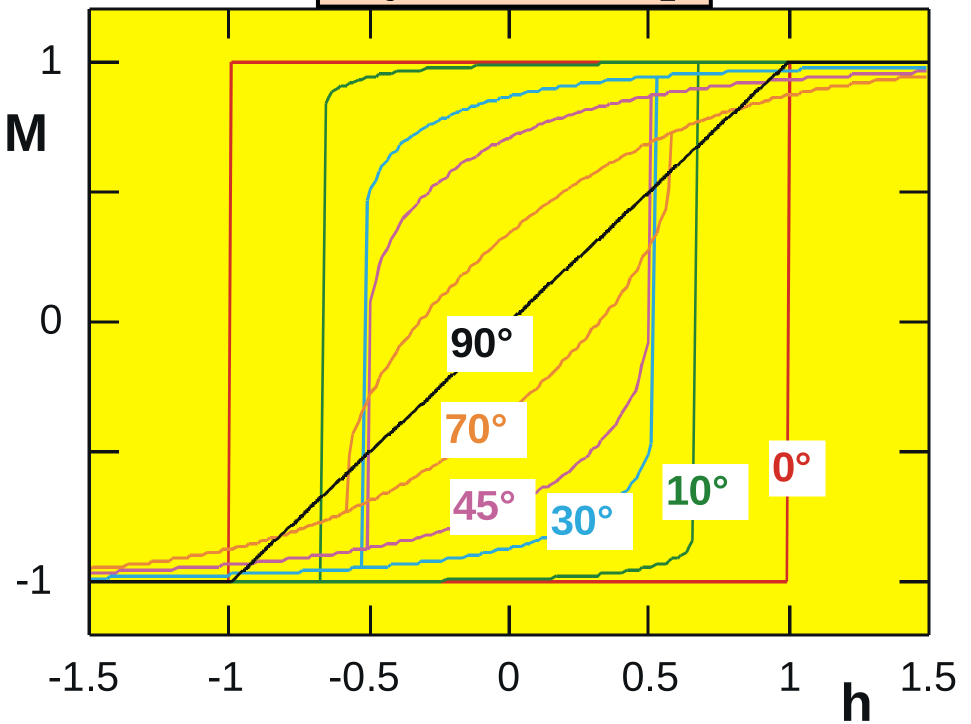


Switching field (polar plot)



Easy and hard axis have identical reversal fields…

Hysteresis loop



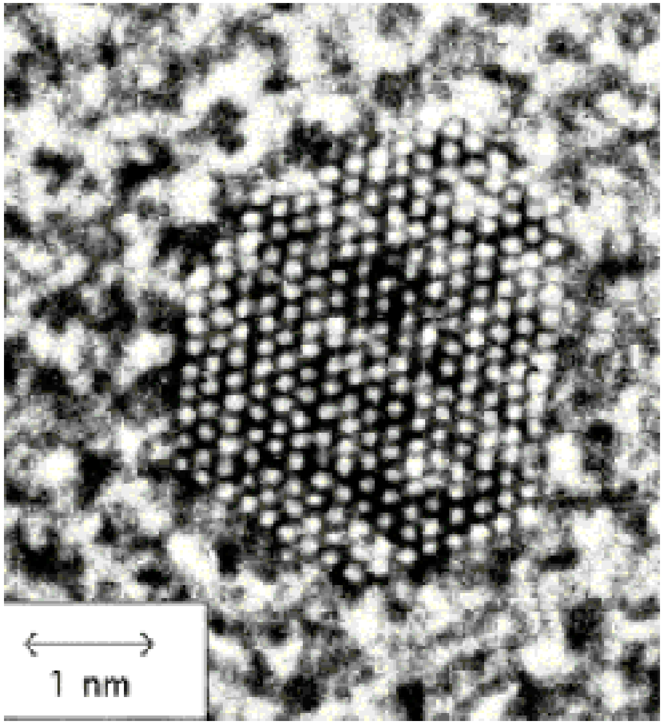
… but very different jump height !

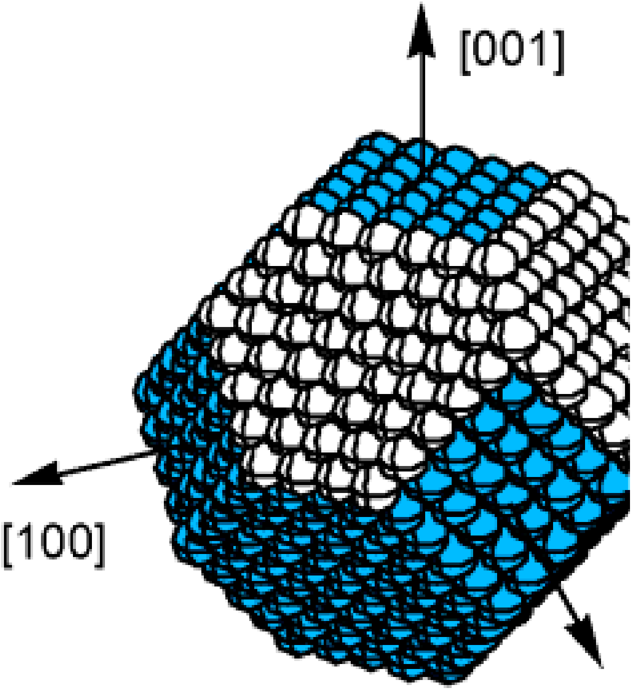
Coherent reversal model dates back to 1947, but the first experimental proof came in 1997!

DPM, CNRS, Lyon, France : LASER vaporization and inert gas condensation source

M. Jamet, V. Dupuis, M. Negrier, J. Tuaillon, A. Perez

Example of experimental evidence of coherent reversal



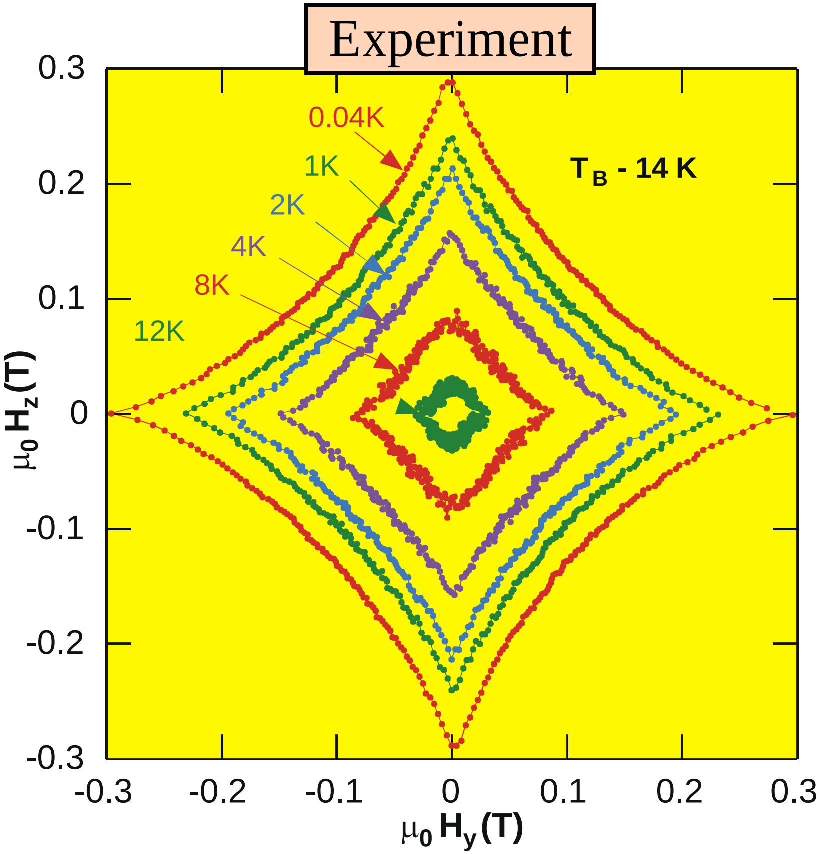


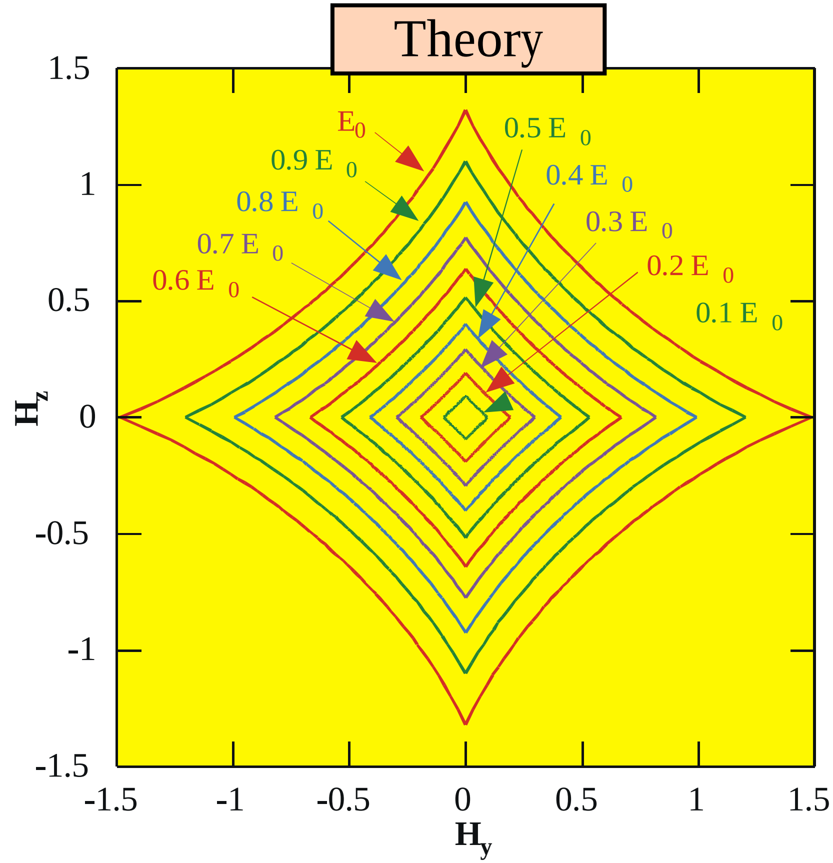
HRTEM along a [110] direction
fcc - structure, faceting

Tiny, model system

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

Experimental evidence for coherent reversal





Good agreement with Stoner-Wohlfarth model

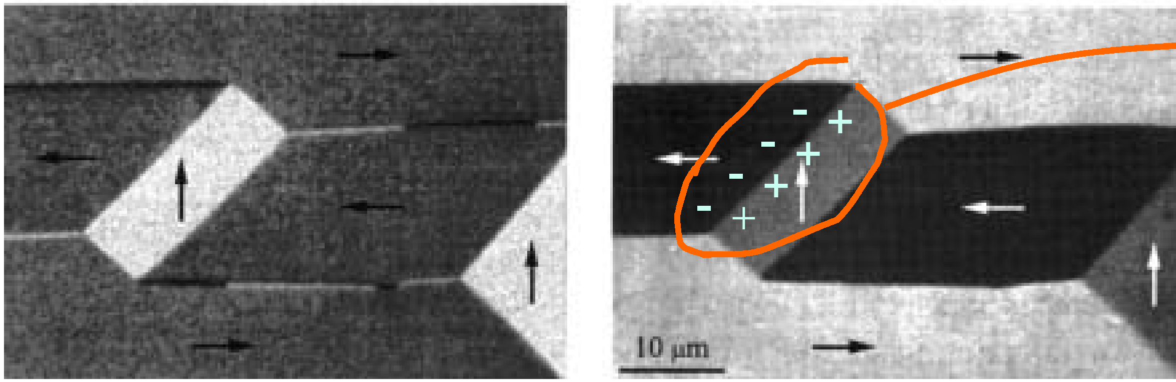
Agreement was found in the late 90's, only in tiny samples : not relevant for 'real' systems

Back to anisotropy well

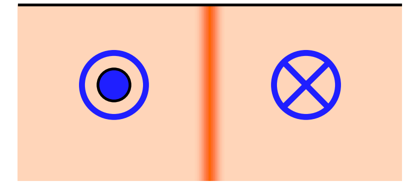
(see temperature dependance later in the lectures)

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

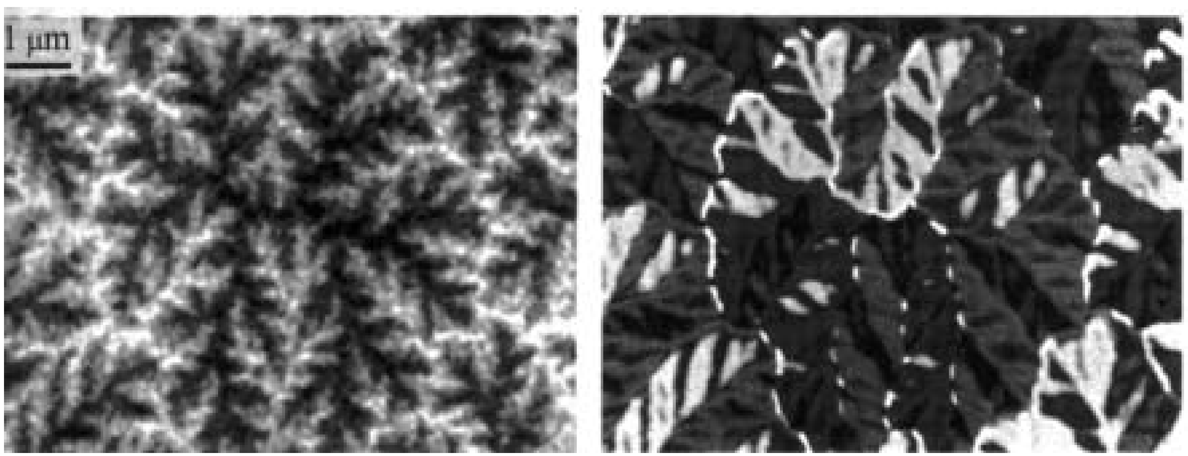
In most samples there are magnetic domains

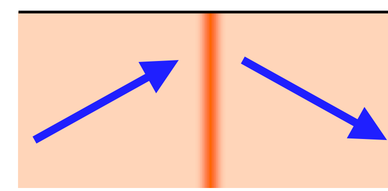


Note magnetic poles annihilation !



In-plane domains in FeSi(100) crystal – Kerr microscopy





Perpendicular M component **In-plane M component**

on Co(1000) crystal – SEMPA

Images: book by Hubert & Schäfer

- **Do domains contradict ferromagnetic theory** (exchange) ?
- What occurs at the **boundary between two domains** ?
- ↳ How domains will influenced by **microscale structures** ?

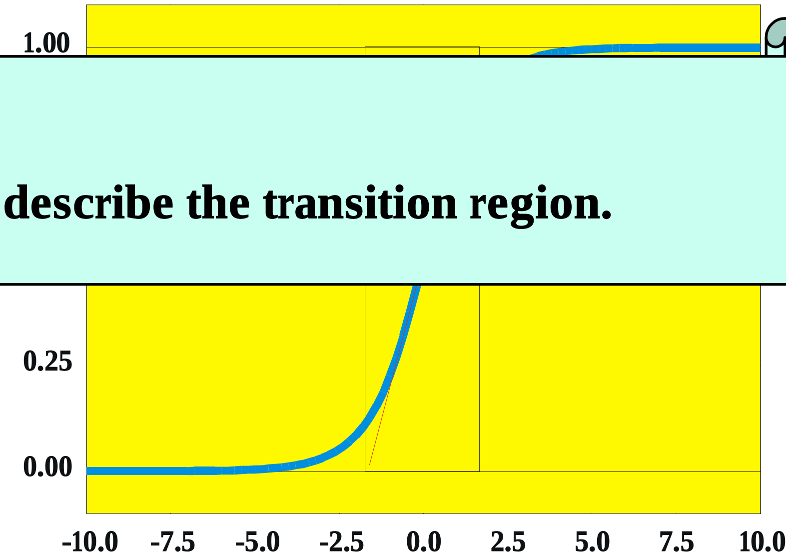
Bloch domain wall profile calculated by variational technique

$$e = A(d\theta / dx)^2 + K\sin^2\theta, \quad K > 0$$

exchange → J/m

anisotropy → J/m^3

$\theta = 0$? $\theta = \pi$



What happens in the middle ?

Try to develop a basic model to describe the transition region.

$$2K\sin\theta\cos\theta = 2A\frac{\partial^2\theta}{\partial x^2}$$

$$\boxed{\theta(x) = 2\,\mathrm{Atan}\left[\exp\left(\frac{x}{\sqrt{A/K}}\right)\right]}$$

(Bloch wall profile)

Asymptotic width: $\lambda_B = \pi\sqrt{A/K}$

(Bloch wall width)

Dimensional analysis: exchange against anisotropy

$\lambda_B = 1\mathrm{nm}$ → $\lambda_B = 100\mathrm{nm}$

Hard (magnets) Soft

See again magnetization reversal

Competition of dipolar and exchange energy

J/m

Exchange energy $e_{\mathrm{ex}} = A(\nabla\theta)^2$

J/m^3

Dipolar energy $e_{\mathrm{d}}^{\max} = \max \dfrac{1}{V} \iiint_{\mathrm{sample}} e_{\mathrm{d}}.d\tau = \dfrac{1}{2}\mu_0 M_{\mathrm{S}}^2$

Determine a length scale characteristic of dipolar / exchange competition

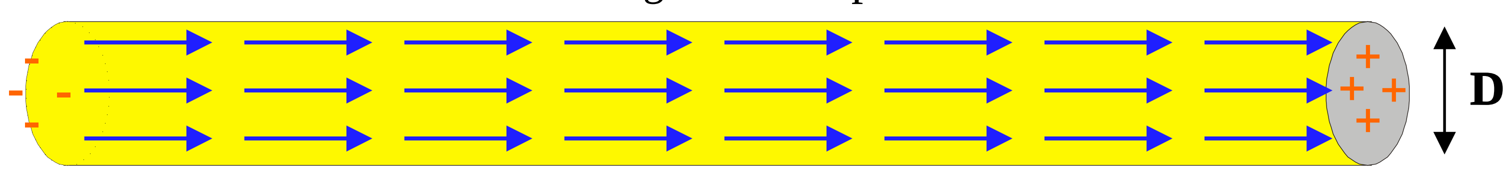
$\lambda_{\mathrm{ex}} = (\pi)\sqrt{2A/(\mu_0 M_{\mathrm{S}}^2)}$

(Exchange length)

Dimensional analysis: exchange against dipolar

Situation 2 : M parallel

Few surface charges : low dipolar fields ➥ favorable



If $D \geq 10\lambda_{\mathrm{ex}}$ Significant magnetization deviations appear at the cylinder length

What if dipolar and anisotropy compete

Anisotropy $$e_{\mathrm{an}} = K\sin^2\theta$$

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

Dipolar energy $$e_{\mathrm{d}}^{\max} = \max \frac{1}{V}\iiint_{\mathrm{sample}} e_{\mathrm{d}}.d\tau = \frac{1}{2}\mu_0 M_{\mathrm{S}}^2$$

Quality factor : $Q = 2K / \mu_0 M_{\mathrm{S}}^2$

Hard (permanent magnet) $Q \succ\succ 1$ ⟶ Anisotropy dominates over dipolar

λ_{B} is the most relevant length scale

Soft material $Q \prec\prec 1$ ⟶ Dipolar dominates over anisotropy

λ_{ex} is the most relevant length scale

Use of characteristic magnetic lengthscales : guess qualitatively the system's behavior.

- Is the magnetization in-plane or out-of-plane ?
- Is the system hard or soft ?
- Does the size of the system play a role ?
- Do we expect some domains ?

Real life is more complicated :

- Zeeman energy was not discussed in the previous slides
  ➥ more definitions of length scales
- Dimensional approach only:
  Exact numerical values depend on the exact sample geometry
- All four energies may play a role simultaneously

Magnetic imaging, analytical and numerical calculation have to be used to unravel the complexity of micromagnetics

Hypotheses:
- Infinitely soft material (K=0) $e_{\mathrm{mc}} = 0$
- 2D geometry (neglect thickness)
- Size >> all magnetic length scales (wall width) $e_{\mathrm{ex}} \longrightarrow 0$
- Zero external magnetic field $e_{\mathrm{Z}} = 0$

Looking for a solution with : $e_{\mathrm{d}} = 0$

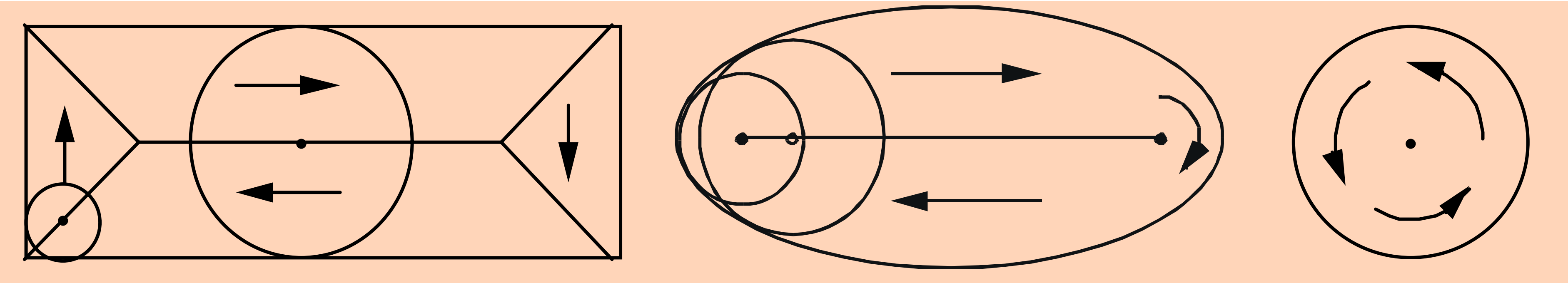
$\mathrm{div}\mathbf{M} = 0$ (no volume charges)

$\mathbf{M}.\mathbf{n} = 0$ (no surface charges)

« Flux closure »

H. A. M. Van den Berg, *J. Magn. Magn. Mater.* **44**, 207 (1984)

EXAMPLES



See walls: charge free

See volume: charge free

Extension for non-zero field :

The domains with magnetization parallel to the applied field are favored

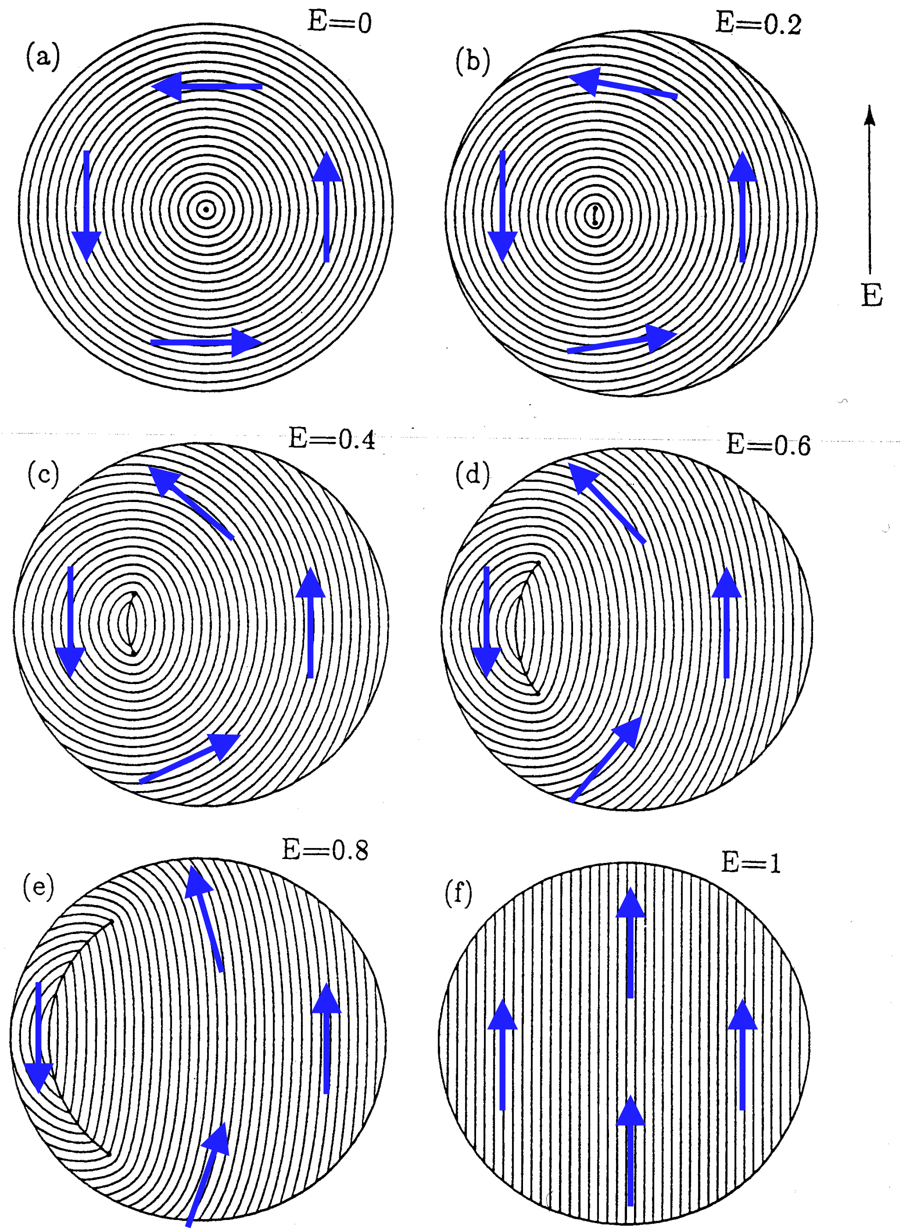


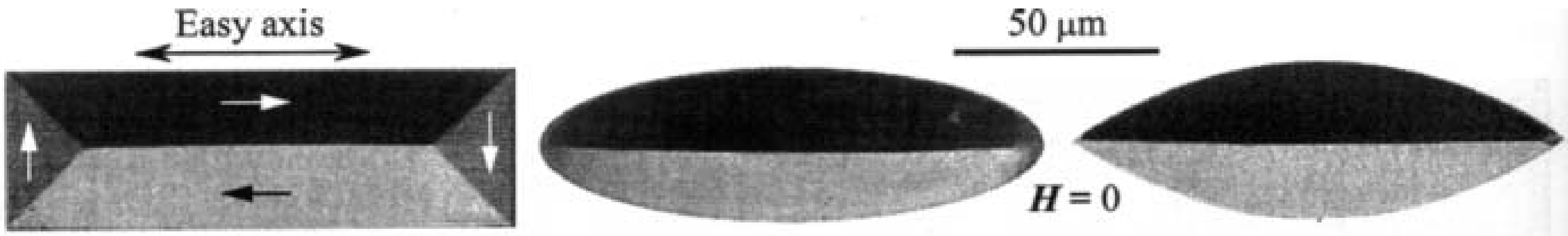
Figure 3

P. Bryant et al., *Appl. Phys. Lett.* **54**, 78 (1989)

In the following, many pictures taken from Hubert's book

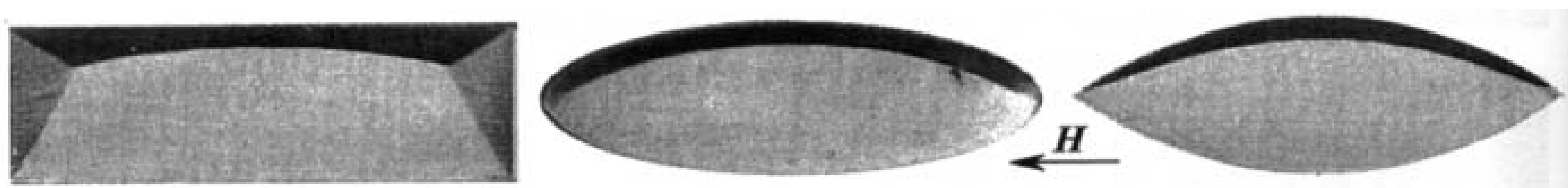
Zero field : agreement with Van den Berg's model

Material : $Ni_{80}Fe_{20}$
'Permalloy', Py.

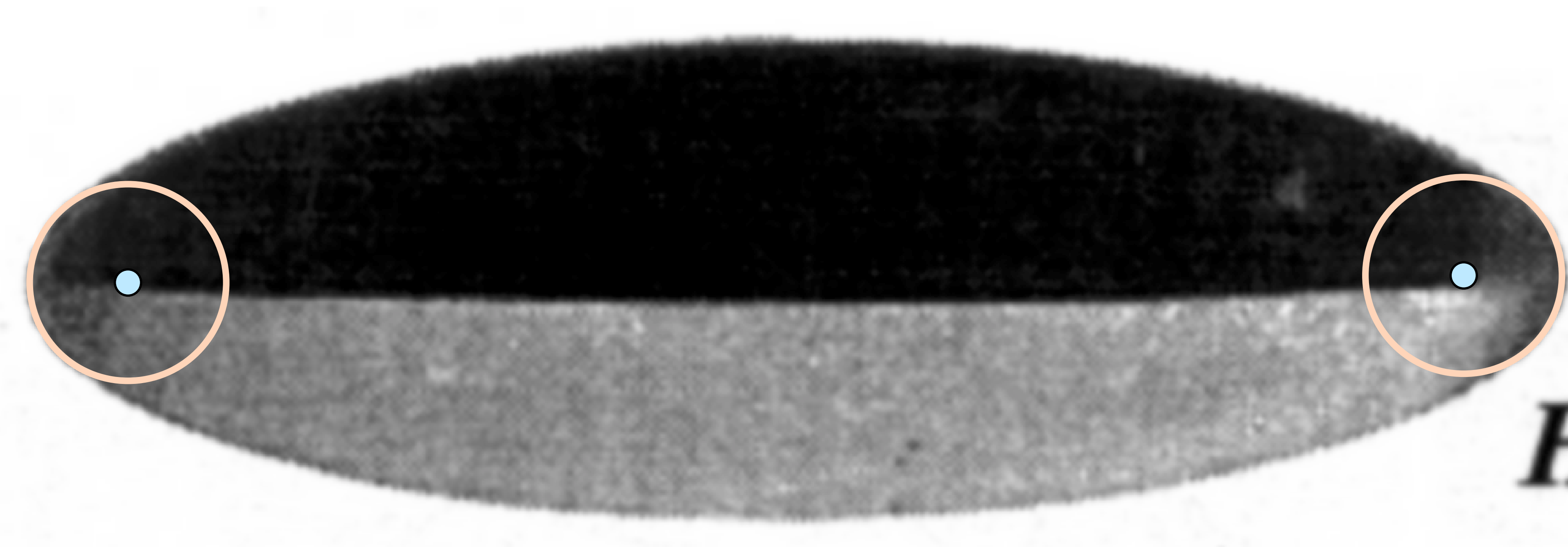


View details

Longitudinal applied field



The domains with magnetization parallel to the applied field are favored

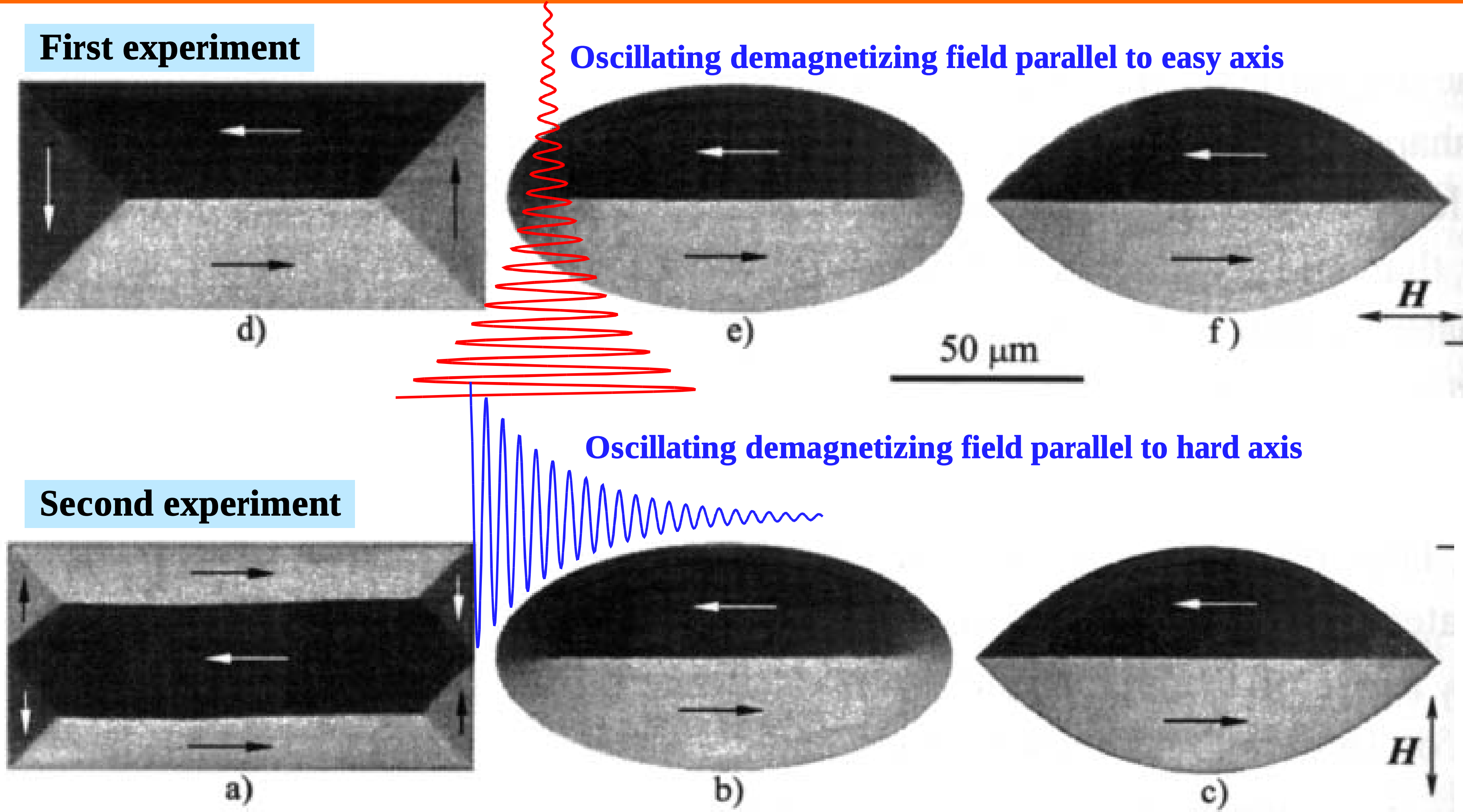


First experiment

Oscillating demagnetizing field parallel to easy axis

Oscillating demagnetizing field parallel to hard axis

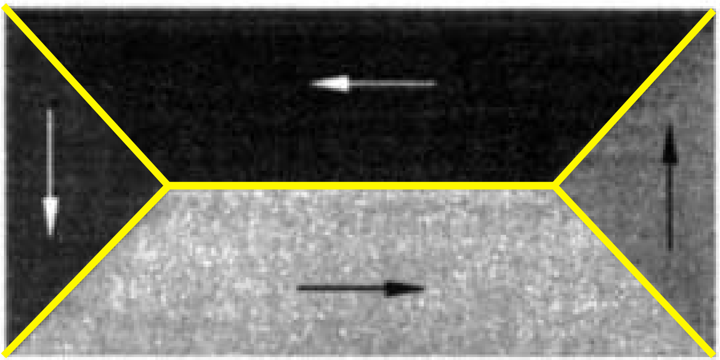
Second experiment

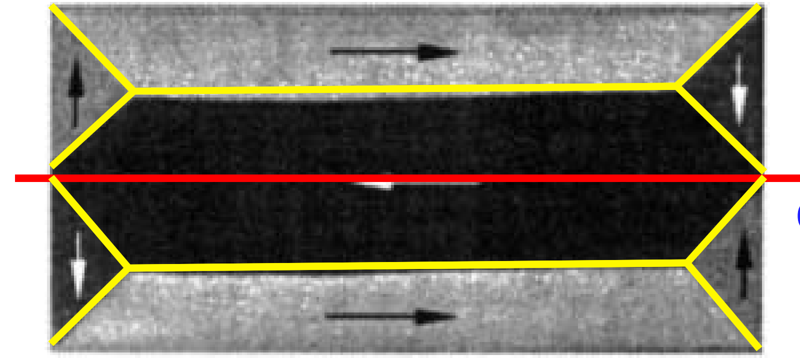


<u>Questions:</u>

- Compatibility with Van den Berg's model ?
- Why more fragmentation with H applied along hard axis ?
- Why leaf and ellipsoid not affected ?

Compatibility with Van den Berg's model ? YES





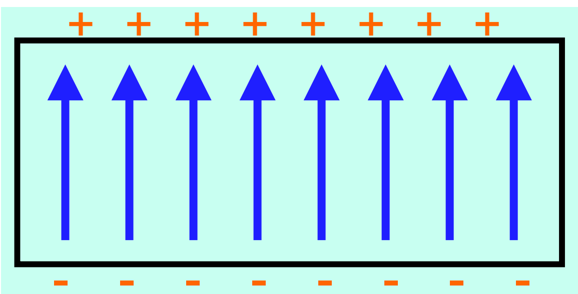
$$\mathrm{div}\,\vec{\mathbf{M}} = 0$$

$$\vec{\mathbf{M}}.\vec{\mathbf{n}} = 0$$

Artificial separation → Still compatible with model

(Analogy with fluid dynamics)

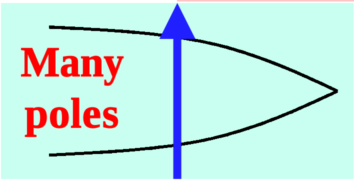
Why more fragmentation with H applied along hard axis ? More poles

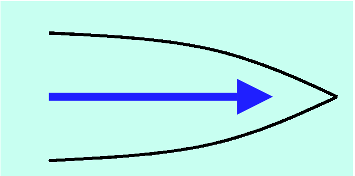


Many magnetic poles at saturation :
spins start to rotate at many places simultaneously
↳ **Fragmentation of domains**

Why leaf and ellipsoid not affected ? Not completely clear !

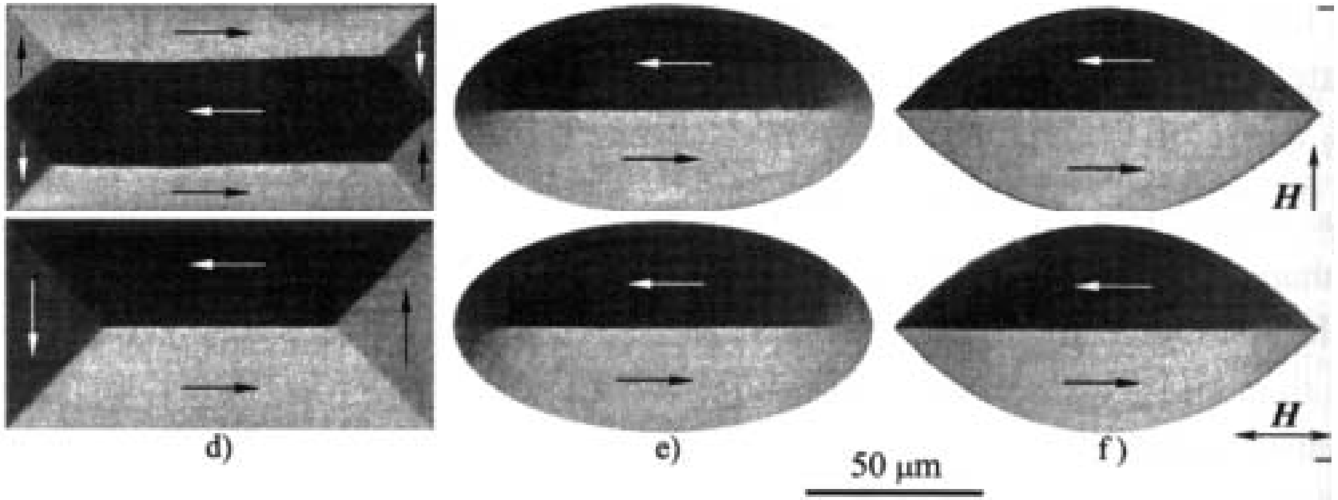
Experimental finding : pointed ends stabilize ('pin') magnetization



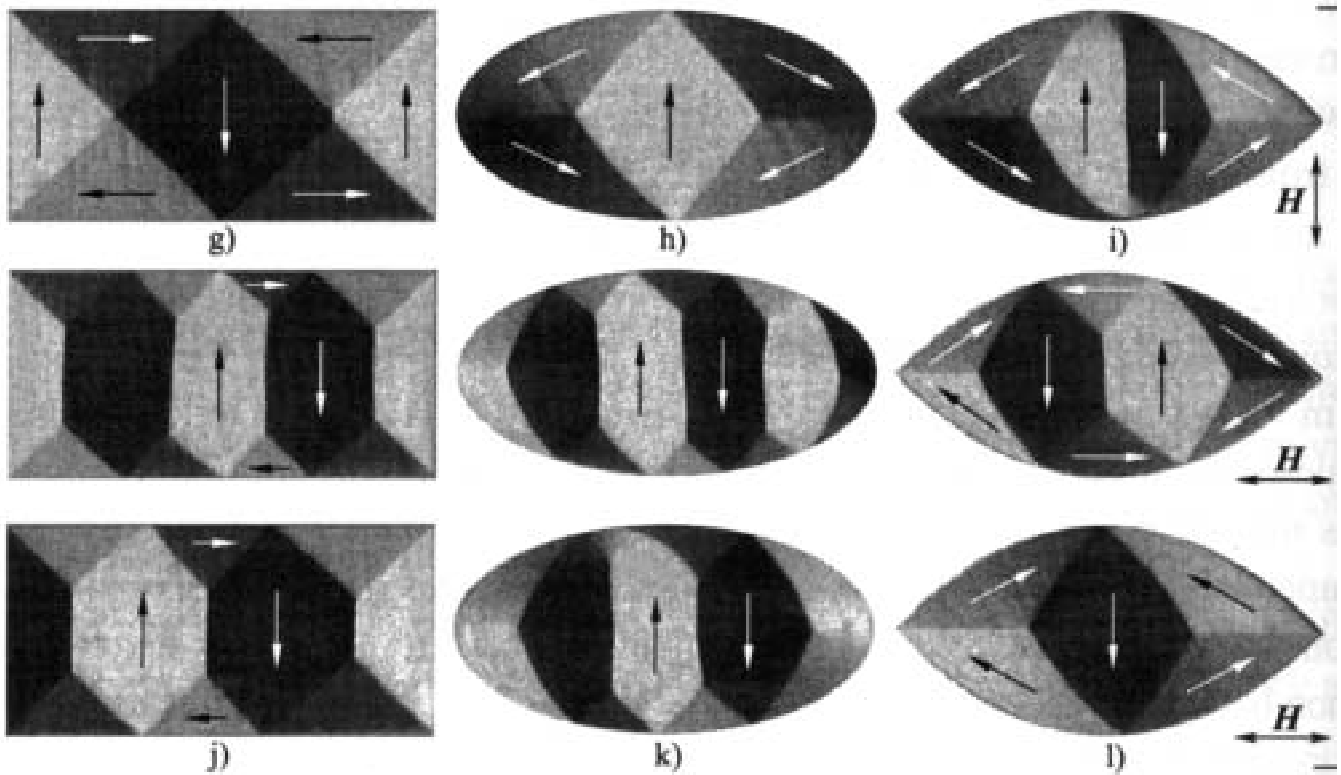


Few poles

Local energy minimum:
magnetization is pinned



Easy axis of **weak** magnetocrystalline anisotropy



Easy axis of **weak** magnetocrystalline anisotropy

Large dots

↪ many degrees of freedom

↪ many possible states

↪ history is important

↪ even slight perturbations can influence the dot (anisotropy, defects, etc.).

History Such structures have been studied for decades.

Sensitivity. As seen above, possibility to have complex and unpredictable magnetization states:

➥ **Great care must be taken for the design of the dot**:

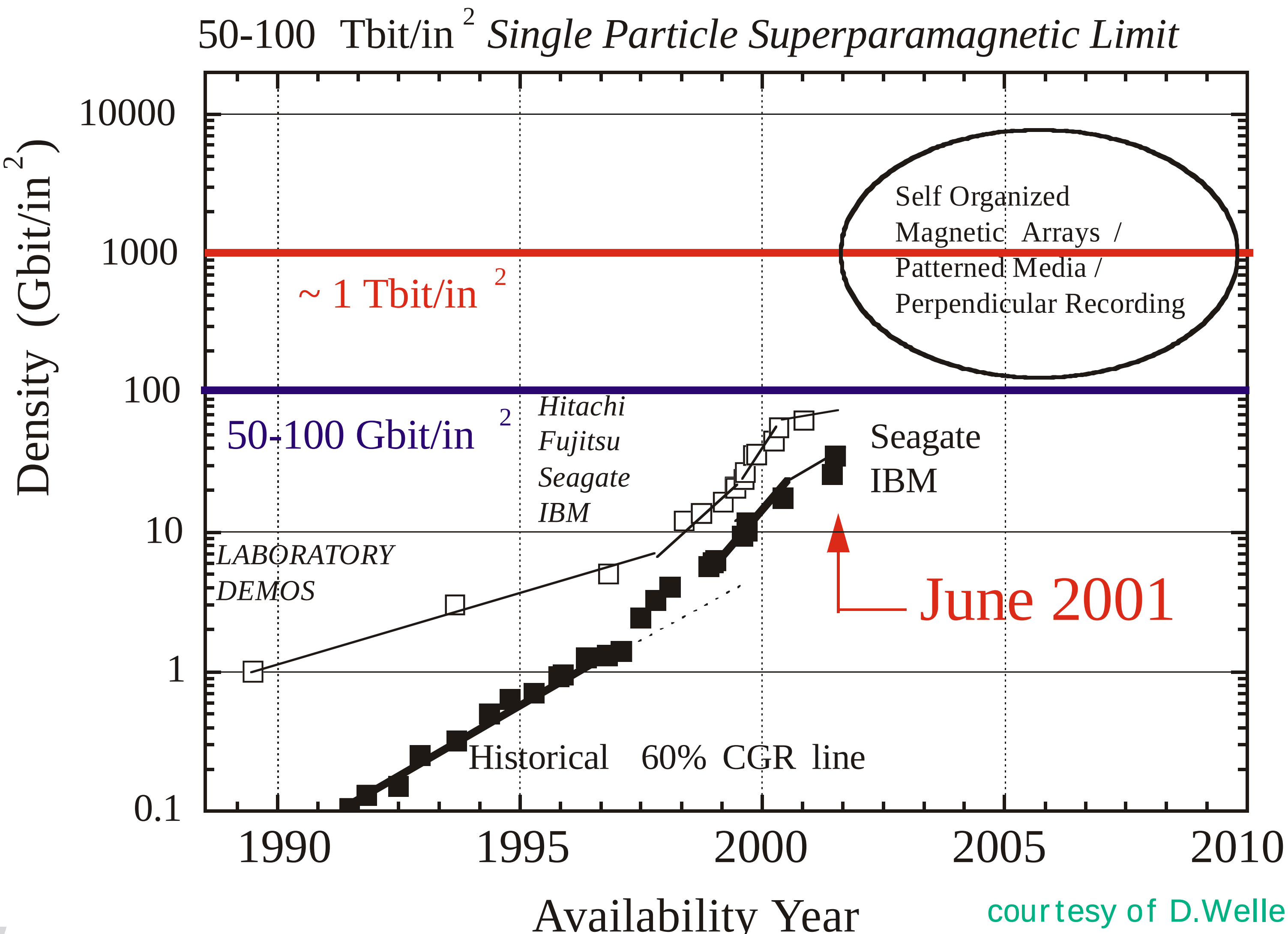
Ground state ?

Magnetization reversal and field response ?

Defects ?

With in-plane magnetization

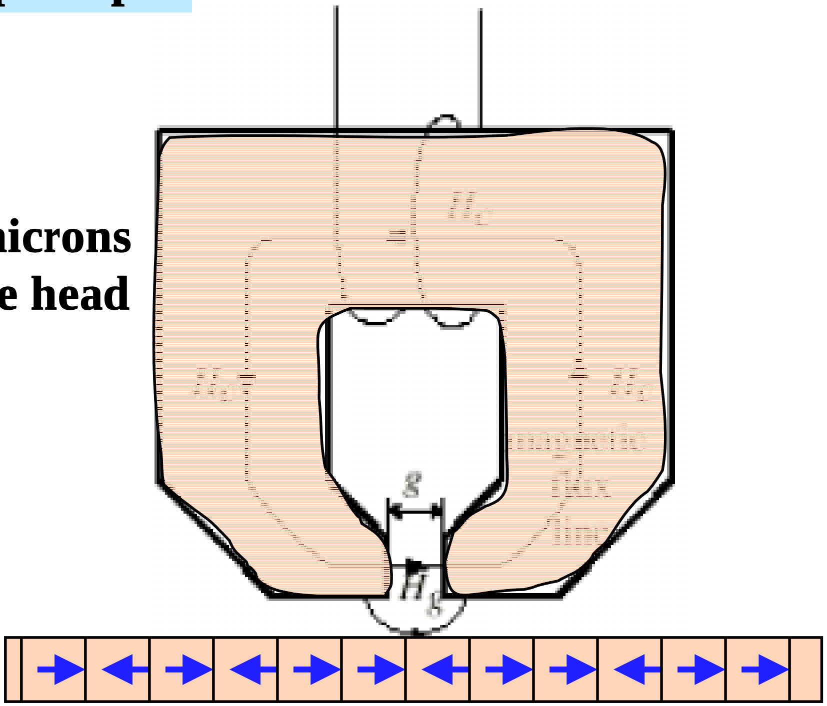
Longitudinal recording media density (Hard disks)



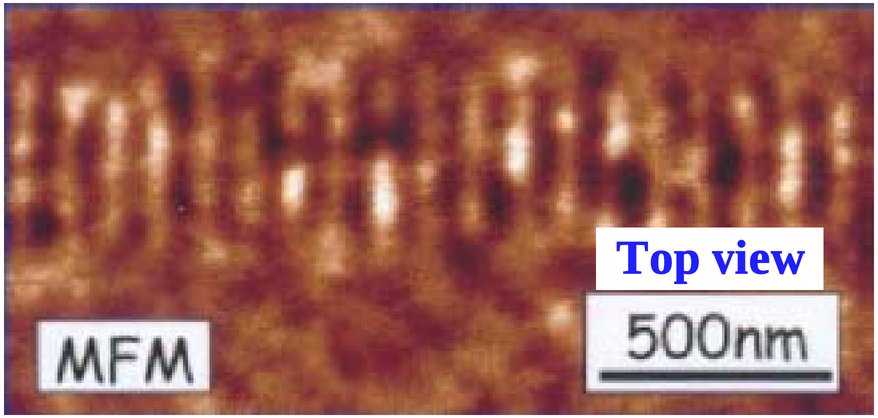
courtesy of D.Weller – Seagate, N. Dempsey, LLN-CNRS

Longitudinal recording : principle

Tens of microns read/write head



Media cross-section



View of state-of-the-art hard disk media

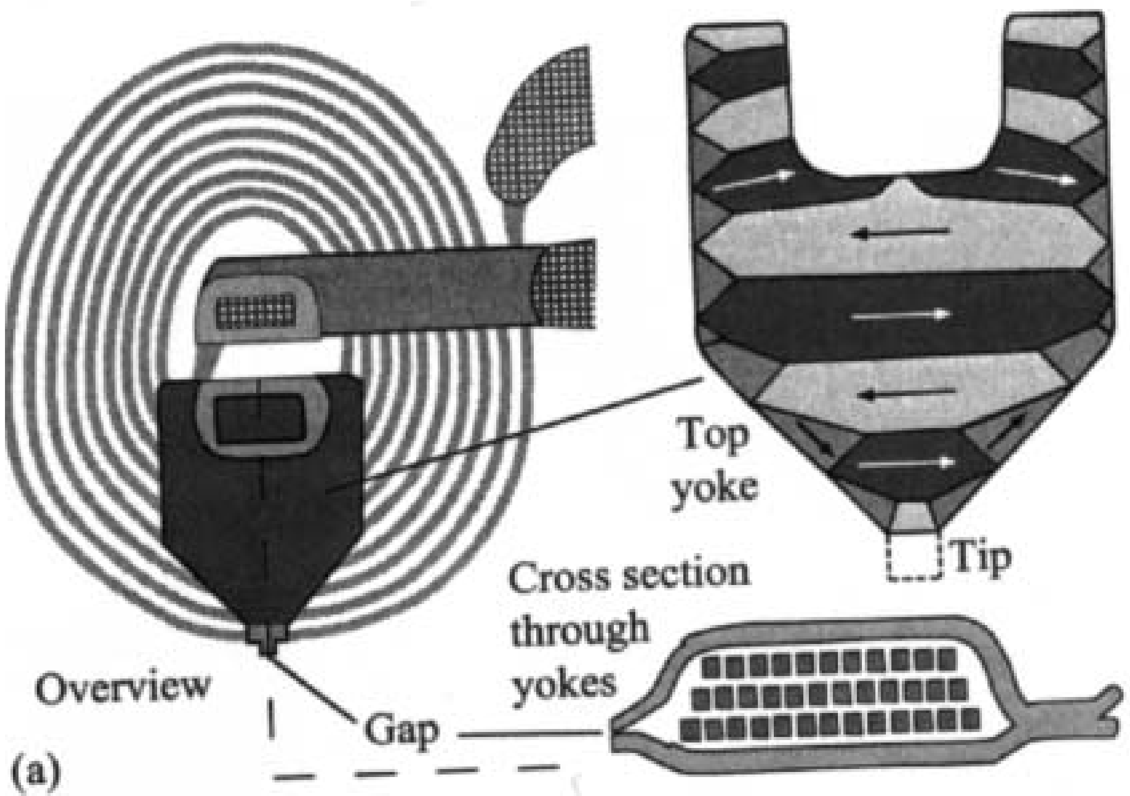
35Gbit/in^2

Images courtesy of J.-P. Nozières, LLN-CNRS,
S. Wang, Stanford University

Domain pattern in a recording head

The yokes are nearly saturated during the writing process…

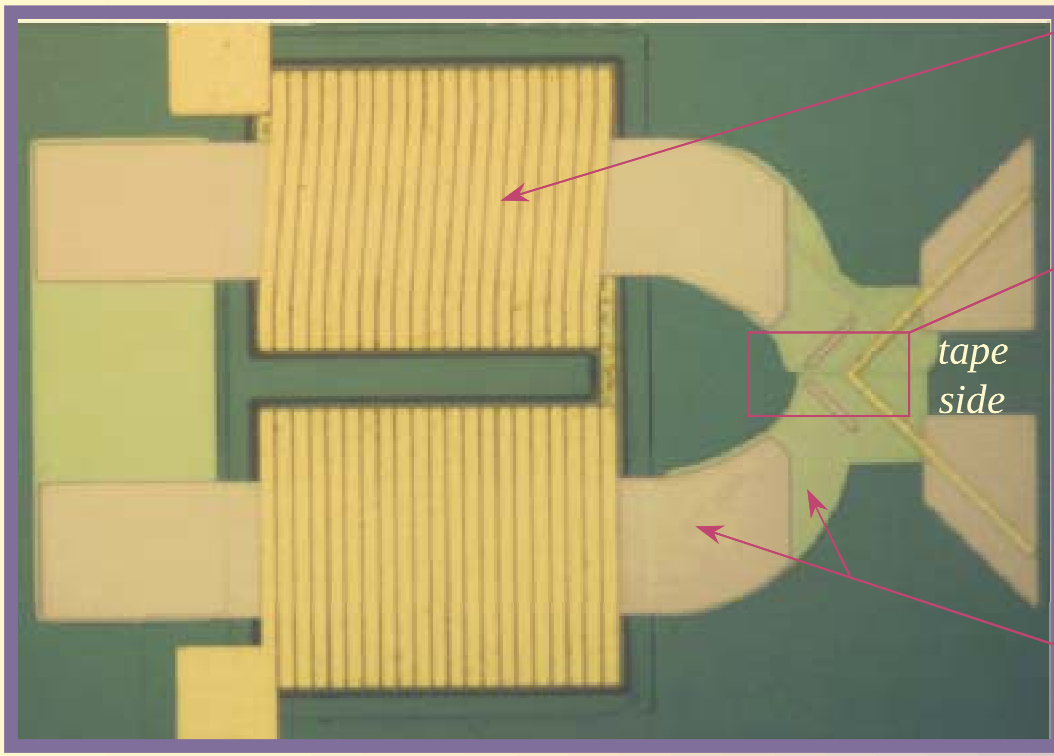
Explain why a slight perpendicular magnetocrystalline anisotropy is used
(interesting during read-out)



- Less noise ('pop-corn')
- Linear response (non-pinned spins)

This type of heads if not anymore used for read-out in HDD

Top View of HSS Head



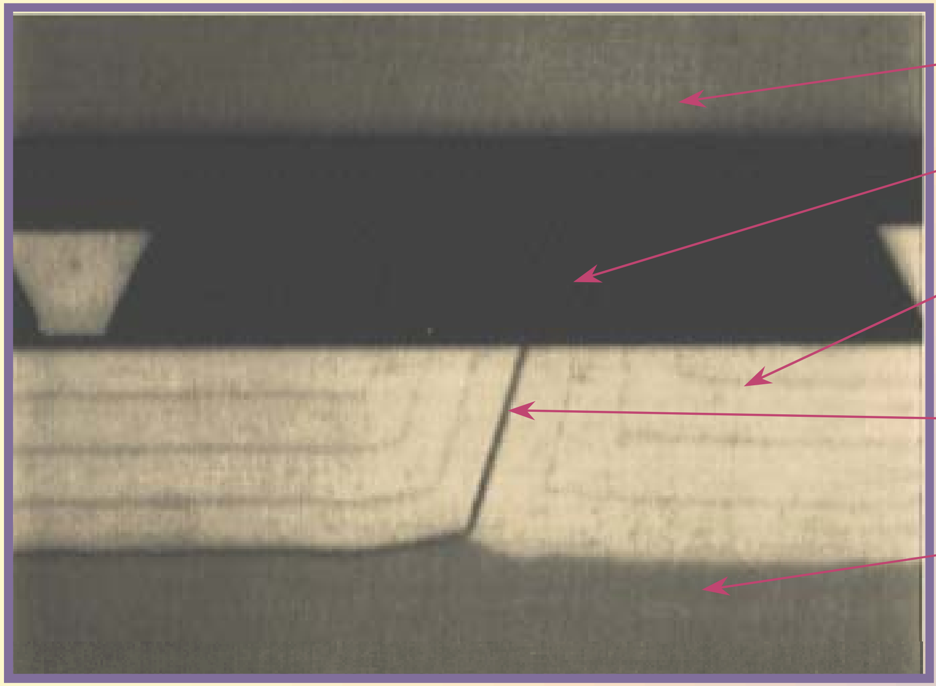
40-turns copper solenoid

marks for gap depth measurement and micromachining

magnetic circuit

ALDITECH *Jean-Baptiste Albertini* *Juin 2001*

Poles and Gap with Azimuth



silicon superstrate

silicon dioxide

magnetic quadrilayer

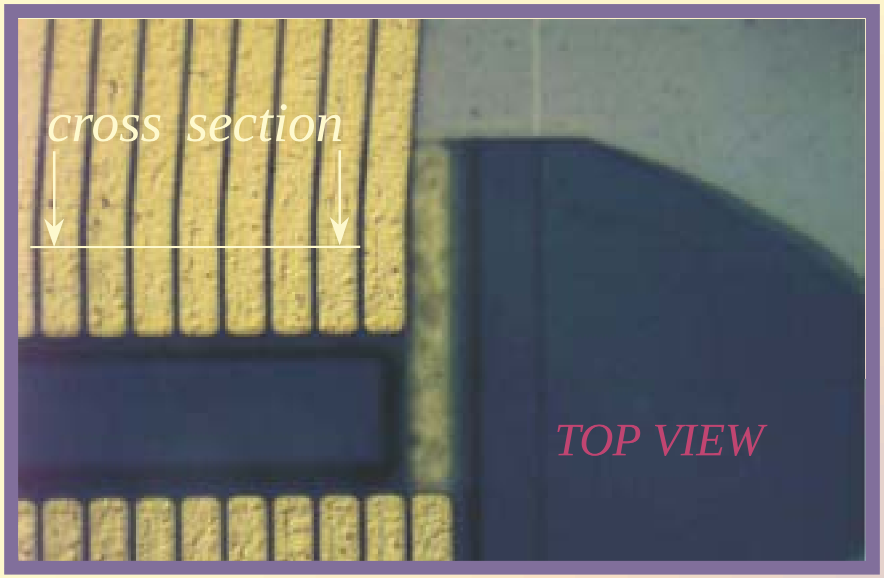
gap with 20° azimuth

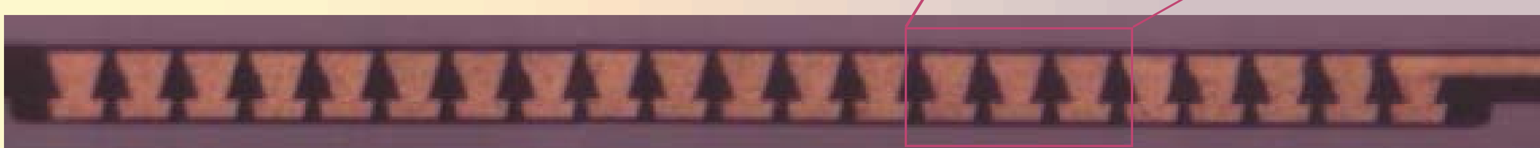
silicon substrate

VIEW FROM TAPE SIDE

ALDITECH　　Jean-Baptiste Albertini　　Juin 2001

Solenoid Coil : *Electrical Connections*

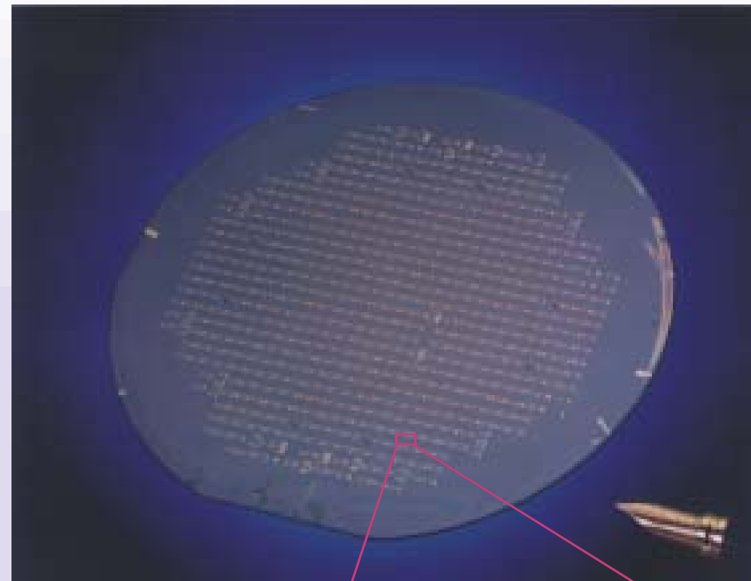




Cross section of the electrical connections in the solenoid coil

ALDITECH *Jean-Baptiste Albertini* *Juin 2001*

Silicon Technology : 2000 heads /wafer



High performance

Extreme miniaturization

Narrow track width

Good uniformity

Mass production

High yield

New features

GMR

Hard material

Integrated azimuth

Multiple heads in a chip

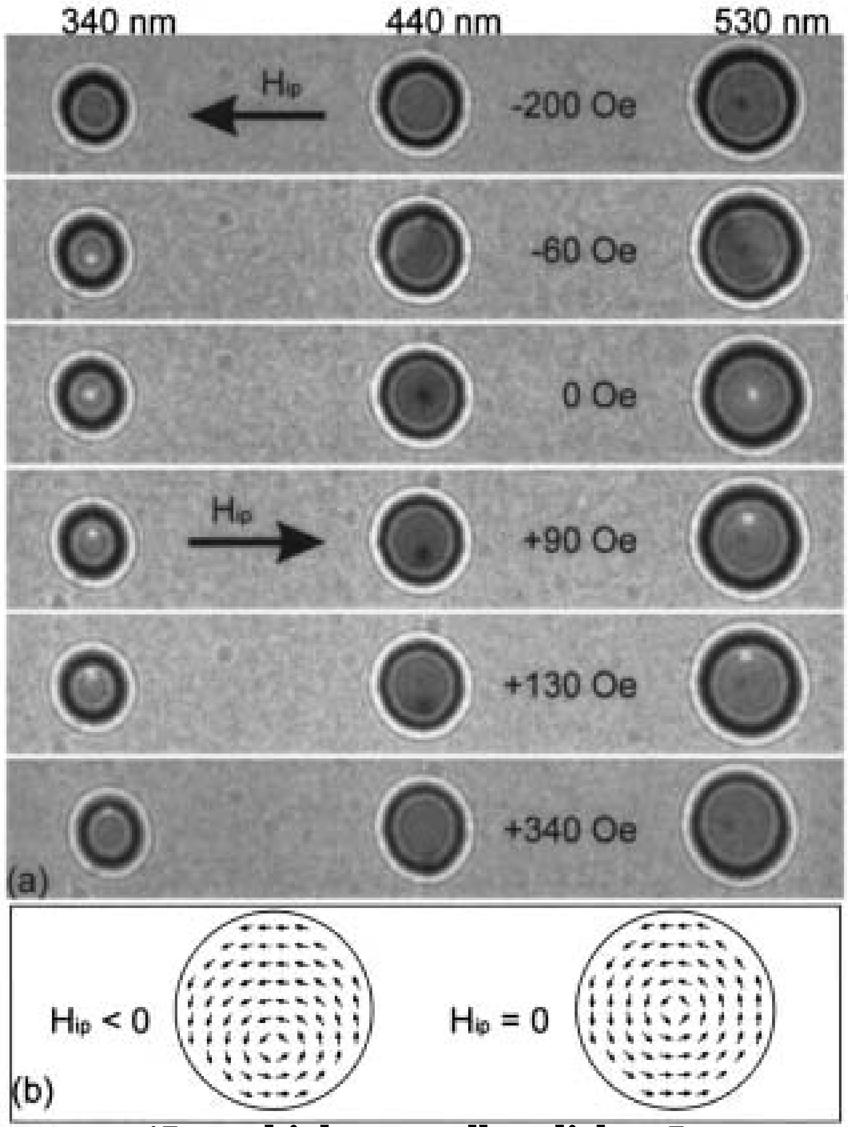
Protected by 16 worldwide patents

ALDITECH *Jean-Baptiste Albertini* *Juin 2001*

Patterned magnetic structures :

current and prospective applications

Macroscopic and microscopic features

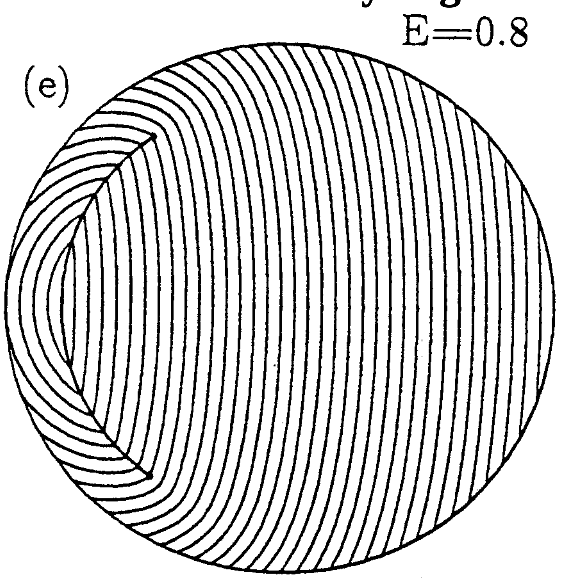


15nm thick permalloy disks ; Lorentz microscopy

M. Schneider et al., Appl.Phys.Lett.77(18), 2909 (2000)

- Macroscopic : Flux-closure configuration

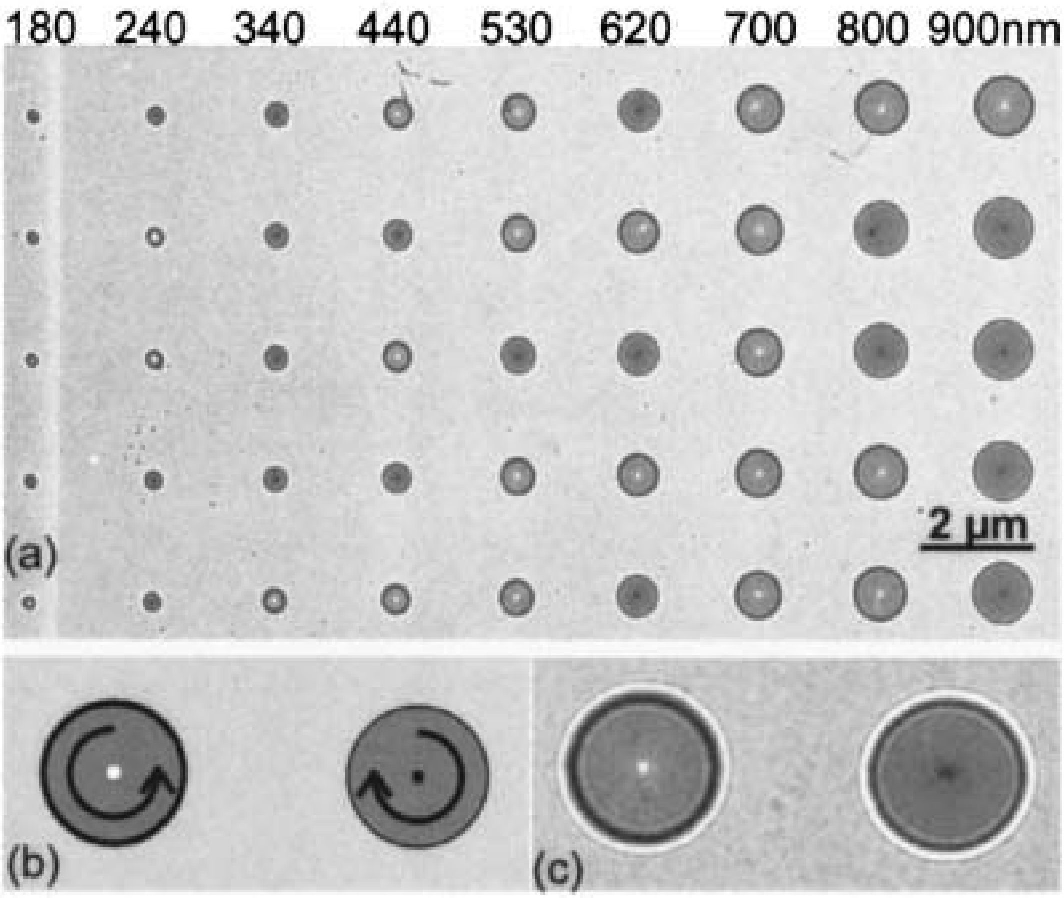
Prediction for infinitely large disk :



P. Bryant et al., *Appl. Phys. Lett.* **54**, 78 (1989)

- Microscopic : vortex, not domain wall

Macroscopic and microscopic features



15nm thick permalloy disks

M. Schneider et al., Appl.Phys.Lett.77(18), 2909 (2000)

Do we expect the vortex state down to very small size ?

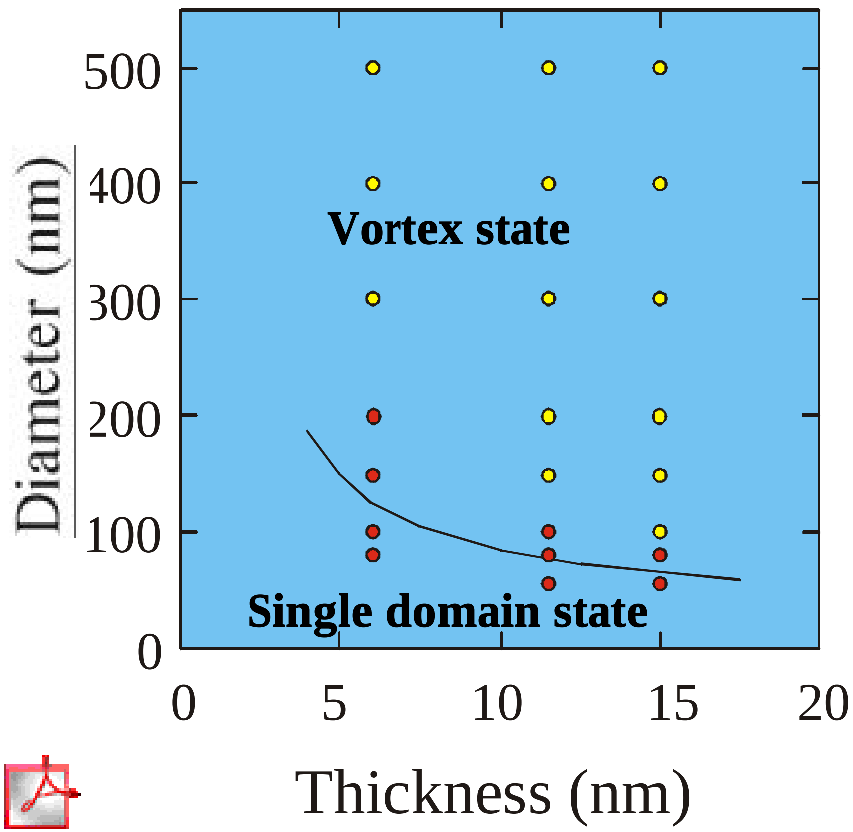
NO

Exchange and dipolar compete

↳ λ_{ex} **is a relevant length scale**

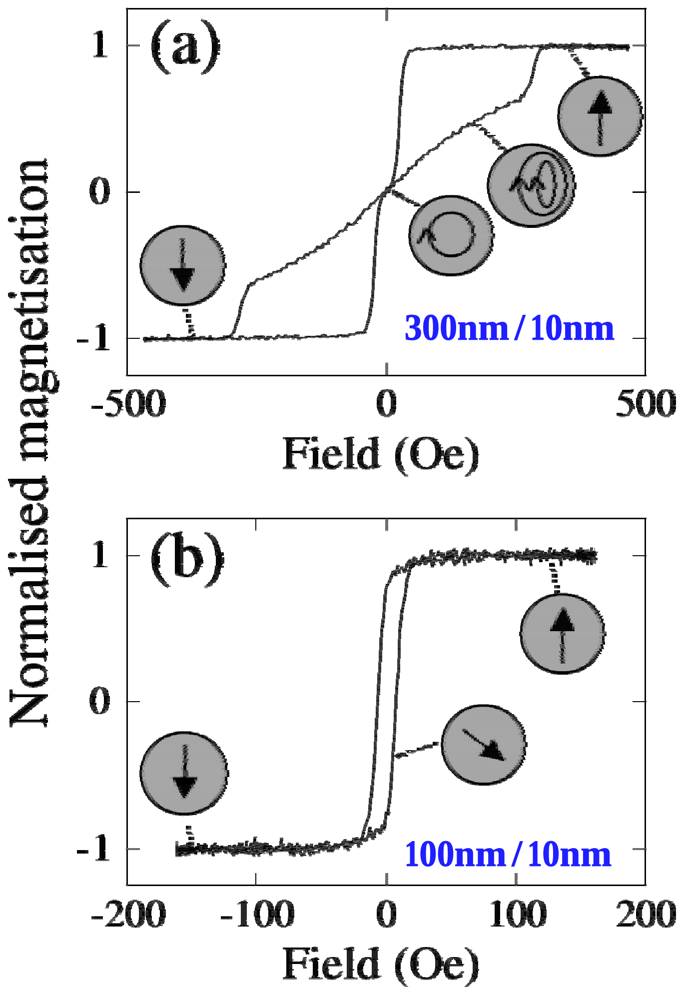
Vortex state should disappear at least below 5-10 times λ_{ex} ➡ 25-50nm diameter

'Phase diagram' of single domain versus flux-closure



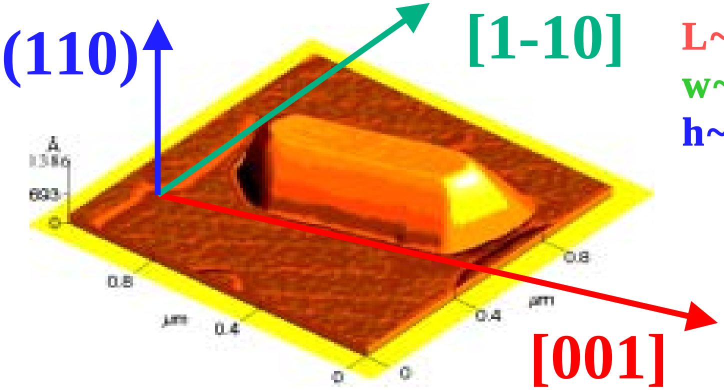
R.P. Cowburn, J.Phys.D:Appl.Phys.33, R1–R16 (2000)

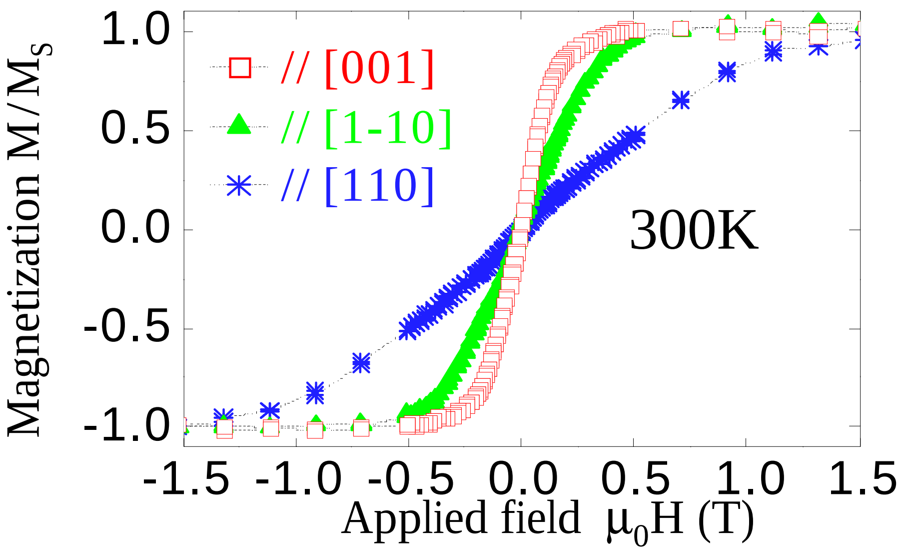
How do reversal loops look like ?



- Single domain state becomes favorable well above λ_{ex}
- Dipolar energy is higher for thicker dots
  (think in terms of magnetic charges)

Magnetometry, microscopy, and calculations in a sub-micron-size 3D dot

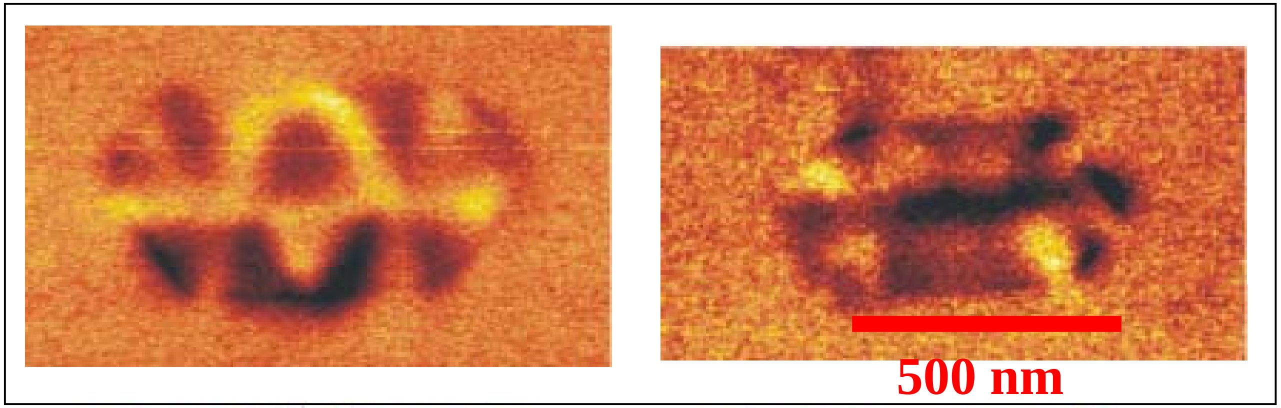




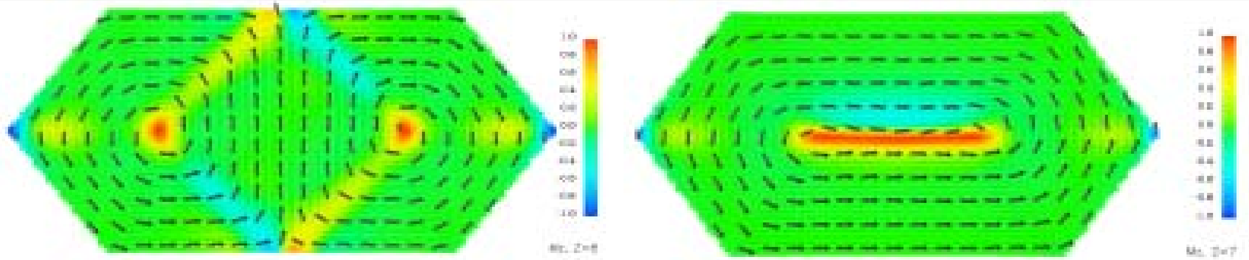
P.-O.Jubert *et al.*, Phys.Rev.B 64, 115419 (2001)

MFM measurements
(Y. Samson, DRFMC)

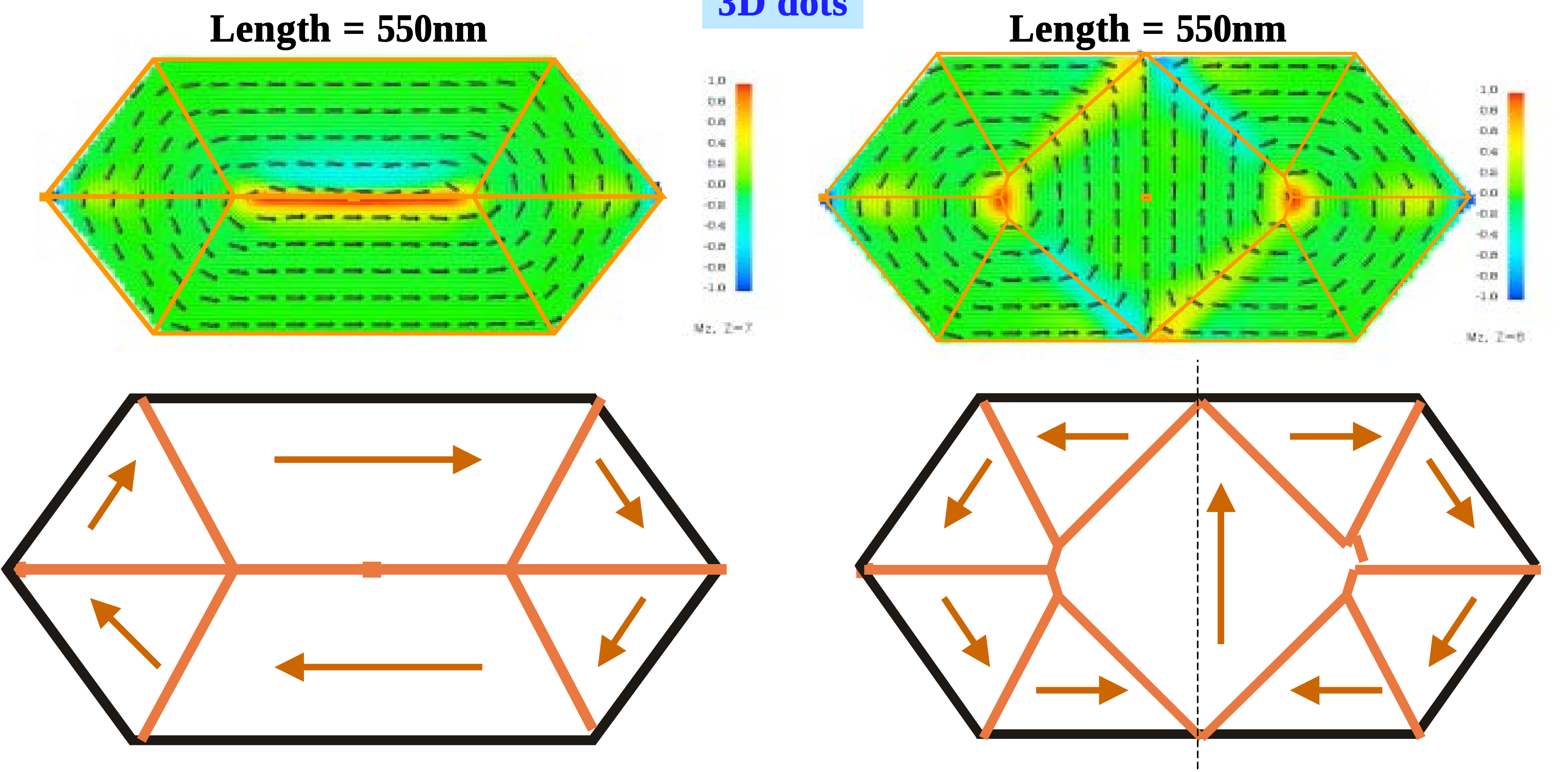
H_{sat} // [001]



Numerical calculations
(J.C. Toussaint)



3D dots



Van den Berg's model is still valid although size is < micron

Reason : High thickness ▶ High dipolar fields ▶ flux closure more favorable

The size is not the only factor determining the single domain/flux closure state. Anisotropy (even weak) and thickness are also key parameters

What recipes can we use to be sure to fabricate single-domain dots ?

Soft materials

- **Moderate thickness**
- **Moderate lateral size**

(Critical size can be increased using shape dipolar anisotropy, see later)

Semi-soft materials

- **Moderate thickness**
- **Moderate magnetocrystalline anisotropy (even for Q<<1)**
- **Arbitrary size**

Note from fundamental studies:
If devices require only one dot per chip is needed, then micron-size or well-above micron dimensions are sufficient
➥ High resolution lithography not required ➥ lower cost.
<u>These devices would make use of</u>:

<u>moderate thickness AND moderate magnetocrystalline anisotropy</u>
(or other tricks)

Applications of micron-size single-domain dots

(current and prospects)

- **Magnetic field sensors**

  Resistance depends on magnetization orientation.

Do not need magnetization reversal: use only susceptibility
➥ 'easy' to achieve low noise

- **Magnetic memories (MRAM)**

  Resistance depends on magnetization orientation.
  ➥ non volatile

- **Magnetic recording**

  Patterned media with one bit per dot ?
  ➥ extremely high density

- **Magnetic computing**

  Replace wires by chains of magnetic dots
  ➥ extremely low consumption

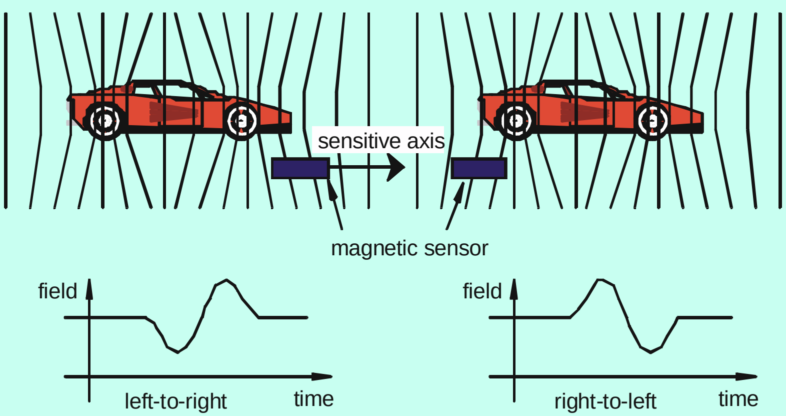
For all these applications:
Thin films and elements ➔ high integration ➔ new devices and low prices

Some physical effects can be used for field sensing…

Applications:

- Hard disks heads
- Tape heads
- Magnetic sensors: position, rotation, etc.

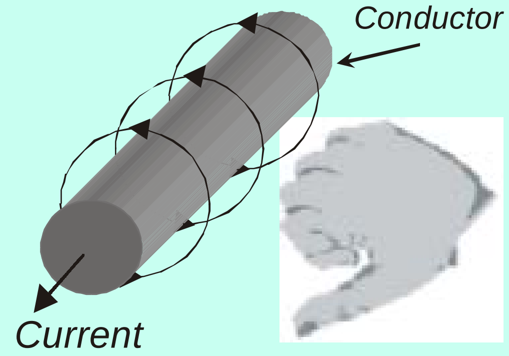
Movement detection



Direction sensing for vehicles driving over magnetic sensor.

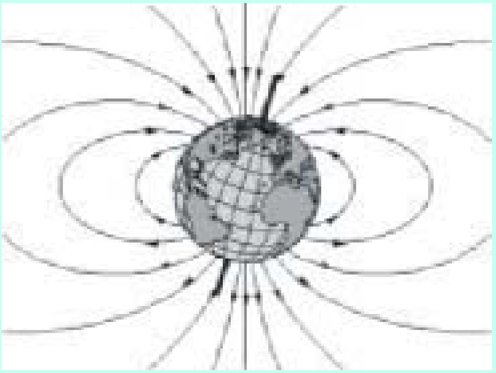
Images from Honeywell

Current sensing



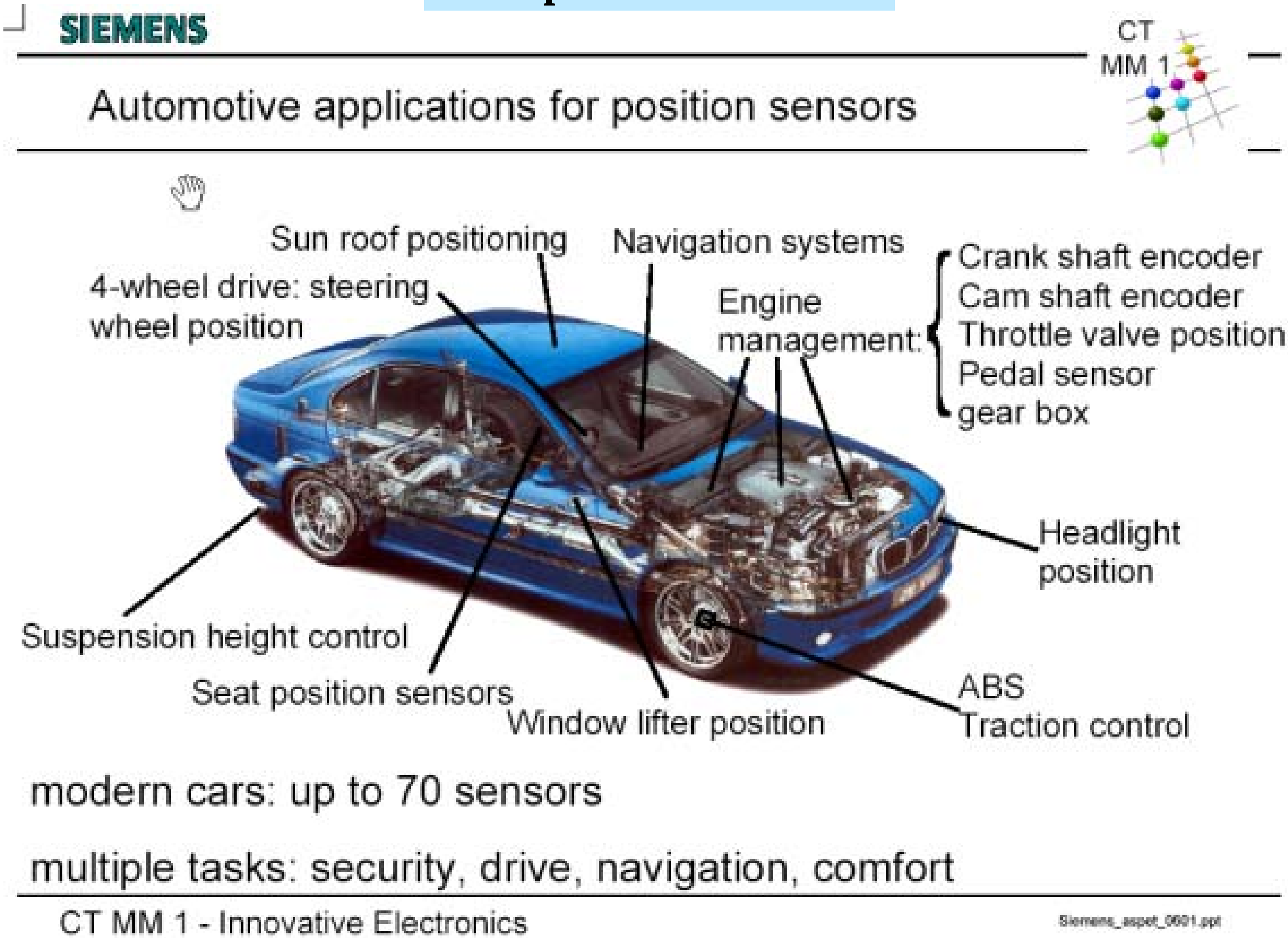
Precise, fast, robust.

Positioning



The earth's magnetic field can be approximated by a dipole field

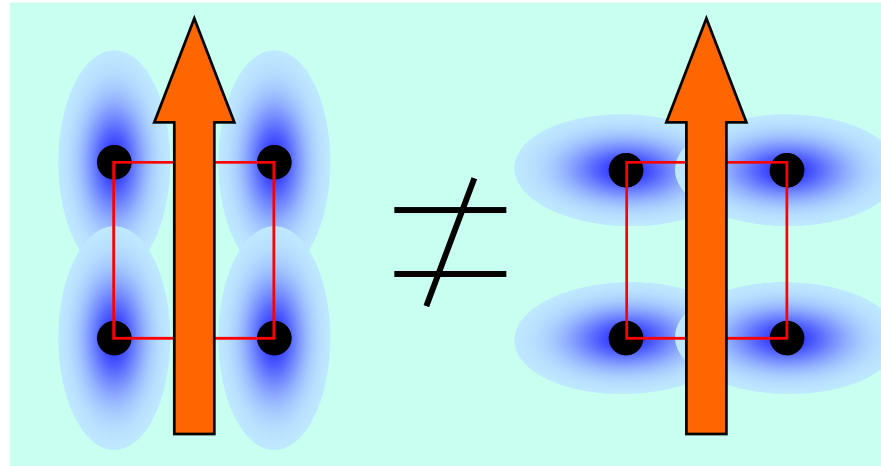
Example of sensors : cars



Slide J. Bangert (Siemens – Erlangen) for Workshop in Aspet (France, 2001)

Field sensing effect : anisotropic magnetoresistance

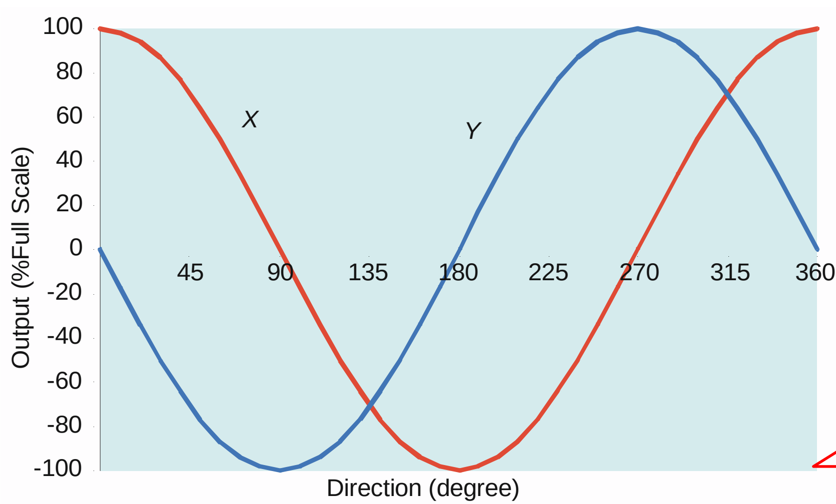
Spin-orbit coupling

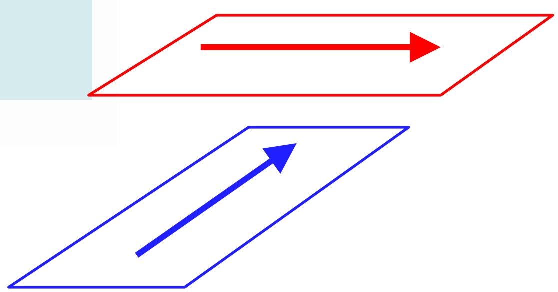


Electrical current

Design: very simple (1 single-domain structure)

Magnitude: ~1%

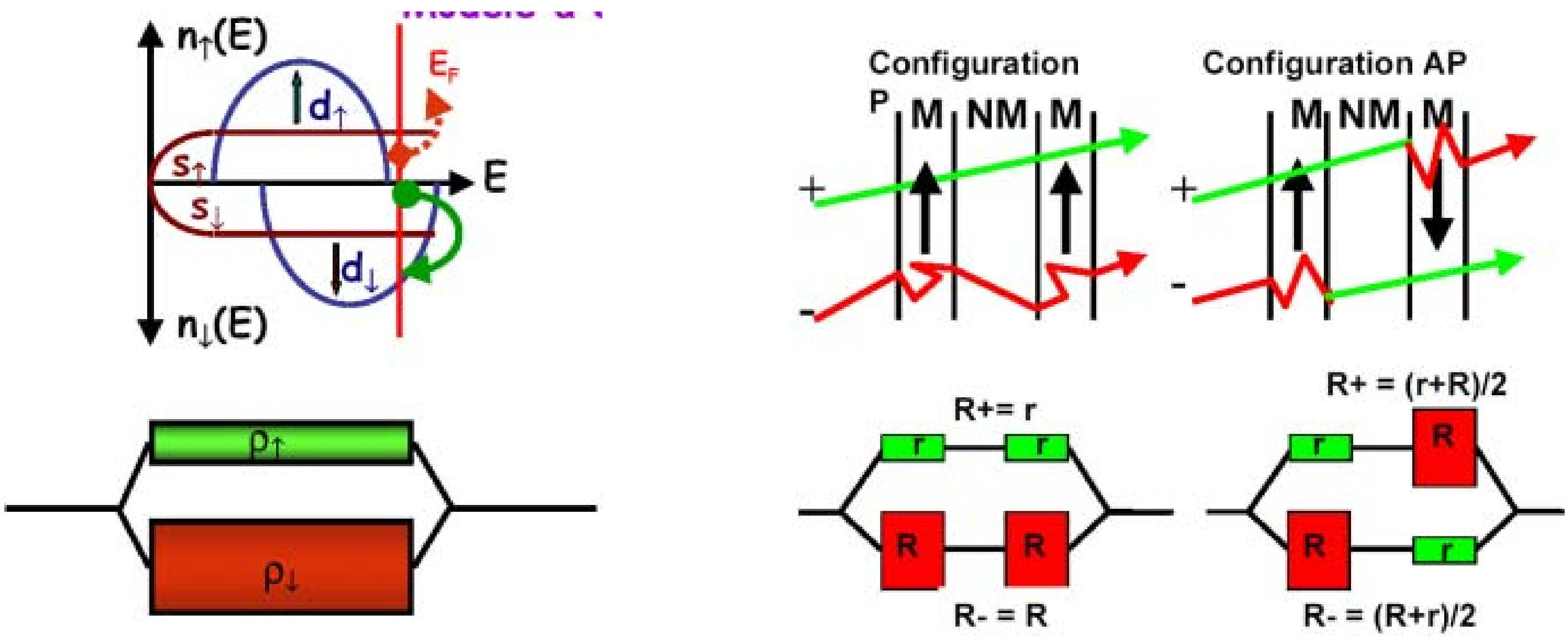




Two crossed sensors for 2D direction sensing

➪ **electronic compass**

Giant Magneto-Resistance (GMR)



<u>Design</u>: more complex: multilayers + small size (for high resistance)

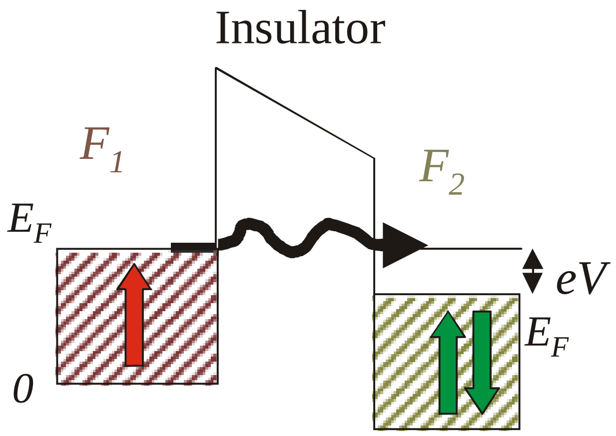
<u>Magnitude</u>: <20%

Currently in use in hard disks heads

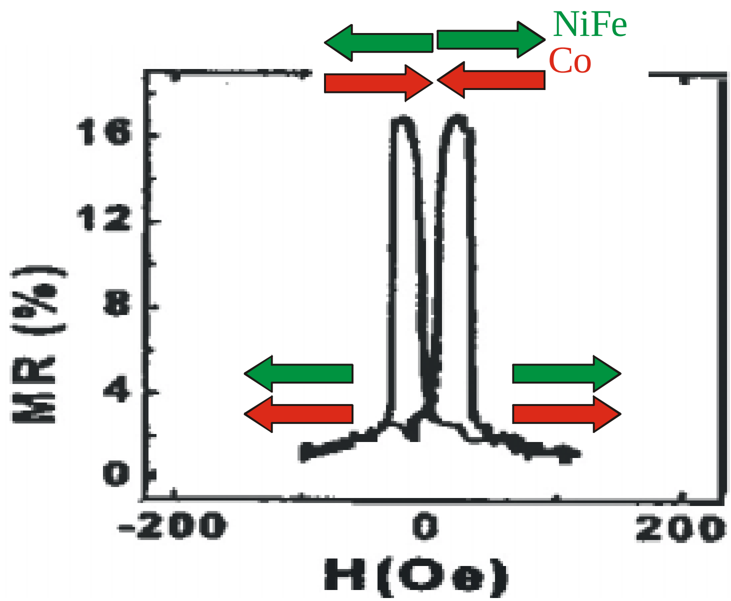
A.Barthélémy et al.;Handbook of magnetic Materials, vol.12, 1, Ed. K.H.J.Bushow (1999), Elsevier.

Slide A. Barthélémy (CNRS-Thalès, France)

Tunneling Magneto-Resistance (TMR)



Tunneling effect



Design: more complex: multilayers + high insulator resistance (electronics !)

Magnitude: <40%

Not in commercial use at the moment

J.Moodera et al.; Ann. Rev. Mat. Sci. 29, 381 (1999)

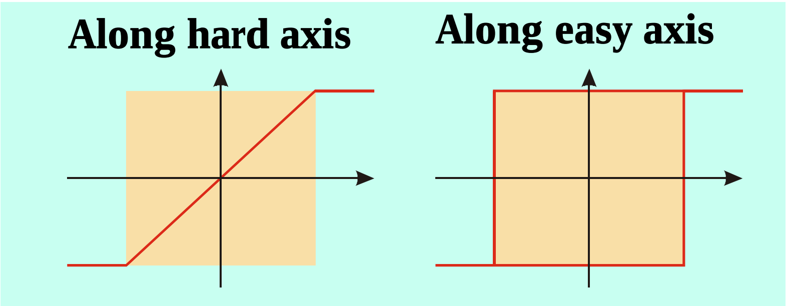
**All these effects (AMR, GRM, TMR) and their applications to field sensors will be studied in great detail in the lecture of Pr. Manon.
I will concentrate on micromagnetics issues in the following**

Some other applications require to switch the dot magnetization

See application table of content

Conventional uniaxial shape effect

- **Reminder** : hysteresis loops for magnetocrystalline anisotropy

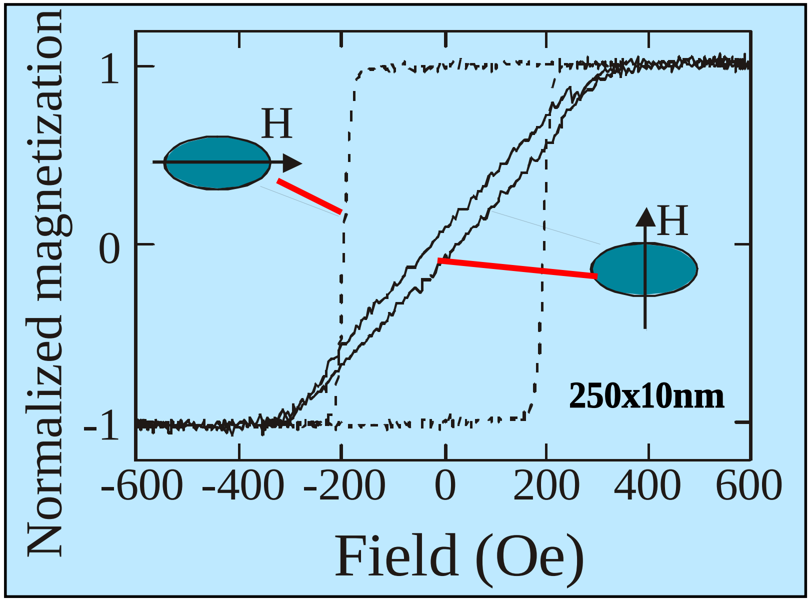


- **Reminder** : for stricly single-domain particles,

$$E_{tot} = K_d \sin^2\theta - \mu_0 M_S H_{ext} \cos(\theta - \theta_H)$$

K_d is the averaged dipolar energy (**shape anisotropy**)

In real world, finite-size dots are not strictly single-domain. However…

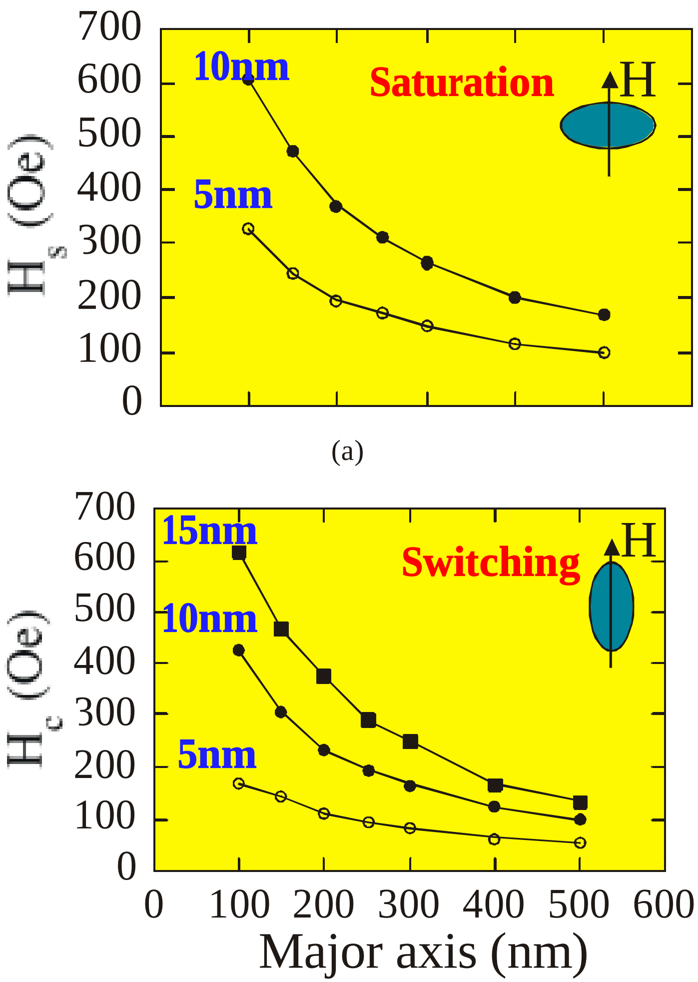


R.P. Cowburn, J.Phys.D:Appl.Phys.33, R1–R16 (2000)

Note:
Switching field is lower than anisotropy field

- **'Shape anisotropy' has some significance (not 100%…)**
- **Understanding of coercivity is very phenomenological**

Shape anisotropy increases with dot thickness



What should we remember about shape anisotropy ?

Shape anisotropy =

- **Phenomenological description only**
- **Predicts reasonably well:**
  - Easy / Hard axis directions
  - Saturation field and susceptibility along hard axis
- **Can be used qualitatively:**
  - Switching field order of magnitude

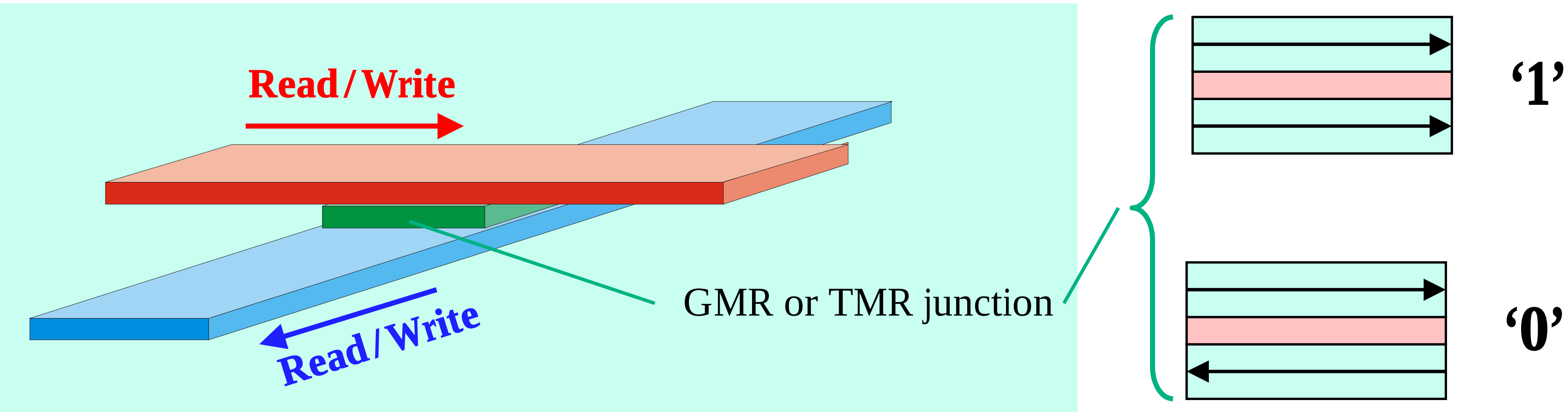
Always remember that is not strictly valid !

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

MRAM's: principle of operation

Magnetic Random Access Memory

Single junction (1bit memory)

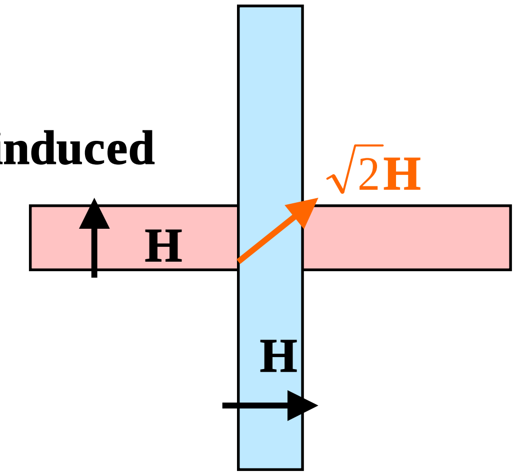


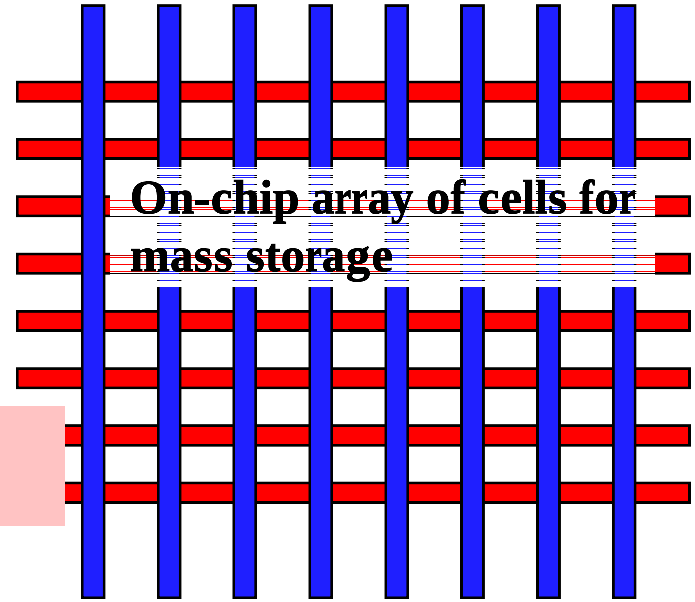
GMR: product by Honeywell (64 kb?)
for space applications (radiation insensitive)

TMR: under intense development :
IBM, Siemens, Japan.
Mbit-Gbits prospects.

MRAM's: write obstacle

Write with current-induced magnetic field





➥ **Roughly speaking: all dots must switch under √2H, but none should switch under H !**

Is it feasible ?

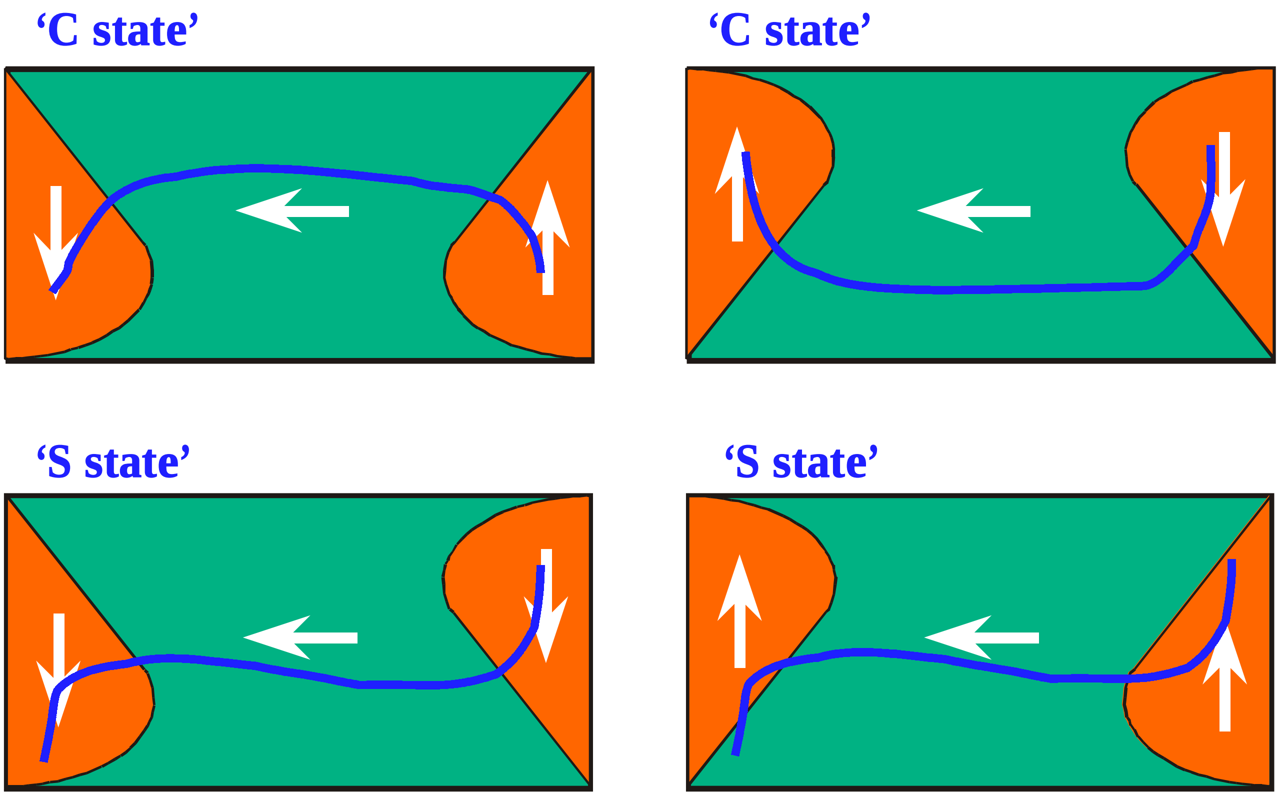
NO in general : one observes a very broad distribution of switching fields !

(From cell to cell, and even cell irreproducibility)

➥ **What factors influence magnetization reversal (Switching field) ?**

➥ **Back to fundamental studies !**

End domains arise in order to avoid surface magnetic charges



At least 8 nearly equivalent ground-states for a dot !

- **how does a dot reverse its magnetization ?**
- **Sensitive to any dissymetry like defects, temperature, stray fields, etc.**
- **Rectangles are not be the best shape for single domaine devices…**

Magnetization is pinned at sharp ends

Numerical micromagnetic calculation

J.G. Zhu

6672 J. Appl. Phys., Vol. 87, No. 9, 1 May 2000

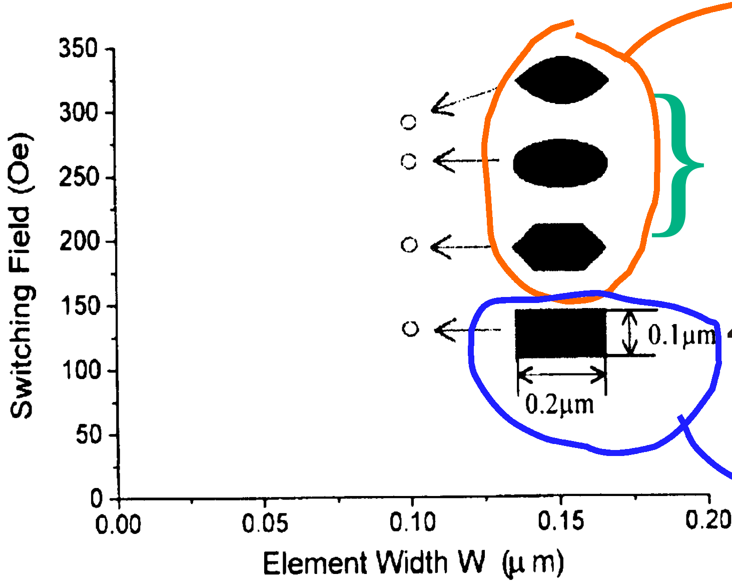
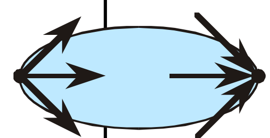


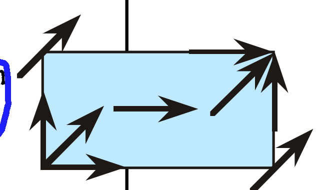
FIG. 11. Calculated switching fields of NiFe film elements with different end shape. All the elements have the same size of $0.2\times0.1\ \mu m^2$, counting tip-to-tip, and a thickness of 20 Å.

Two ground-states each



↳**GOOD**: Better reproducibility

↳**BAD**: Higher switching field



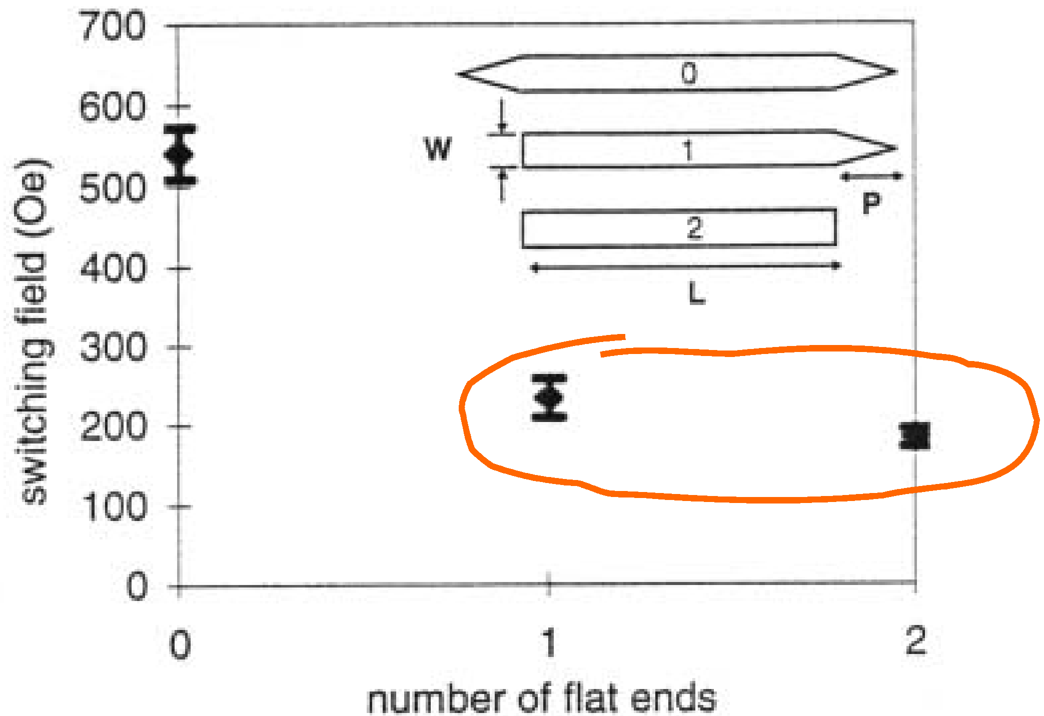
Eight ground-states

Essentially Equivalent Topological Properties

(Images courtesy of J. Miltat – CNRS, Orsay, France)

Magnetization is pinned at sharp ends

Experiments **Permalloy** (soft)



Similar

Fig. 8 Dependence of switching field of acicular elements on the number of flat ends. Element geometry is also shown: L=2.5 μm, W=200 nm, P=500 nm.

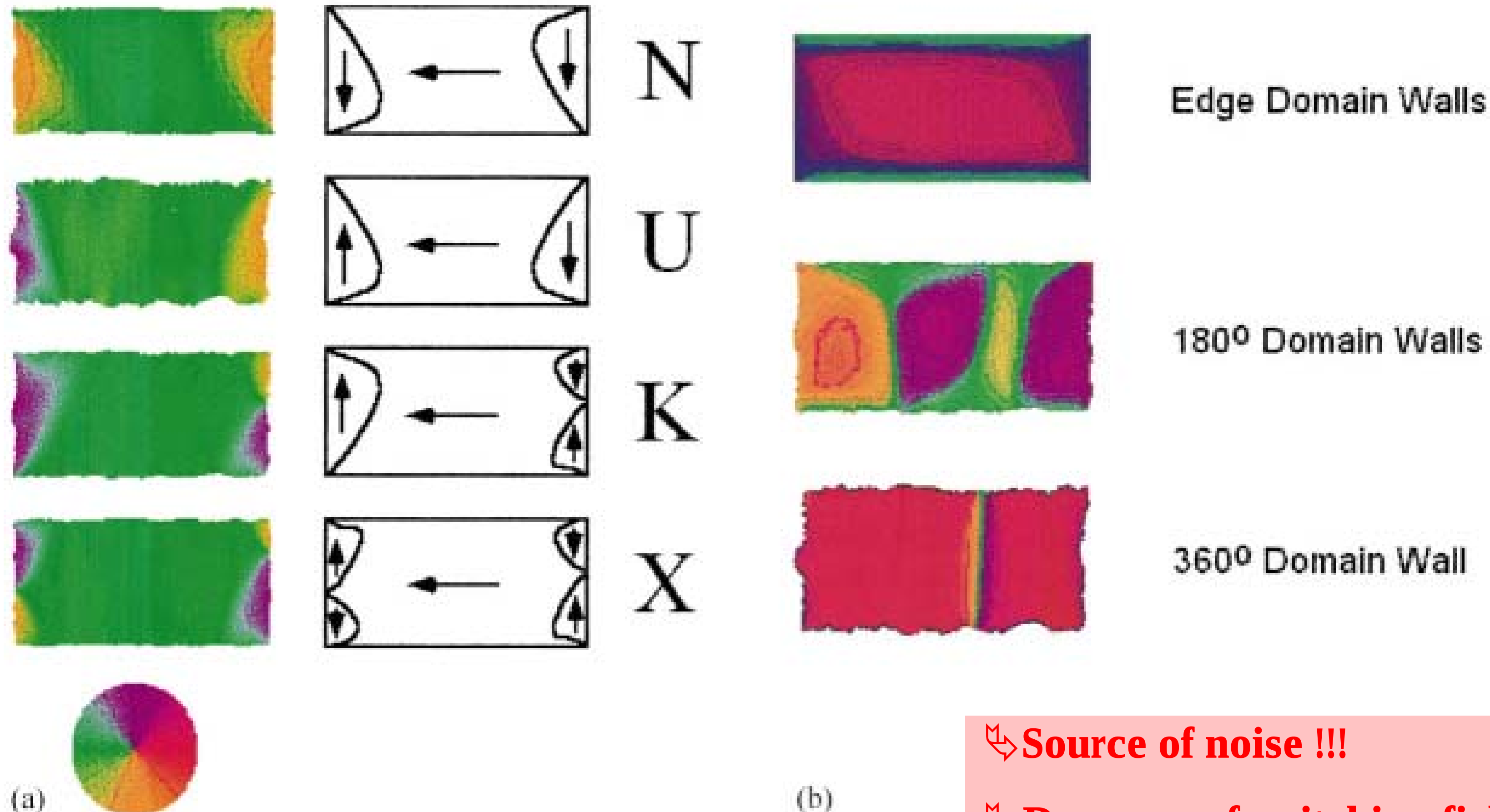
Experimentally confirmed

- **GOOD: Better reproducibility**
- **BAD: Higher switching field**

K.J. Kirk et al., J.Magn.Soc.Japan, 21 (7), (1997)

Roughness influences the dot ground state and reversed state

Numerical micromagnetic calculation



↳ **Source of noise !!!**

↳ **Decrease of switching field (not controlable)**

J.G. Deak et al., J.Magn.Magn.Mater.213, 25(2000)

Configurational anisotropy : deviations from single-domain

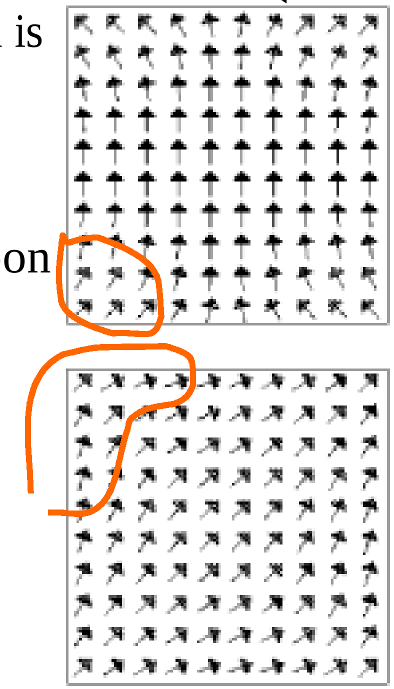
Strictly speaking, 'shape anisotropy' is of second order:

$$e_{\mathrm{d}} = \frac{1}{2}\mu_0\left(N_x M_x^2 + N_y M_y^2 + N_z M_z^2\right)$$

2D: $$E_{\mathrm{tot}} = V K_{\mathrm{d}} \sin^2\theta$$

However, in real samples magnetization is never perfectly uniform

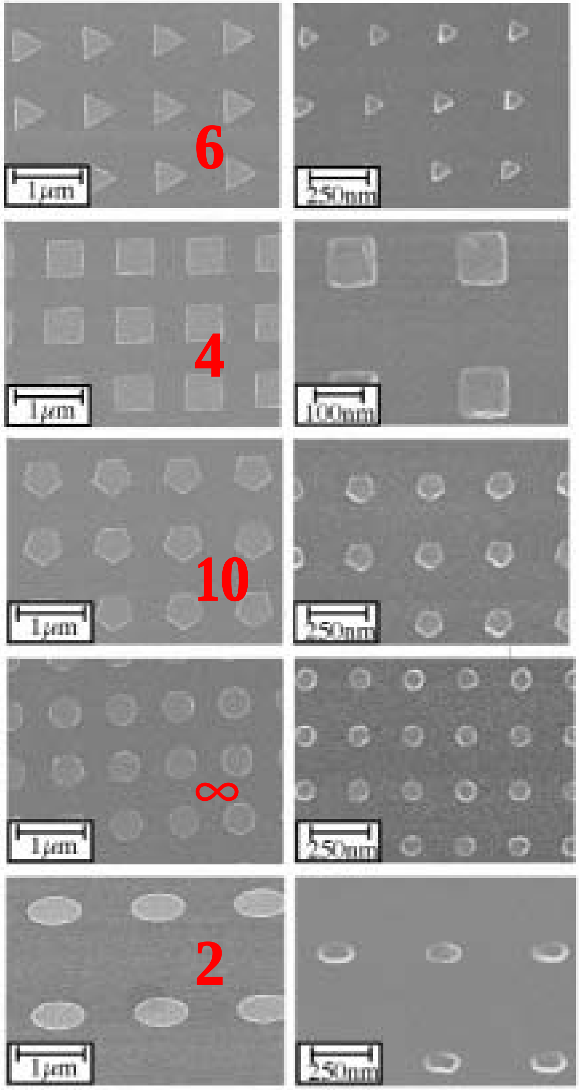
Num.Calc. (100nm)



Corrective energy terms, that depend upon the average magnetization angle

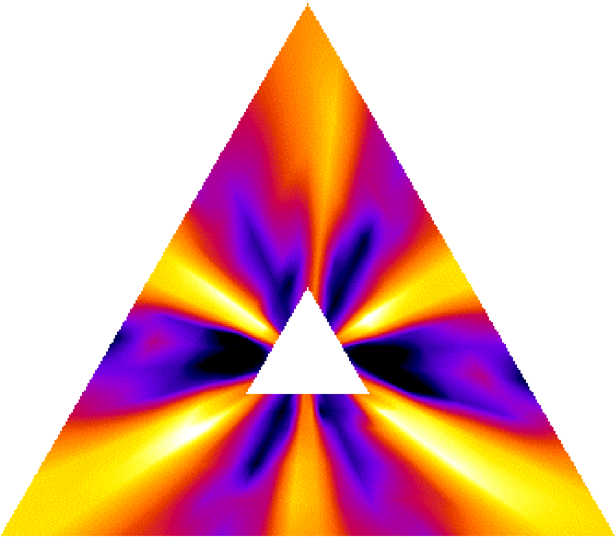
↳ **higher order contribution to the anisotropy ?**

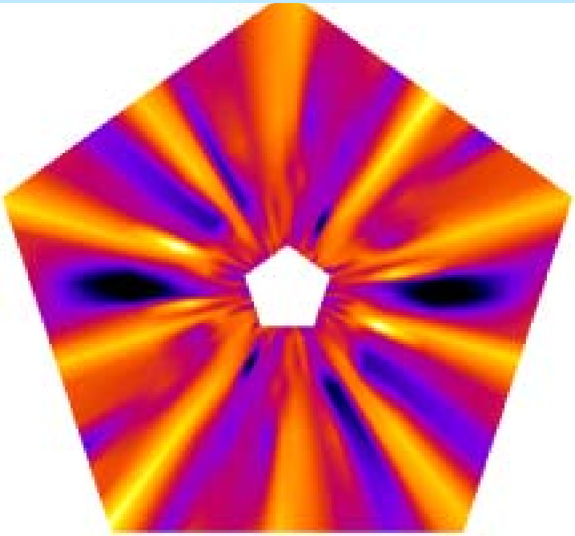
'Configurational anisotropy'

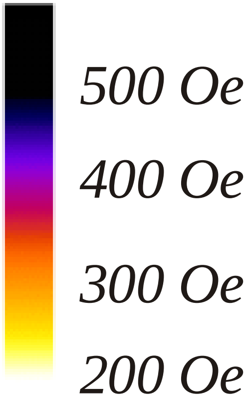


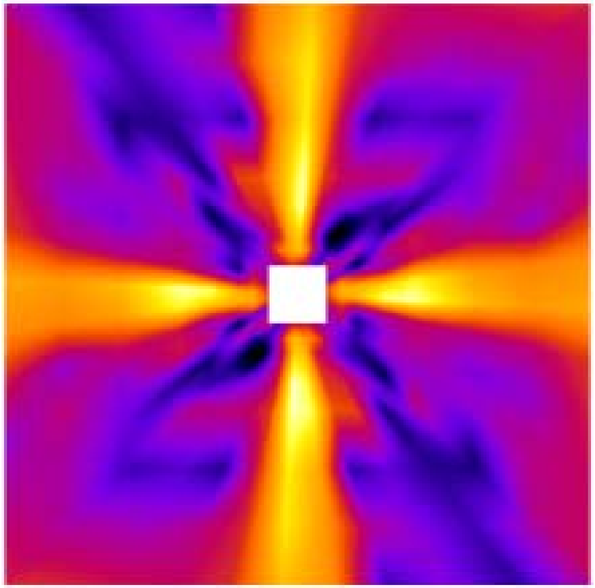
R.P. Cowburn, J.Phys.D:Appl.Phys.33, R1–R16 (2000)

Polar plot of experimental configurational anisotropy with various symmetry









Color code: strength of anisotropy in a given direction

Radius: size of measured pattern

Direction: direction of measurement

Configurational anisotropy may be used to stabilize stable configuration

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

What should we remember about the design of small near-single-domain magnetic elements for memories ?

(dots that require to be magnetically switched forth and back)

- **The subject is not trivial ! Approaches need to be three-fold to give a complete view:**
  *** experiments**
  *** analytical**
  *** numerical calculation**

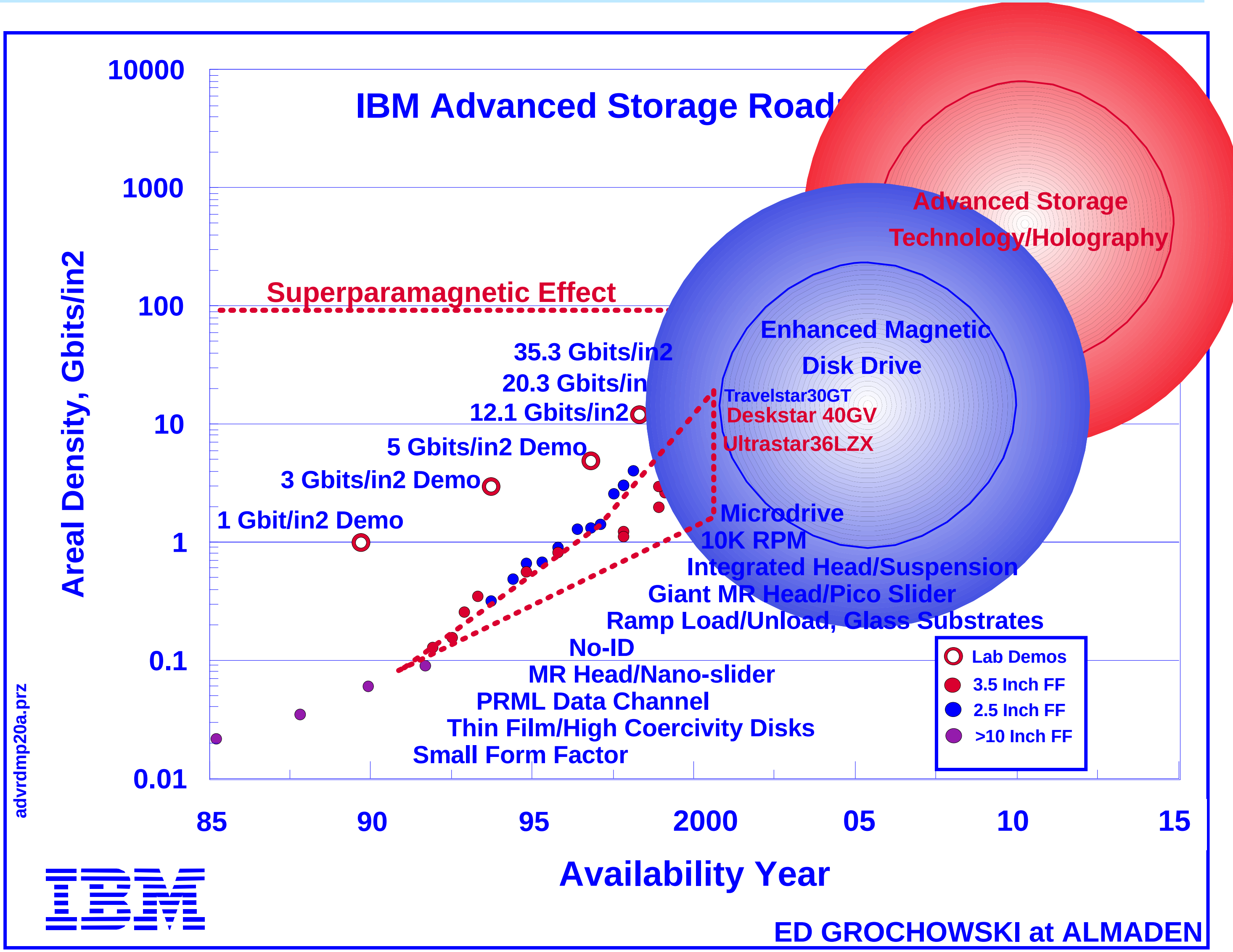
- **Single domain favored by :**
  *** small lateral size**
  *** moderate thickness**
  *** even weak in-plane magnetocrystalline anisotropy**

- **Coercivity is obtained from :**
  *** magnetocrystaline anisotropy**
  *** shape anisotropy**
  *** configurational anisotropy**
  * other means not mentioned here…

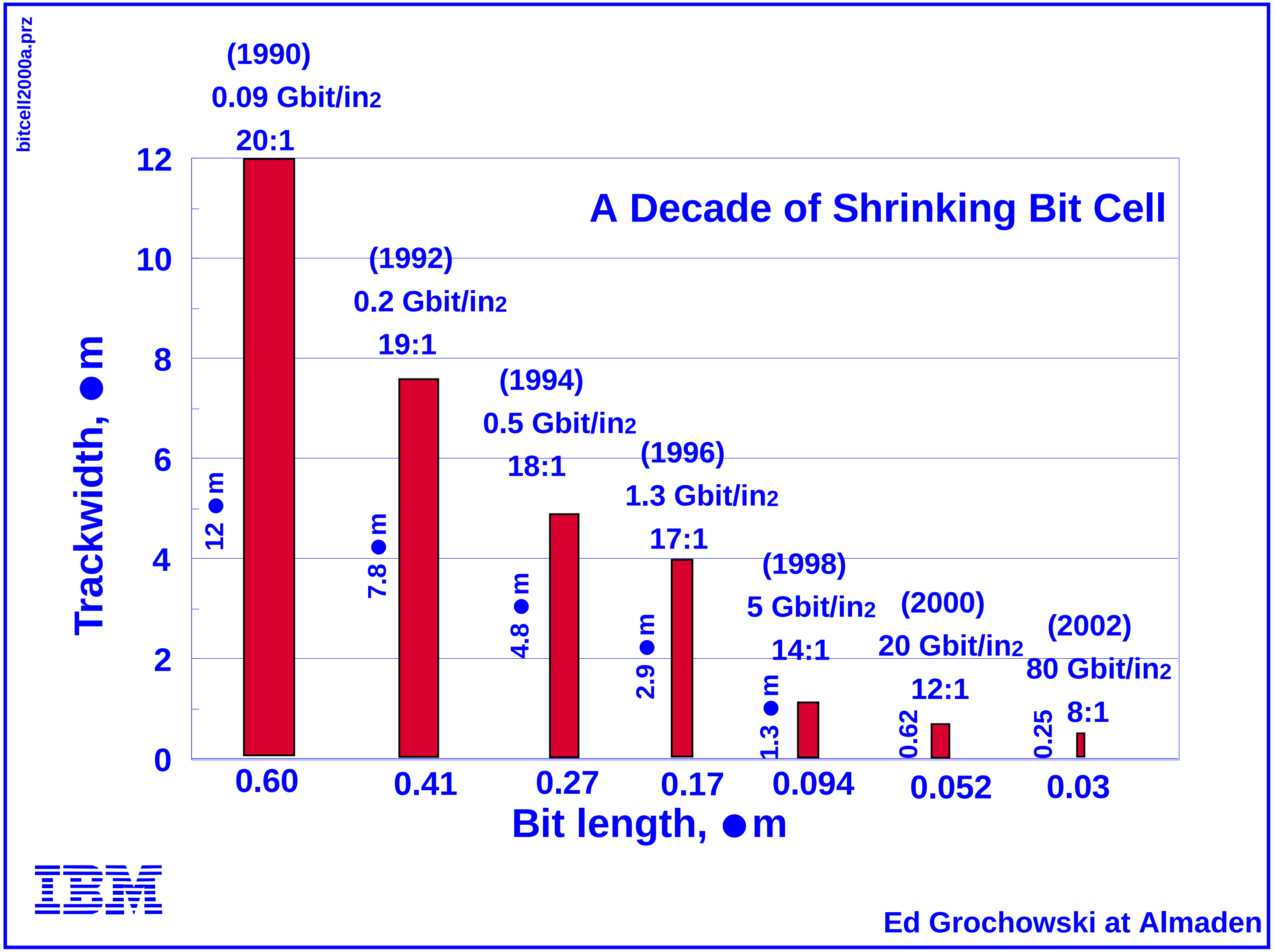
- **Switching control is better achieved for :**
  *** structures with pointed ends**
  *** low edge roughness**

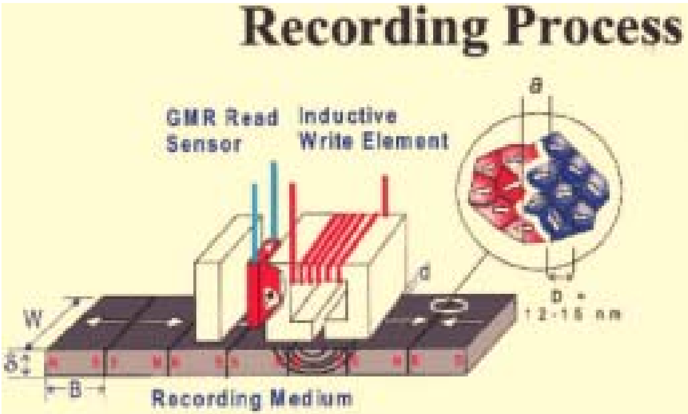
Back to list of applications

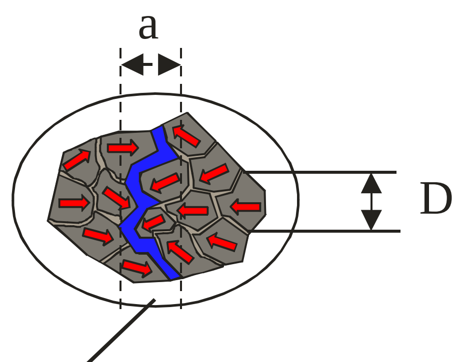
Increase of areal density of Hard Disk Drives (HDD), as viewed by IBM

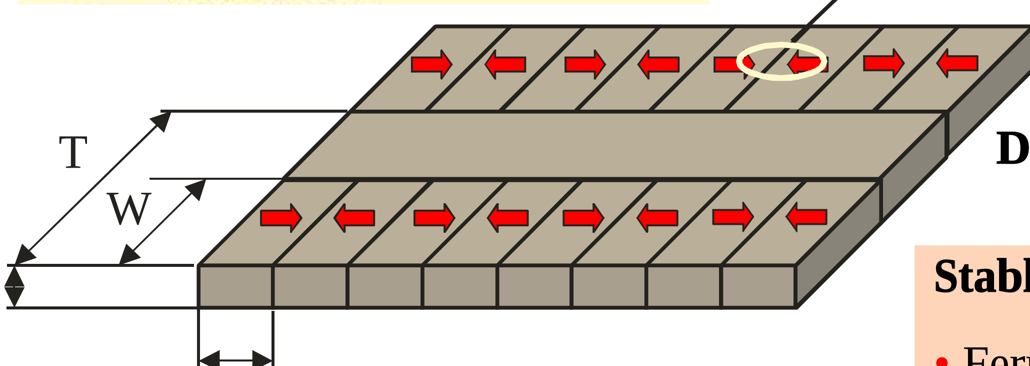


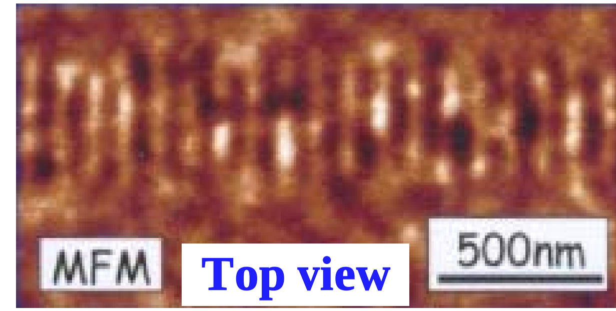
Size of magnetic bits written on IBM Hard Disk Drives (HDD)











Commercially shiped : 10-20 Gbit/in^2

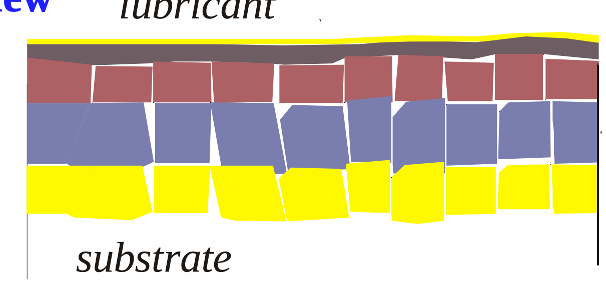
Demonstrated (summer 2001) : 100 Gbit/in^2

Stable magnetic recording requires :

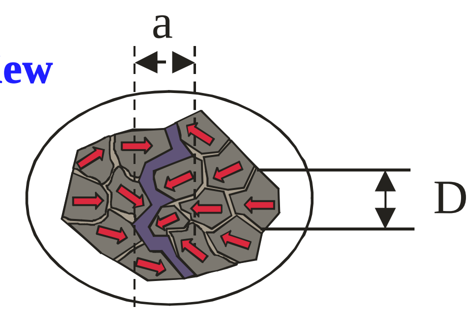
- Ferromagnetic grains (nano-magnets)
- Many grains per bit (high signal to noise ratio)

(Images courtesy of D. Weller – Seagate
C. Chappert – IEF-Orsay)

Side view



Top view

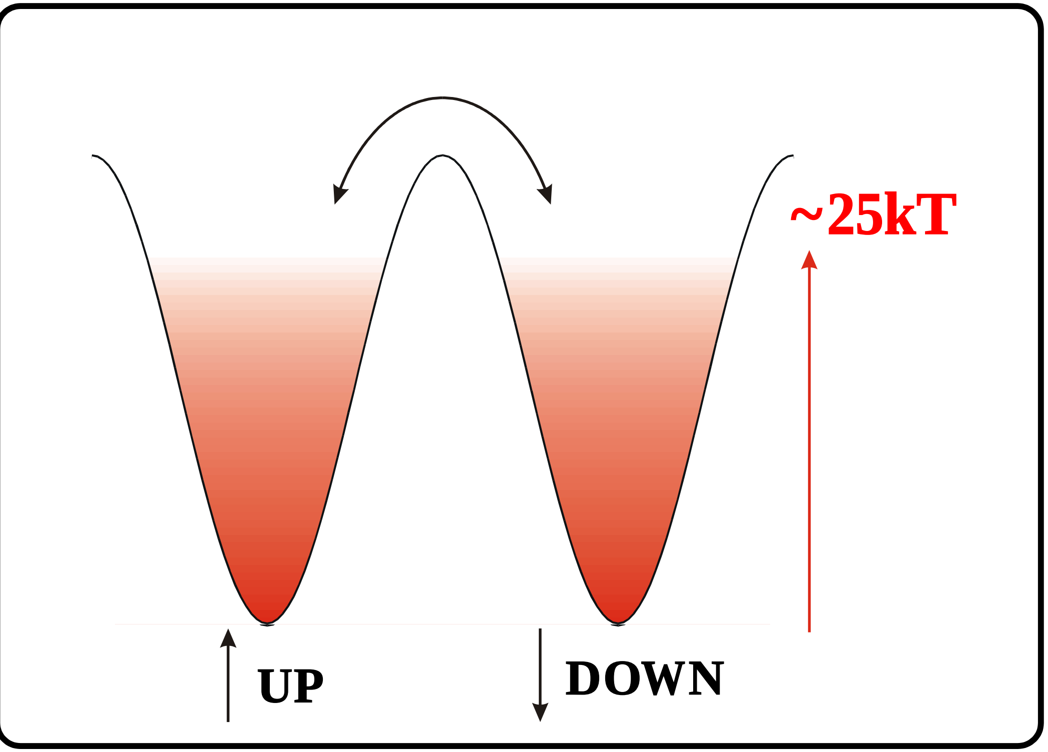


- **Current HHD**: longitudinal granular media
(weak coupling between grains ; in-plane magnetization)
- **High S/N ratio needed for read-out**: number of grains per bit must remain high (10^2-10^3)
- **Increase media density** ⇨ shrink grains size ⇨ **face superparamagnetism**

Keep number of grains constant

E_B=KV

Anisotropy barrier E_B~KV



Phenomenological description of thermal activation : Néel-Brown theory

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

- Probability of not having switched

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

- Mean reversal time

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

Barrier for not switching during time t

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

Lab Observer : t=1s $\quad E_B \approx 25\, k_B T$

Magnetic recording : t>>10^9s $\quad E_B \approx 60\, k_B T$

Blocking temperature

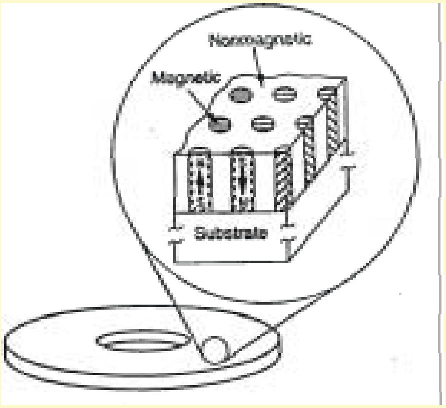
$$T_B = E_B / 25\, k_B$$

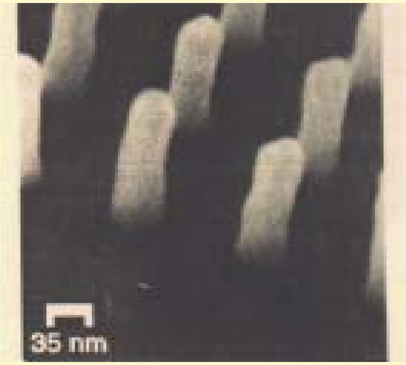
Back to roadmap

Patterne d magneti c média

S. Chou et al.' proposition (ca 1994) : *1 bit ~ 1 grains*

2 orders or magnitude gain on superparamagnetism





Electrodeposition of Ni into arrays of holes
- *in PMMA resist*
- *in a SiO_2 layer*

Requirements :
- *ultra smooth media* → *planarization*
- *low dispersion of magnetic properties in media*

(Slide courtesy of C. Chappert – IEF-Orsay)

- **This prospect has triggered a lot of work in the past five years**
  ➥ sub-micrometer-sized single domain dots (see previous section…)
- **However**: how to meet the above two requirements ?
- (many other issues ; we focus here on magn.)

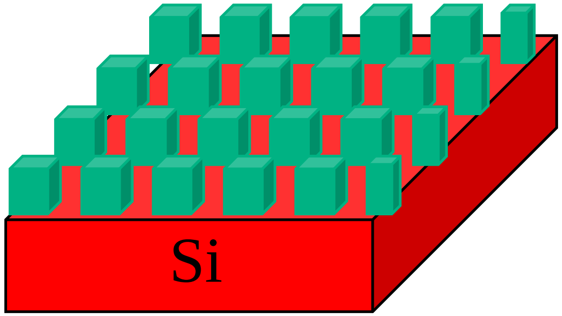
Preparation of a topographic pattern on Si (well established processes)

Preparation of arrays of resist dots or lines by either :

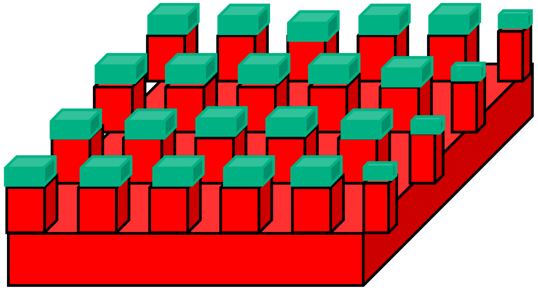
-electron beam lithography (CEA/LETI) : resolution~50nm

or

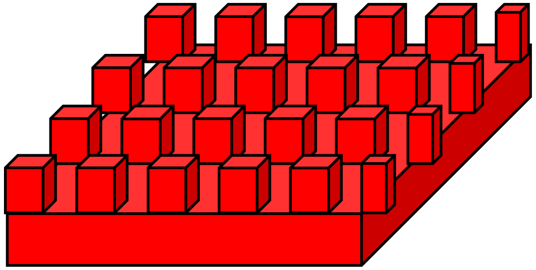
-nano-imprint using a mold made by e-beam (A.Lebib, Y.Chen, CNRS/L2M) : resolution 30nm



resist dots



RIE etching



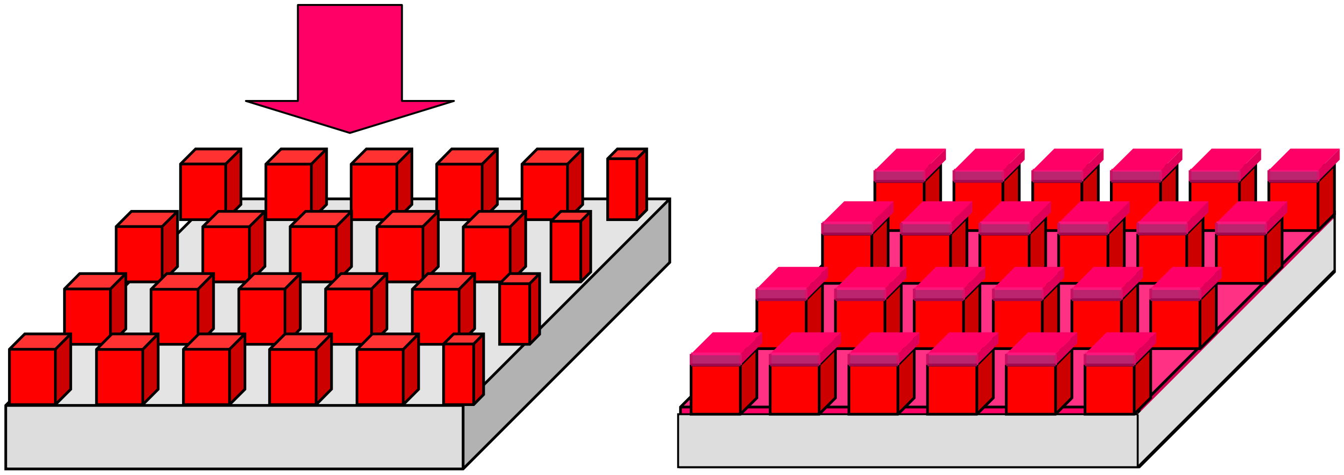
Removal of resist

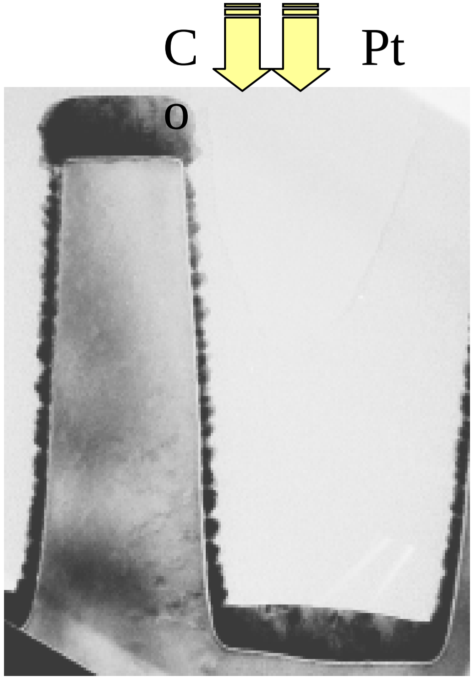
Smallest size by nano-imprint: 30 nm dots with edge to edge spacing of 30nm.

(Slide courtesy of B. Diény – CEA/SpinTech-Grenoble)

Magnetic materials overgrowth

Deposition of magnetic material
(sputtering or MBE)





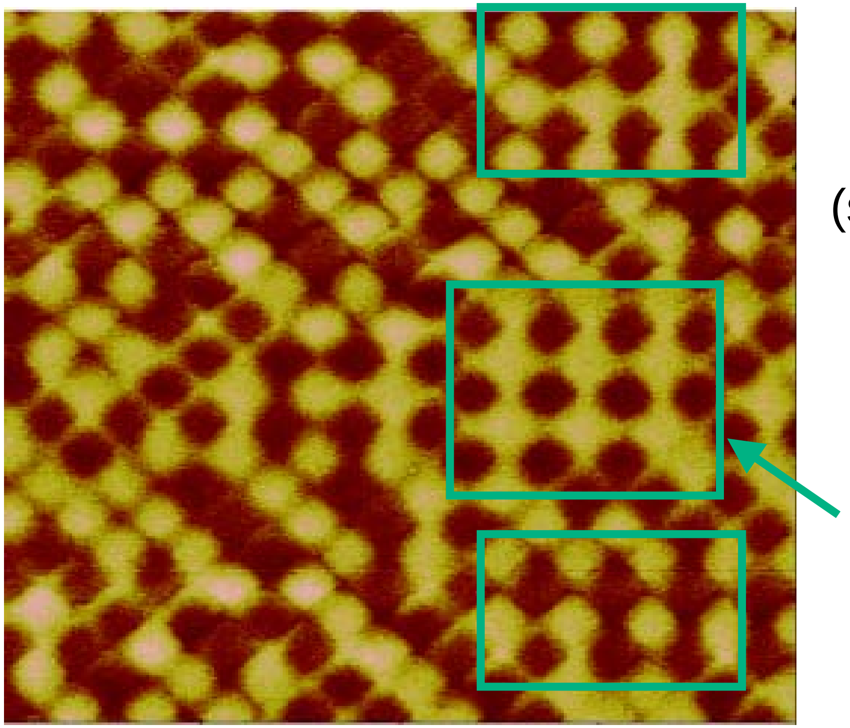
Advantages :

-Etching of Si very well controlled in microelectronics,
-Possibility of very high aspect ratio,
-Substrate preparation independent of the choice of the magnetic materials,
- No processing after deposition of the magnetic materials,
-Possible large scale preparation by nano-imprint (180Gbit/in^2 demo).

(Slide courtesy of B. Diény – CEA/SpinTech-Grenoble)

Magnetic state : single domain ('bits')

Pt 20 nm/(Co 0.5 nm/Pt 1.8 nm)$_4$ multilayer with
perpendicular magnetic anisotropy :



400 nm square dots
(spacing of 100 nm, height of 47 nm)

Local checkerboard patterns most stable from magnetostatic point of view

8 µm x 8 µm image

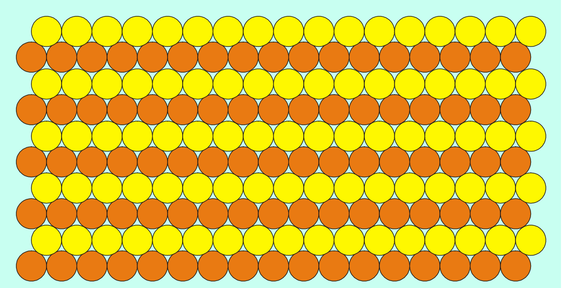
MFM: magnetic pattern, as-deposited

GOOD: magnetic properties more homogeneous (less edge defects)
BAD: topography

(Slide courtesy of B. Diény – CEA/SpinTech-Grenoble)

Ion beam irradiation patterning : initial media with perpendicular anisotropy

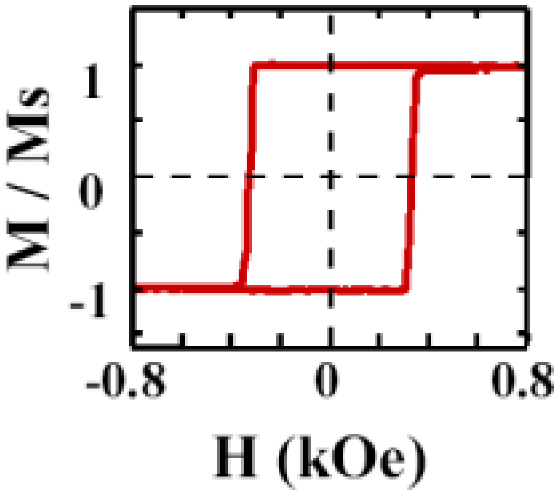
- Epitaxial Pt/Co(1.4 nm)/Pt grown by sputtering

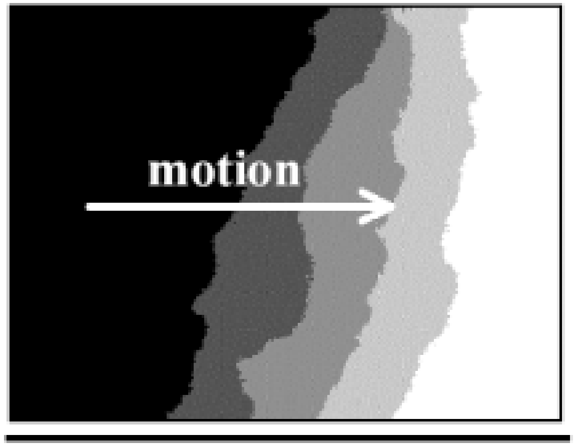


- Perpendicular anisotropy
  - Film 2D-Ising
  - Magnetization reversal: domain wall motion

  Distribution of propagation field $\Delta H_p \sim 20$ Oe

Hysteresis loop



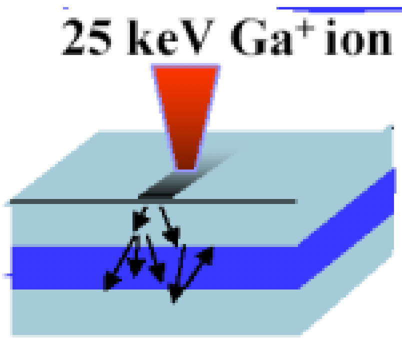


Strongly anisotropic spin-orbit coupling

Perpendicular anisotropy despite thin film shape effect

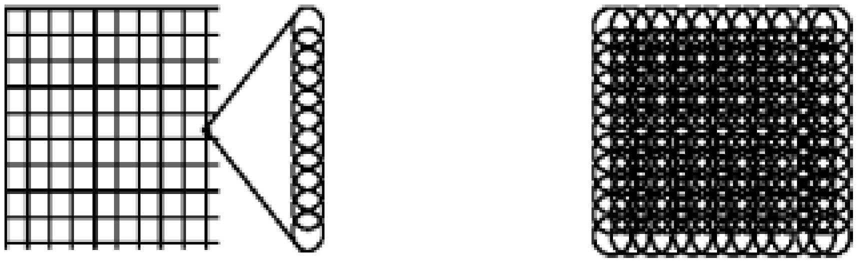
(Slide courtesy of A. Mougin – LPS-Orsay)

Ion beam irradiation patterning : irradiation physical effect



- Interface roughness
- Interface mixing
- Cascade defects
- Low fluences: minor etching and few cascades
  1.3 nm for 10^{15} ions/cm^2

- Modifications on a nanometric scale
- Patterns: scan of the beam, step after step
- Quasi-uniform irradiation

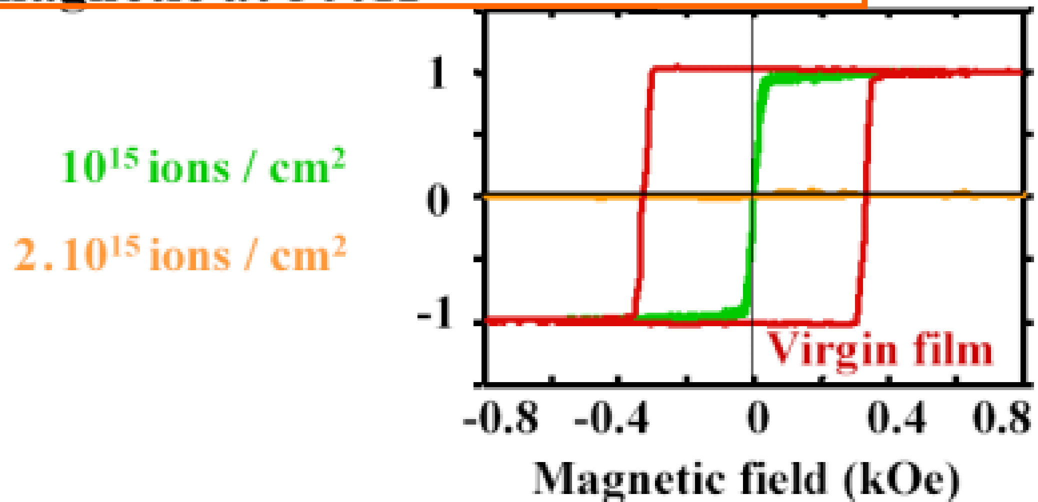


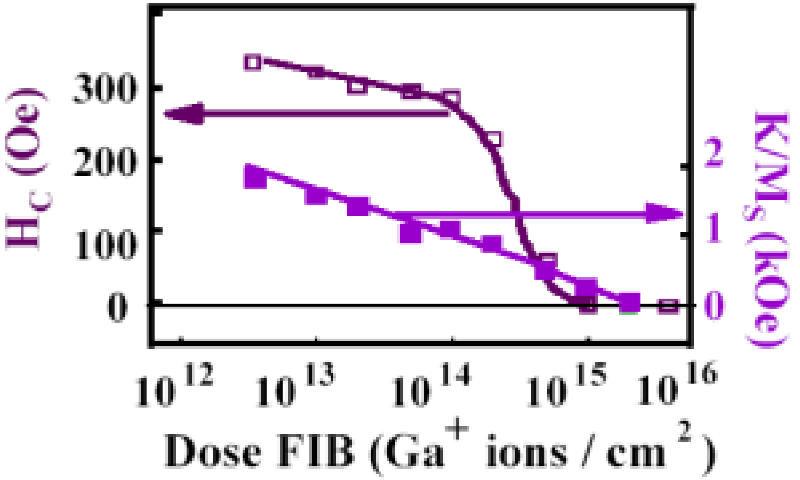
∅ Beam diameter ≤ 10 nm Step ~ 15 nm

(Slide courtesy of A. Mougin – LPS-Orsay)

Ion beam irradiation patterning : irradiation magnetic effect

Reduction of coercivity and anisotropy
Paramagnetic at 300K

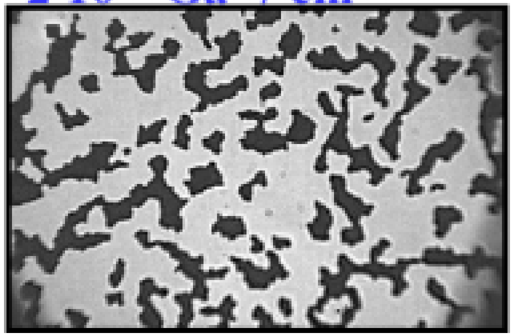




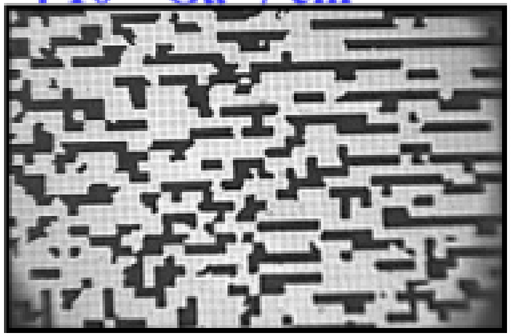
(Slide courtesy of A. Mougin – LPS-Orsay)

Ion beam irradiation patterning : flat patterned magnetic media

$2\ 10^{13}\ Ga^{+}\ /\ cm^{2}$

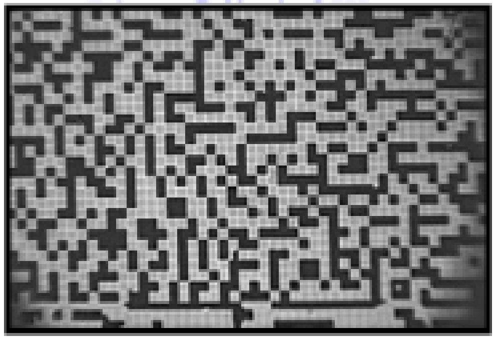


$4\ 10^{14}\ Ga^{+}\ /\ cm^{2}$

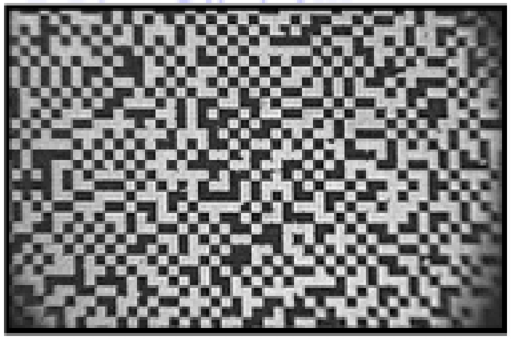


↳ **Virgin film behavior: large ↑↓ domains**

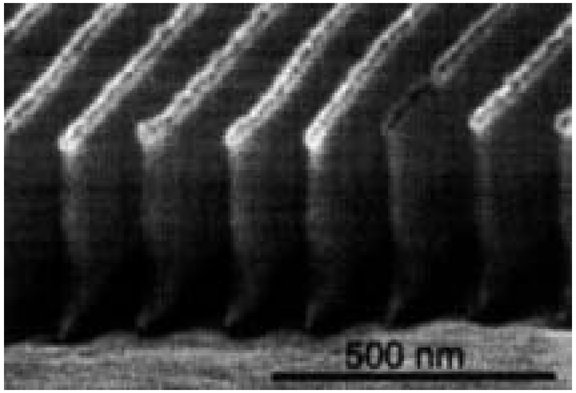
$10^{15}\ Ga^{+}\ /\ cm^{2}$



$2\ 10^{16}\ Ga^{+}\ /\ cm^{2}$



↳ **Pattern of dots in dipolar interaction**



Replication lithography possible

↳ **Mass production**

GOOD: magnetic properties more homogeneous (less edge defects)

GOOD: flat topography

(Slide courtesy of A. Mougin – LPS-Orsay)

In principle interesting:

* More homogeneous properties
* flat topography possible
* one grain per bit : no more superparamagnetism

However many unsolved issues:

* how to read/write
* demo density of cenventional media is now 100Gbit/in^2 (with read/write !!!), whereas reasonnable demo with patterned media is 100Gbit/in^2.

↳ **Patterned media came to late ? Obsolete idea ?…**

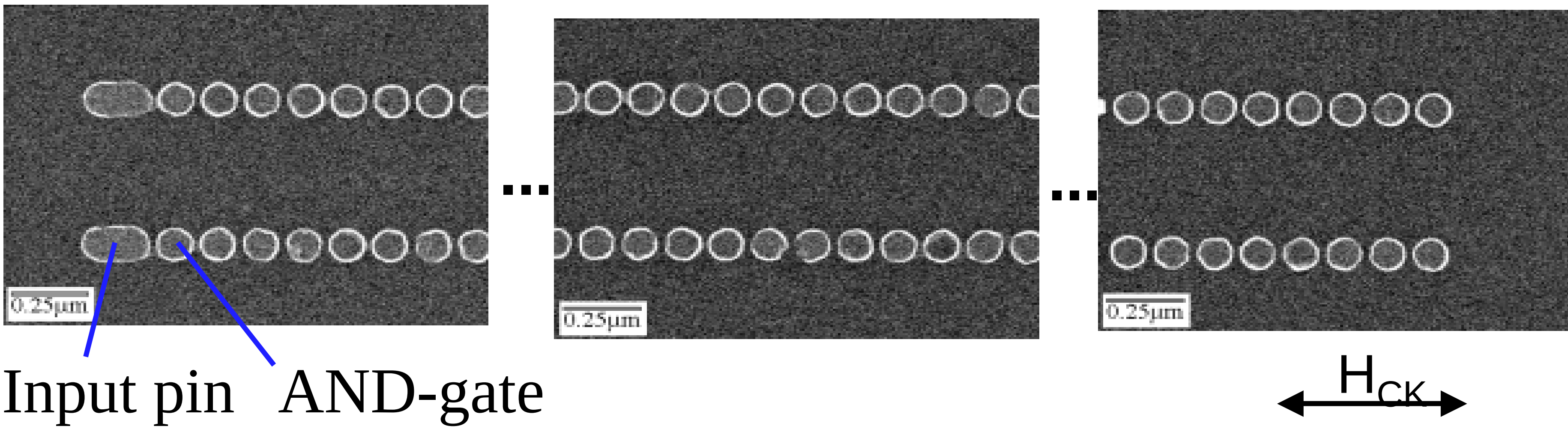
(see roadmap…)

Very prospective subject…

A working magnetic logic device

Transmission line: replace copper wires by macrospin dots

Dots are superparamagnetic if isolated, but stabilized by dipolar interactions in a chain



ROOM TEMPERATURE

- Number of dots per chain = 70
- Dot diameter = 110nm
- Dot pitch = 135nm
- Dot thickness = 10nm

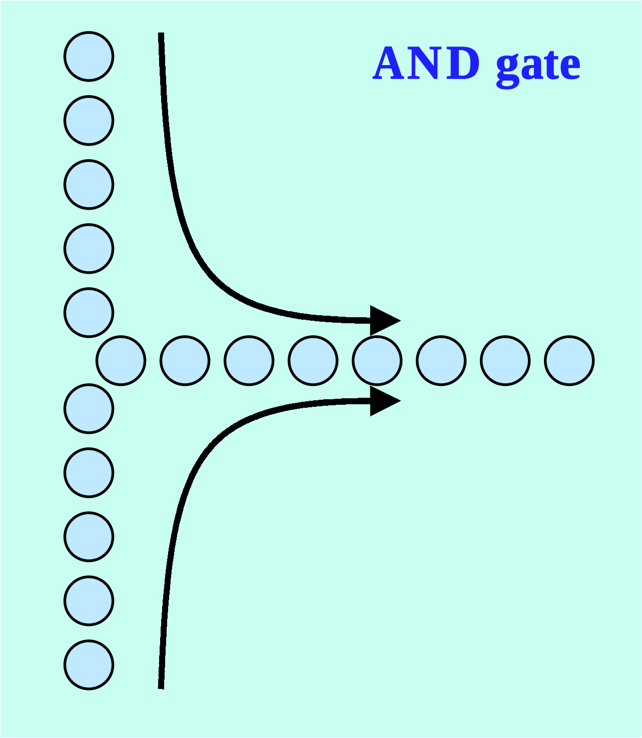
Cowburn *et al., New J. Phys. 1, 16.1* (1999)

Cowburn *et al. Science* **287**, 1466 (2000)

(Slide courtesy of R.P. Cowburn – Durham, UK)

A working magnetic logic device

All logic functions are possible : AND, OR, …



- Higher density on chips than conventional semiconductor processors
- 10^{-3} less power dissipation (propagation is not dissipative !).

Cowburn *et al. Science* **287**, 1466 (2000)

Field of patterned magnetic structure…

- **Extremely rich from the fundamental point of view.**

  50 years old subject

  Renewed recently (demand, technology)

  Computer simulations from the 90's

$ $ $

- **Extremely promising from the technological point of view**

  Sensors : sensitivity and integration

  Storage : memories, Hard disks, tapes, etc.

  Prospects:

  magnetic processing ?

  Spintronics ?