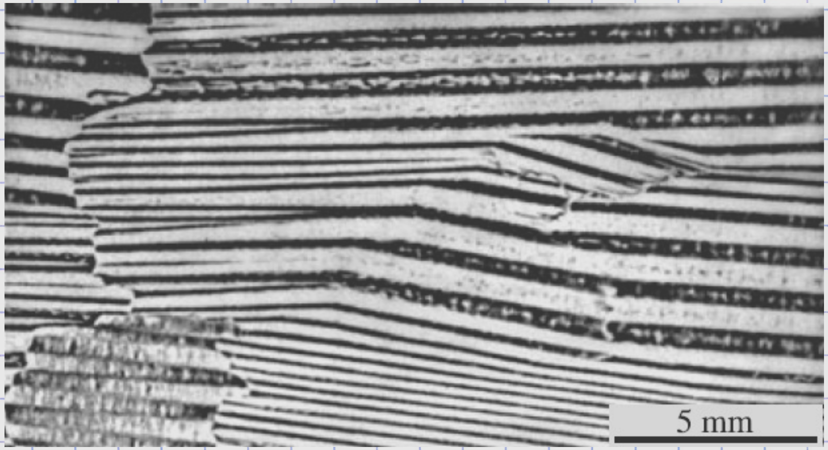
TEM for magnetism: challenges and competitors

Olivier Fruchart
Institut Néel (CNRS-UJF-INPG)
Grenoble - France
http://neel.cnrs.fr

Magnetic domains

Numerous and complex magnetic domains



(History : Weiss domains)

Anisotropy exchange length (domain wall width)

$$E = A\left(\partial_{x_i} m_j\right)^2 + K\sin^2\theta$$

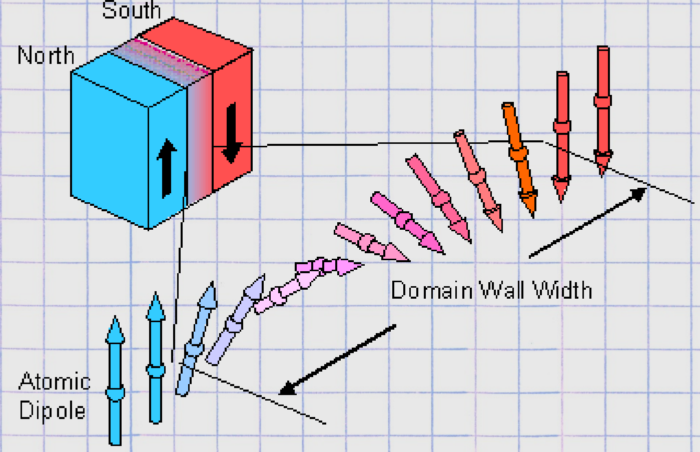
Exchange $\rightarrow$ $\mathrm{J/m}$

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

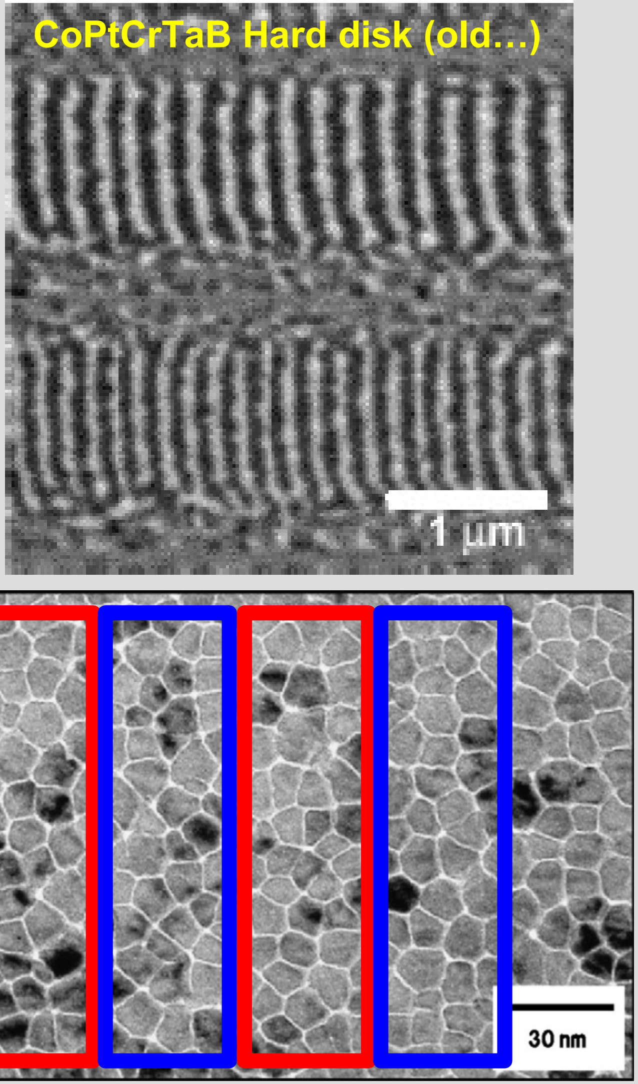
Anisotropy exchange length: $\Delta_u = \sqrt{A/K}$

$\Delta_u \approx 1\ \mathrm{nm}$ → $\Delta_u \geq 100\ \mathrm{nm}$

Hard Soft



Magnetic bits on hard disk drives



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

Relevant spatial resolution

10-100nm

Relevant time resolution

- **>1 µs** : thermally-activated magnetization processes
- 1 ns : precession of magnetization
- 1 ps : ultrafast demagnetization

Basics of precessional switching

Magnetization dynamics:

Landau-Lifshitz-Gilbert equation:

$$\frac{d\mathbf{M}}{dt} = -\gamma_0\left[\mathbf{M}\times\mathbf{H}_{eff}\right] + \frac{\alpha}{M_s}\left[\mathbf{M}\times\frac{d\mathbf{M}}{dt}\right]$$

γ_0 Gyromagnetic factor

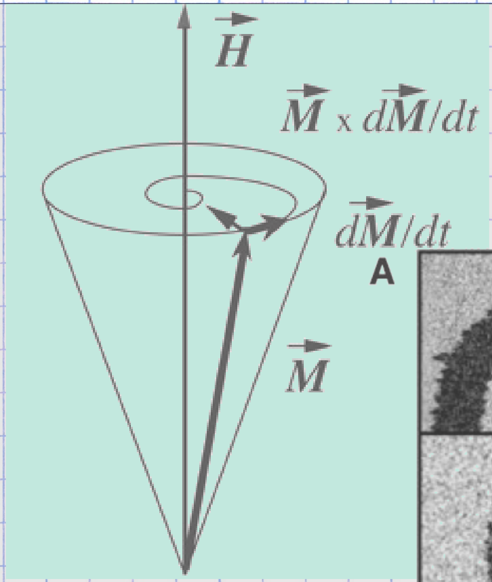
$\gamma_0 = \mu_0\gamma$ $\qquad \gamma = \dfrac{gq}{2m}$

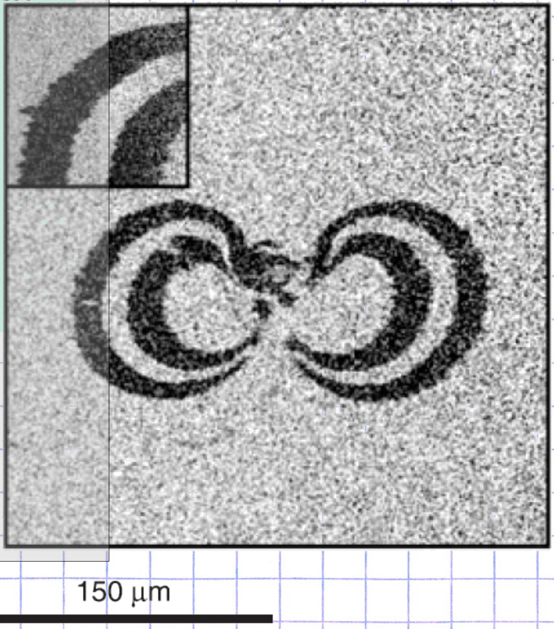
$\gamma/2\pi = 28\,\mathrm{GHz/T}$

H_{eff} Effective field (including applied)

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

Demonstration: 1999

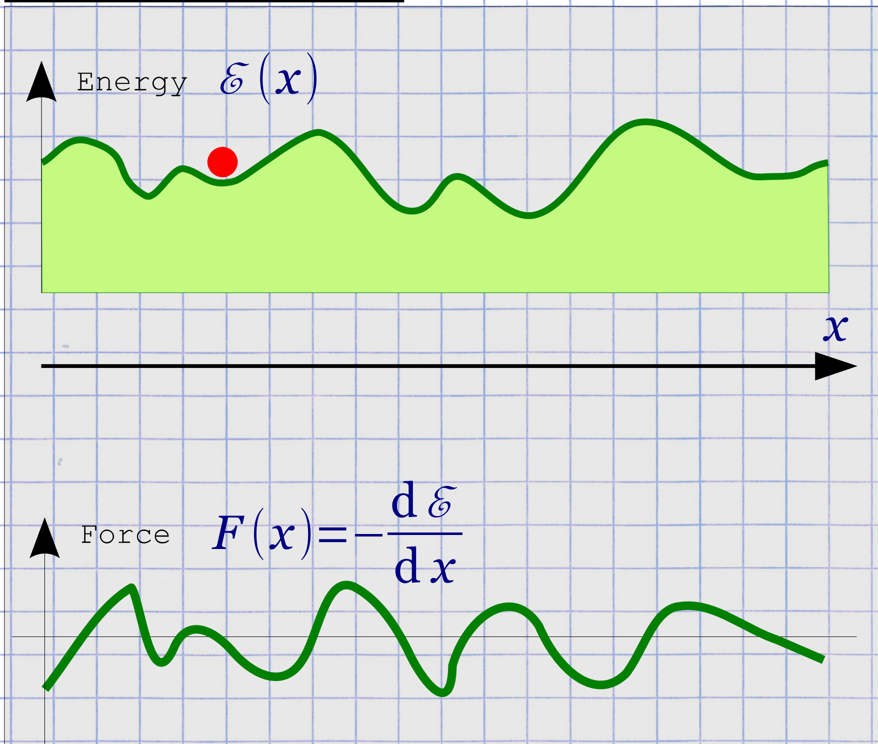




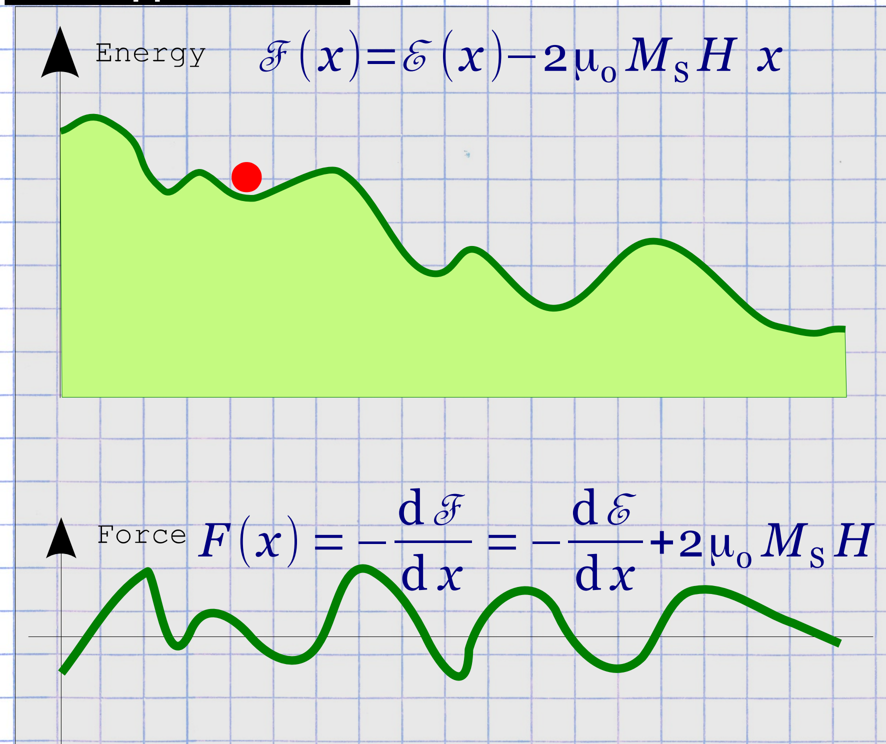
C. Back et al., Science 285, 864 (1999)

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

Spectroscopy, diffraction etc.

Versatility

- Samples made with lithography or ex situ OK ?
- Need for sample preparation ?
- Compatible with various environments ? (temperature, field etc.)

Speed of acquisition

- Sample preparation needed ?
- How much time for one image ?

Access

- Large-scale instrument or in-lab ?
- Expensive or cheap ?

What is probed

- Surface or volume technique ?
- Sensitivity ?
- Magnetization, stray field, other ?

Conclusion

No universal technique

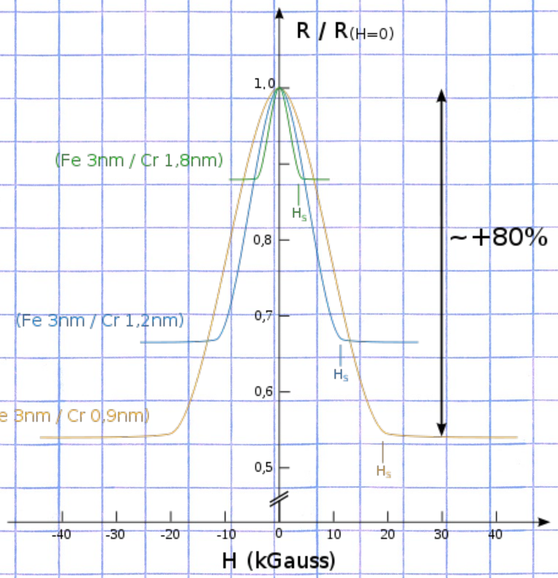
Many criteria to be balanced

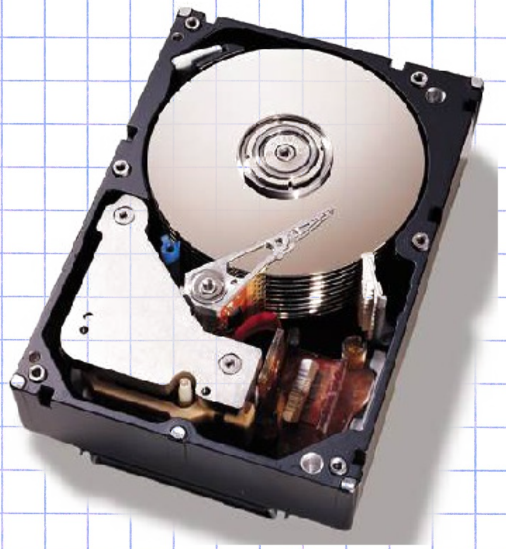
1956

RAMAC, IBM, first hard disk drive

1986

1998



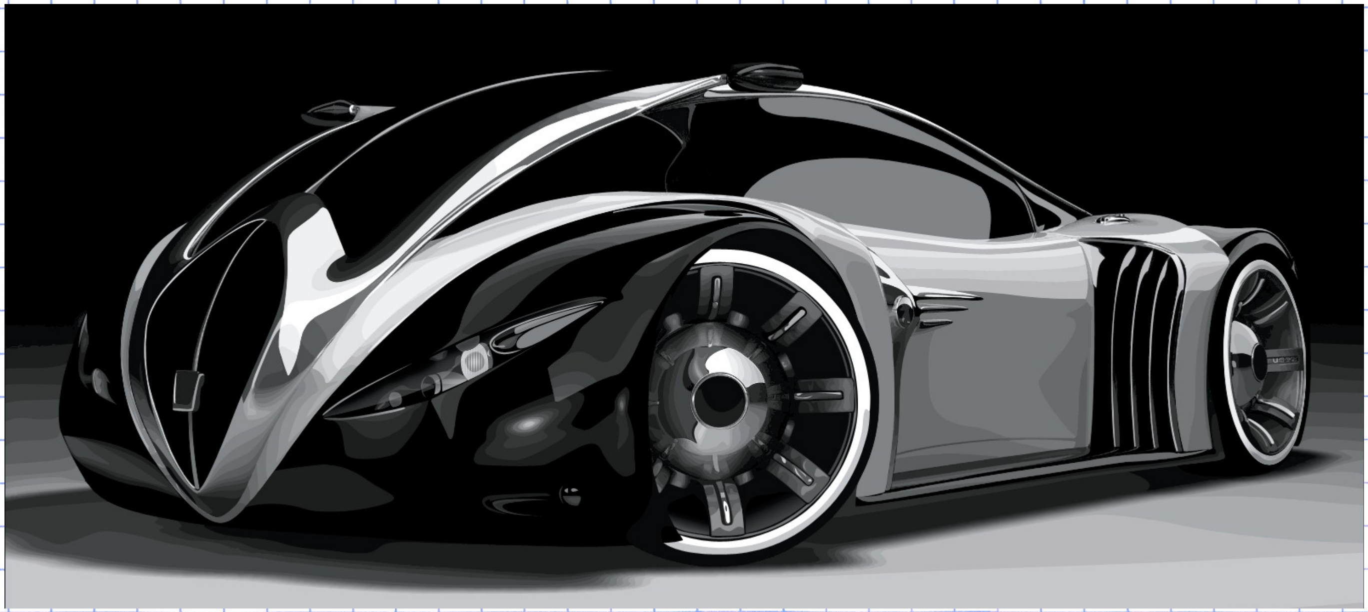


Discovery of Giant Magneto-Resistance

→ Nobel prize in Physics 2007

GMR implemented in HDD read heads

X10^6 increase of density after 1956



Physics (recent)

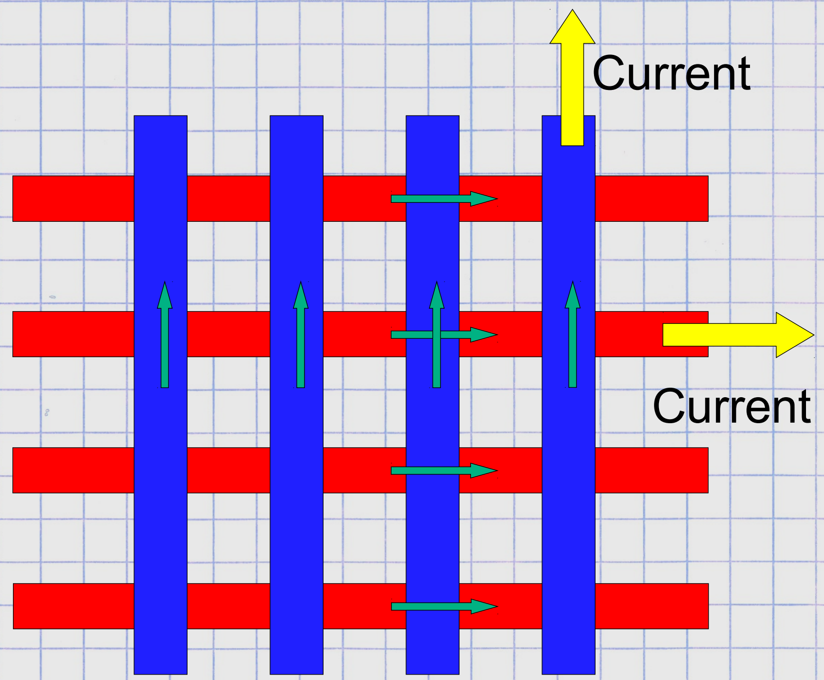
- Spin-transfer torques. Induces magnetization switching, oscillations
- Interfacial effects, chirality

Technology (to come)

- Magnetic Random Access Memories (dots)
- Logic and memory devices based on domain walls. 3D memories ?

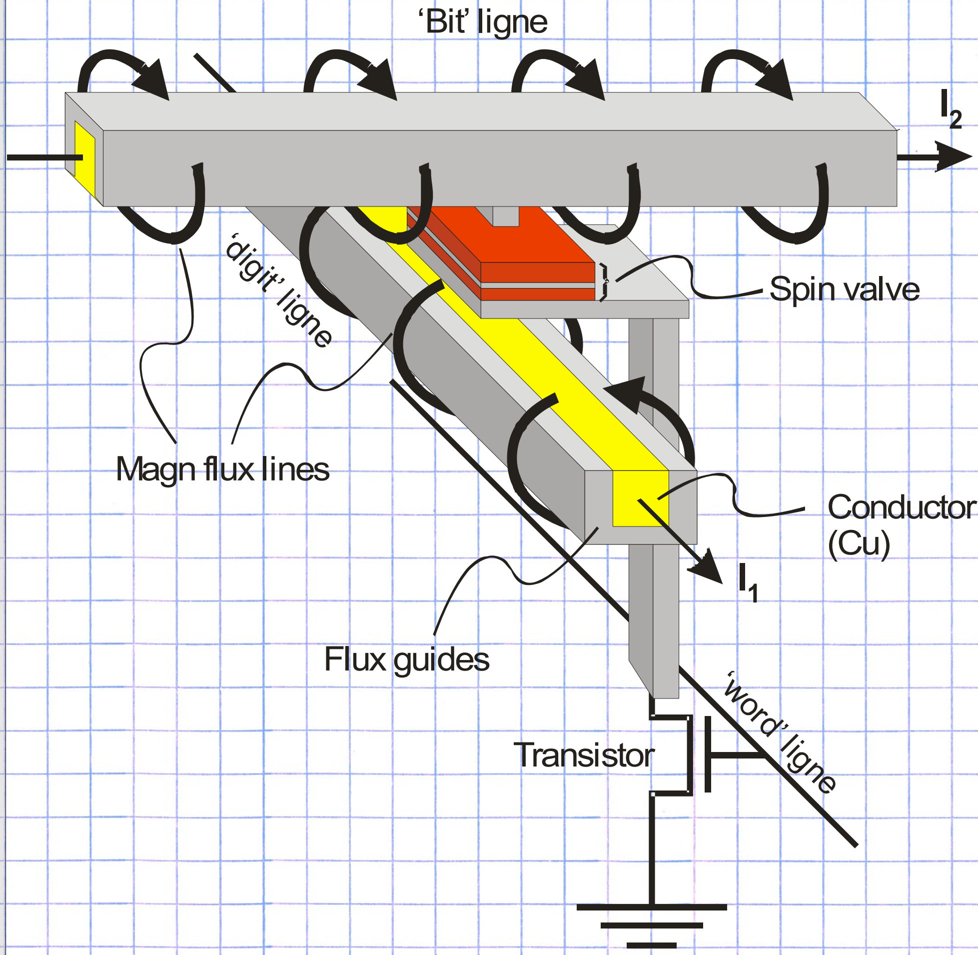
MRAM = Magnetic Random Access Memory

Overview

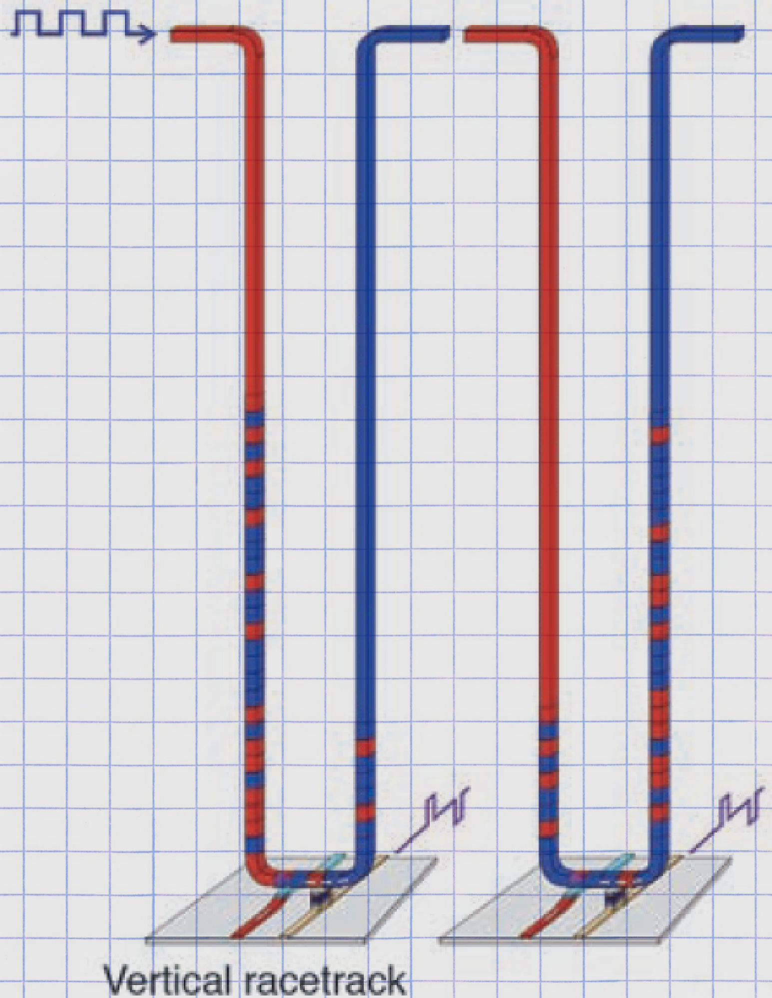


Main features:
Solid state memory
Non-volatile and fast
Still issues remaining

Detail of a cell (nb : old design)



Race-track memory in arrays of vertical nanowires



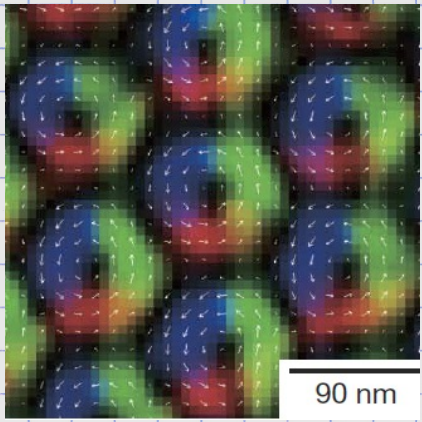
IBM, patents (2004)

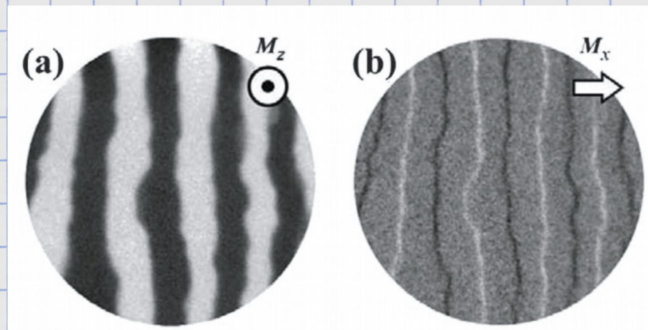
Advantages

- Goes beyond areal density
- Only 2D R/W devices

OBJECTS TO INVESTIGATE

Spin textures : 2D/3D — Skyrmions and helix





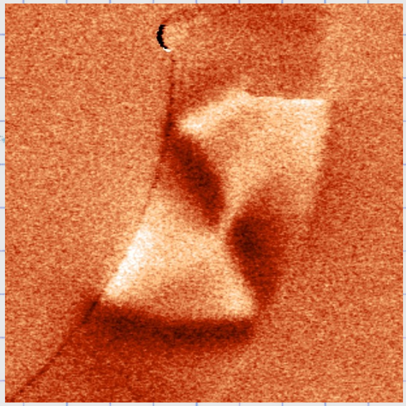
Cu\Fe\Ni stackings, interfacial

$Fe_{0.5}Co_{0.5}Si$, bulk

X. Z. Yu et al., Nature 465, 901 (2010)

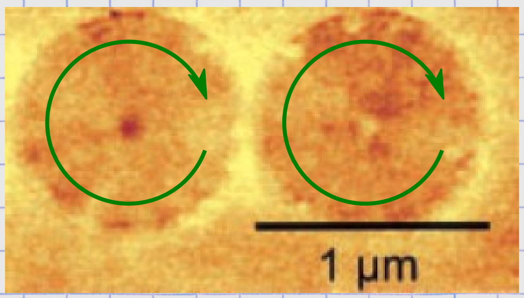
G. Chen et al., Phys. Rev. Lett. 110, 177204 (2013)

Constrained walls (eg : in stripes) : 1D/2D



Permalloy (15nm) - Stripe 500nm

Magnetic vortices (1D/0D)



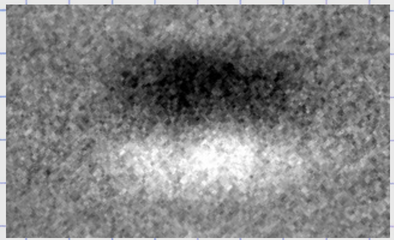
Diameter ~ 10nm

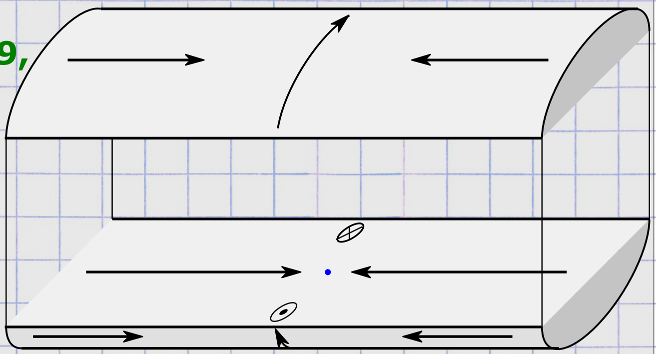
T. Shinjo et al., Science 289, 930 (2000)

Bloch point (0D)

⇨ Point with vanishing magnetization

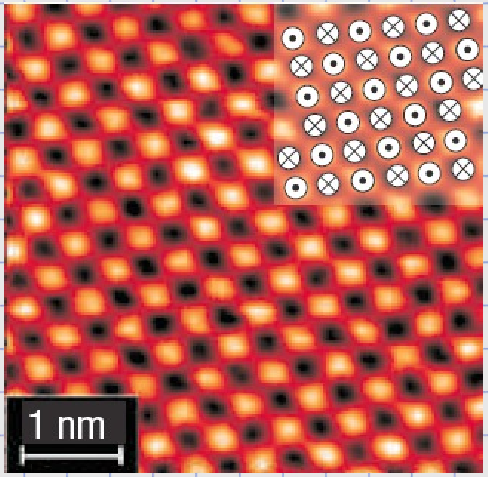
W. Döring, J. Appl. Phys. 39, 1006 (1968)





Spin-polarized STM

Fe(1ML)/W(001)



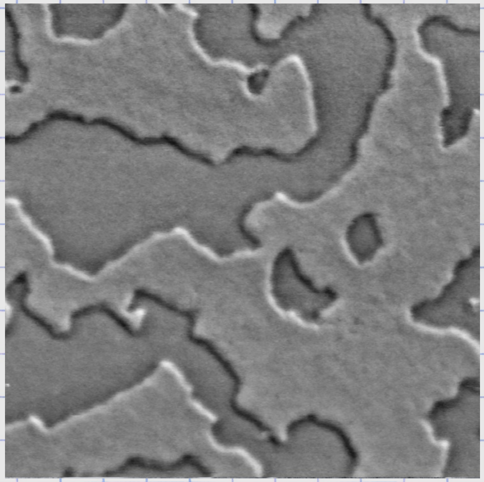
Antiferromagnetic domain

M. Bode et al., Nat. Mater. 5, 477-481 (2006)

REVIEW :
R. Wiesendanger, Rev. Mod. Phys. 81, 1495 (2009)

Magnetic Force Microscopy

FePt thin films



2 µm

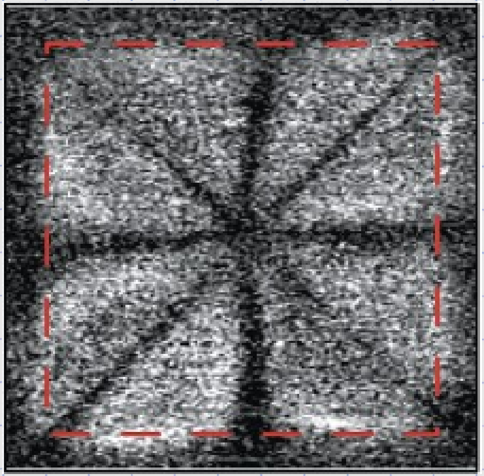
Magnetic domain walls

O.F.
Sample courtesy: A. Marty

REVIEW :
R. Proksch et al., Modern techniques for characterizing magnetic materials, Springer, p.411 (2005)

NV center microscopy

Square Fe20Ni80 dot



5 µm

Signature of flux-closure

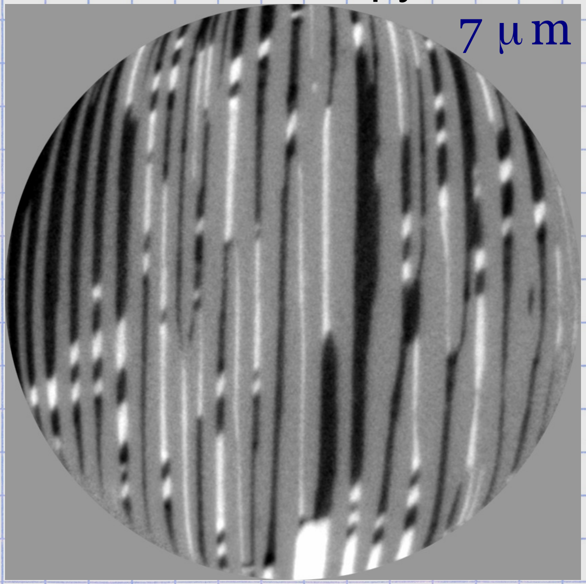
L. Rondin et al., arXiv:1302.7307

Others : BEMM, scanning Hall probe, near-field optical etc.

Overview
- Large variety
- Rather slow

SPLEEM

Spin-Polarized Low Energy Electron Microscopy

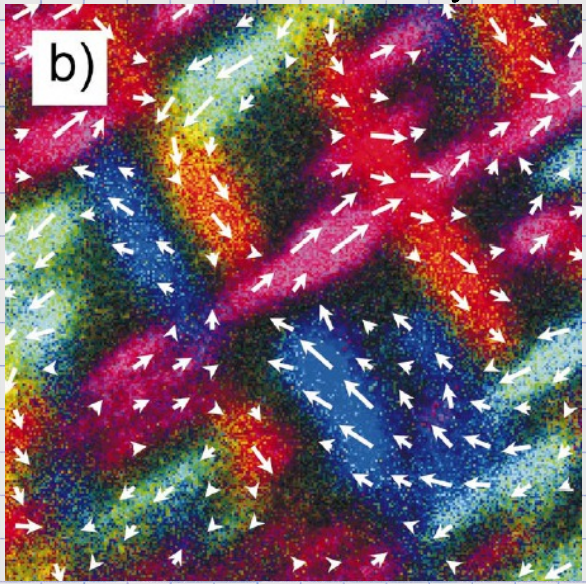


Stripes of Fe/W(110)

REVIEW:
N. Rougemaille et al., Eur. Phys. J. Appl. Phys. 50, 20101 (2010)

SEMPA

Scanning Electron Microsc. with Polarization Analysis



Maze of Fe/W(001) 1.5 μm

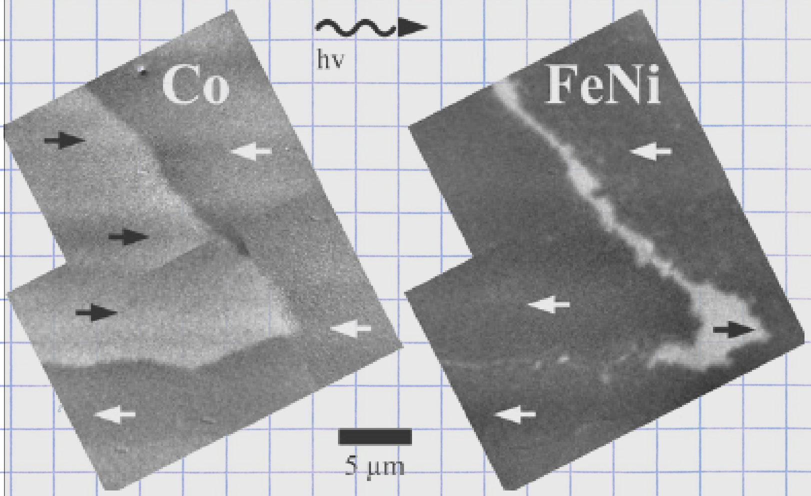
W. Wulfhekel et al., Phys. Rev. B 68, 144416/1-9 (2003)

Overview

- Requires sample preparation
- Good spatial resolution
- Some information about structure

XMCD-PEEM

X-ray Magnetic Circular Dichroism
Photo-Emission Electron Microsc.



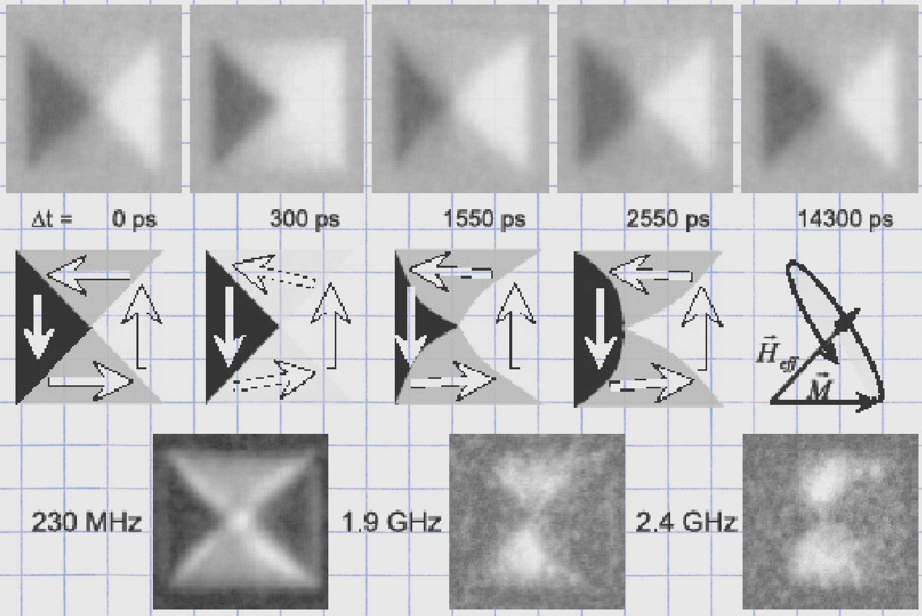
Co\Cu\FeNi trilayer

→ elemental resolution

J. Vogel et al., J. Phys. : Condens. Matter 19, 476204 (2007)

TXM

Transmission X-ray Microscopy



FeNi 6µm square dot → time resolution

J. Raabe et al., Phys. Rev. Lett. 94, 217204 (2005)

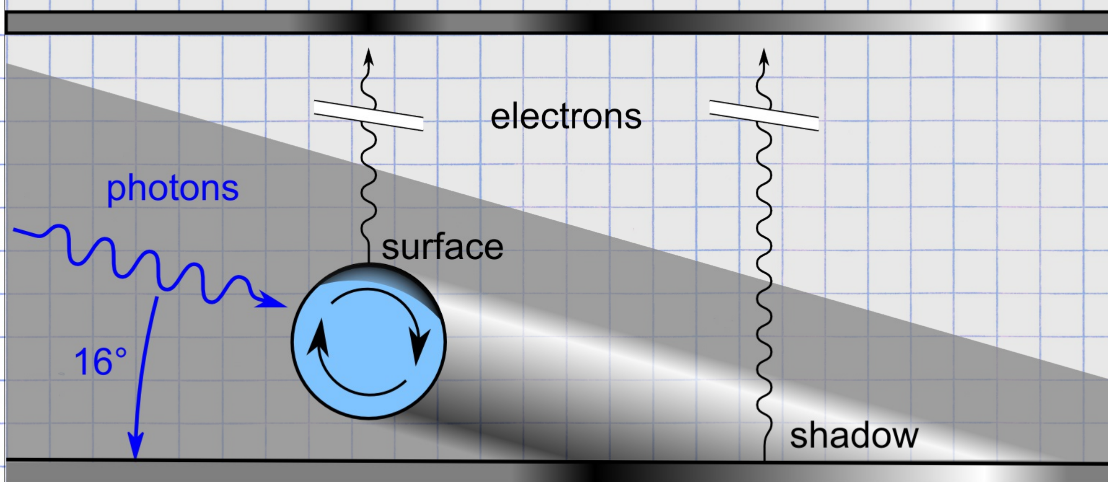
Others : holography, scattering

Overview

- Elemental sensitivity
- Compatible with time resolution
- Rather versatile

Understanding the contrast

Magnetic dichroïc contrast (XMCD) on the image plate



Supporting surface

⇨ Above wire → inform about surface magnetization

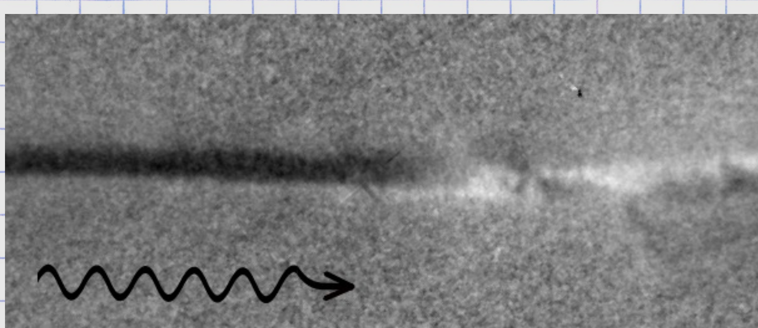
⇨ In the shadow → inform about volume magnetization

Identification

Previous PEEM in shadow : **J. Kimling et al., Phys. Rev. B 84, 174406 (2011)**

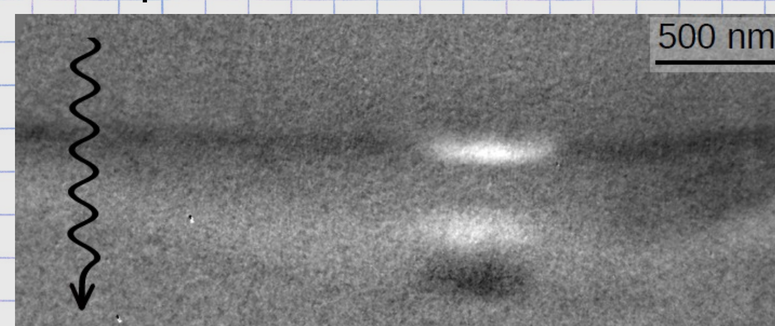
Beam along wire

⇨ Locate domain walls



Beam across wire

⇨ Inspect domain wall



O.F., unpublished

Overview of some magnetic microscopies with spatial resoltuion better than 50nm

	Sp-STM	MFM	NV	BEMM	SEMPA	SPLEEM	TEM	XMCD -PEEM	XMCD-microscopy (Fresnel ZP)
Resolution	<1nm	15nm	5-10 nm	1-5nm	10nm	10nm	1-2nm	25nm → 10nm	15nm
Sensitivity	High	Med	High	Med	Med	High	Low	High	High
In-field	YES	Limited	Limited	YES	local	No?	Limited	No?	YES
Versatile*	No	YES	Yes	No	Yes	UHV	Limited	Yes	Limited
Dynamics	No	No	No	No	No	No	New	Yes	Yes
Element-sensitive	Limited	No	No	No	No	Limited	Limited	Yes	Yes
Probes	m_i	$\mathbf{H}_\mathrm{d}$	$\mathbf{H}_\mathrm{d}$	m_i	$\mathbf{m}$	$\mathbf{m}$	$m_{x,y}$	$m_\mathbf{k}$	$m_\mathbf{k}$

**Versatile* may mean: Sample preparation, measurement of brought-in samples etc.

Conclusions

- Worse and best come together
- Need for combining various instruments