FOR DUMMIES

Magnetic force microscopy : basics and tricks

Imaging nanodevices and materials at the frontiers of the NTEGRA microscope

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France

http://neel.cnrs.fr

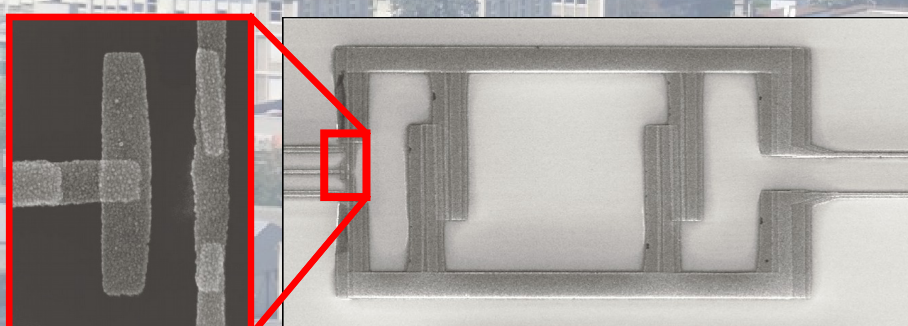
Science and technology area in Grenoble

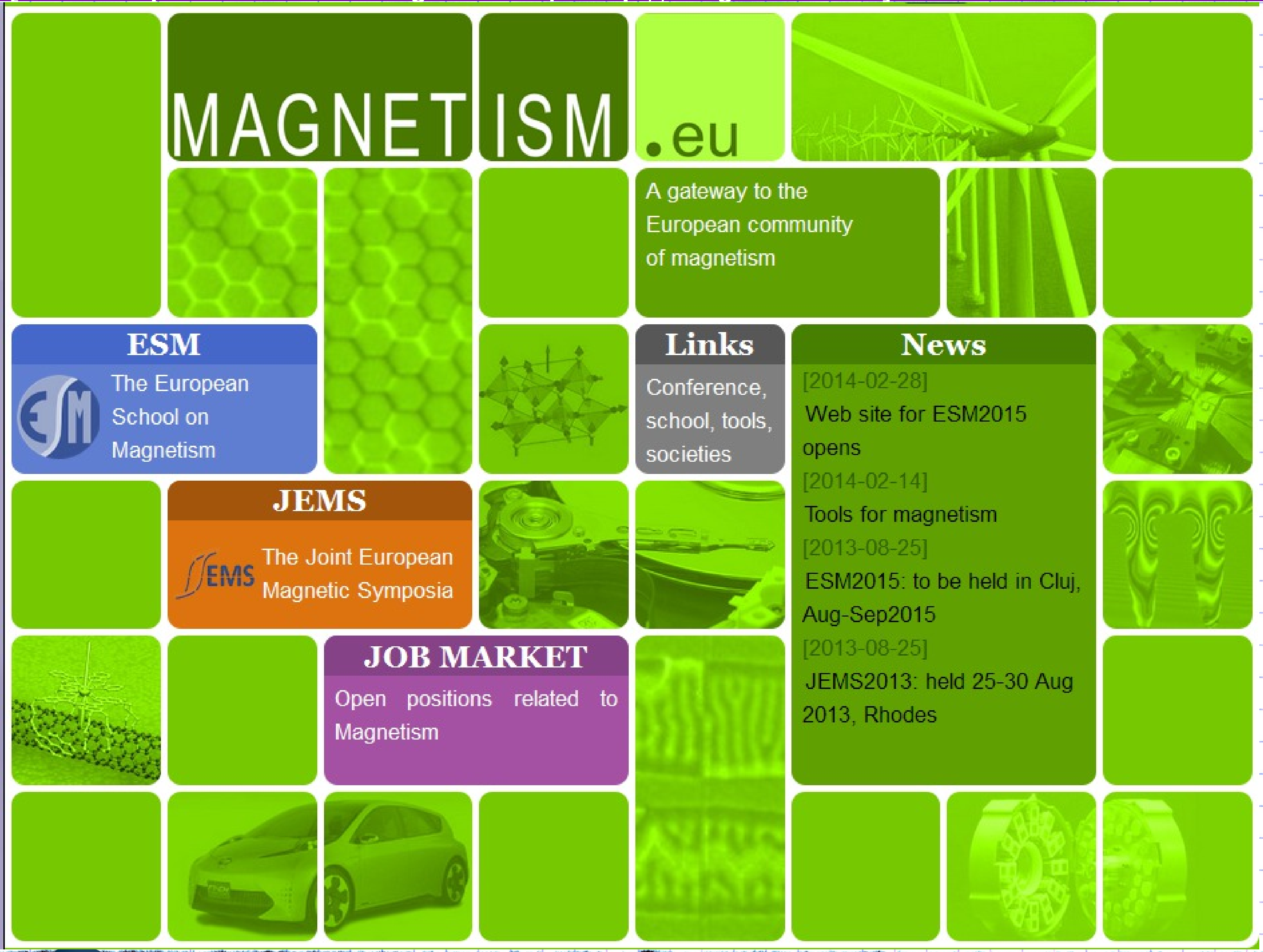
Facts

- Core of Condensed Matter Physics
- 180 full-staff scientists, 130 technical staff
- 40 PhD / year

Internal structure

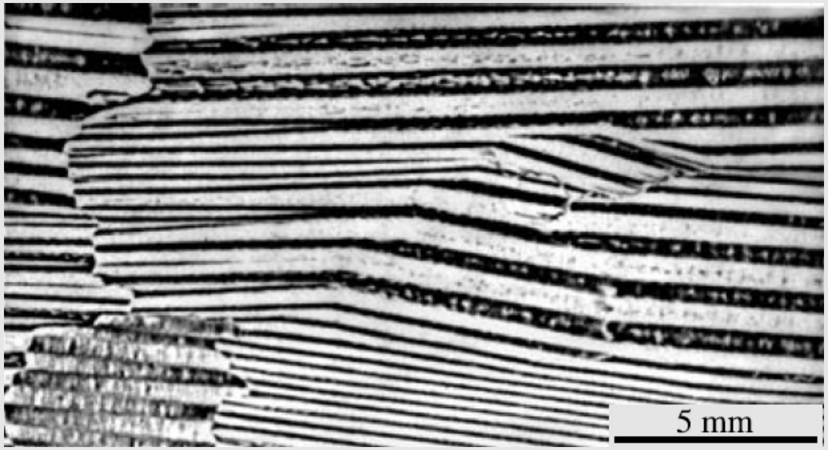
- Research teams + technological support groups
- Three scientific departments
  - Condensed Matter – Low Temperatures
  - Condensed Matter – Functional Materials
  - Nanosciences




MAGNETISM.eu
A gateway to the European community of magnetism
ESM
The European School on Magnetism
Links
Conference, school, tools, societies
News
[2014-02-28]
Web site for ESM2015 opens
[2014-02-14]
Tools for magnetism
[2013-08-25]
ESM2015: to be held in Cluj, Aug-Sep2015
[2013-08-25]
JEMS2013: held 25-30 Aug 2013, Rhodes
JEMS
The Joint European Magnetic Symposia
JOB MARKET
Open positions related to Magnetism

Magnetic domains

Numerous and complex magnetic domains



(History : Weiss domains)

Anisotropy exchange length (domain wall width)

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

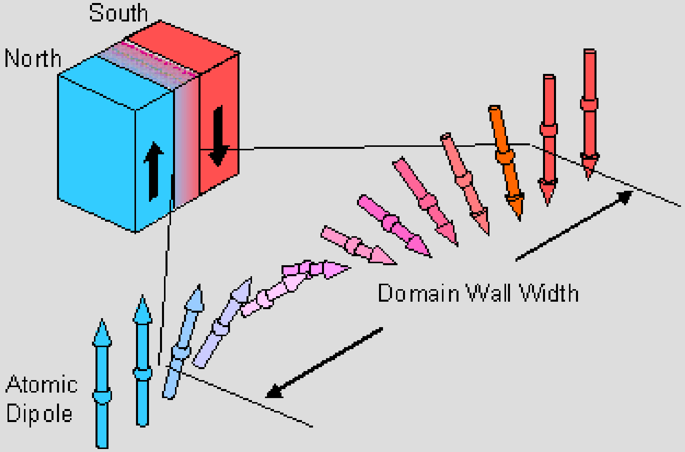
Exchange → J/m

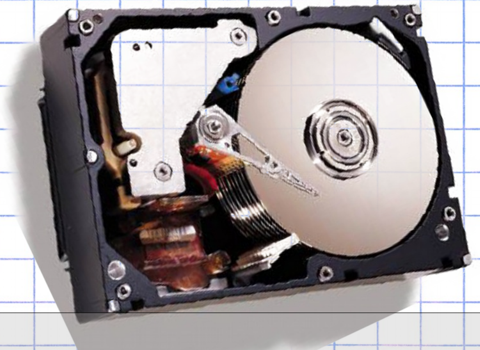
Anisotropy → J/m^3

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

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

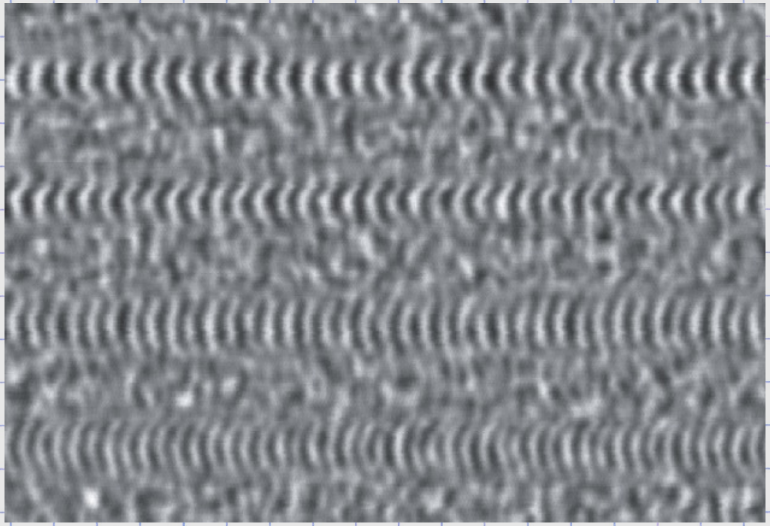
Hard — Soft





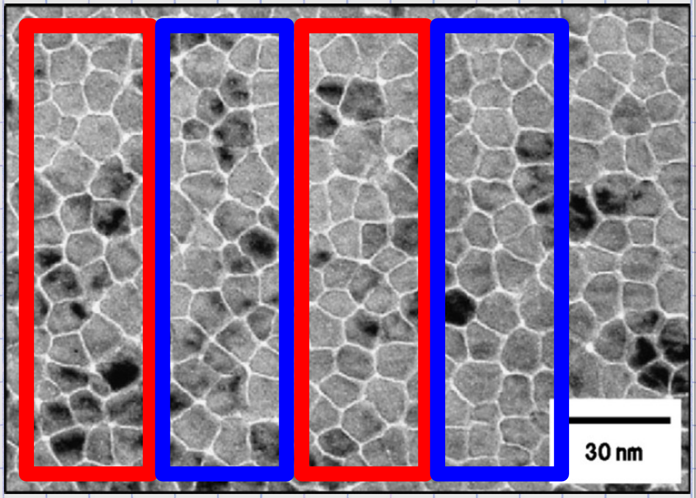
Magnetic bits on Hard Disk Drive

Co-based hard disk media : bits 50nm and below



B. C. Stipe, Nature Photon. 4, 484 (2010)

Underlying microstructure



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

Relevant spatial resolution

↳ 10-100nm

Relevant time resolution

- >1µs : 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

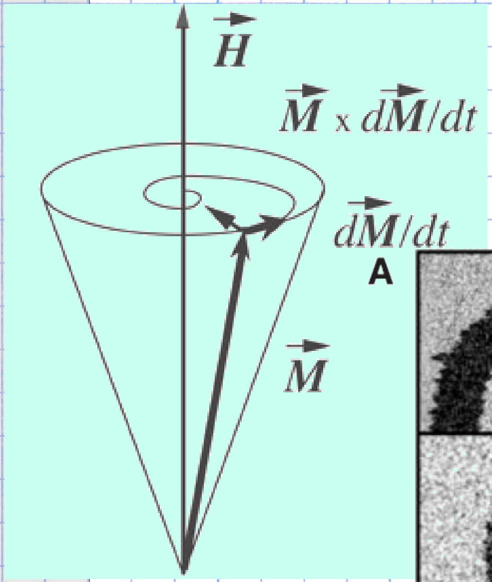
$$\gamma_0 = \mu_0\gamma \qquad \gamma = \frac{gq}{2m}$$

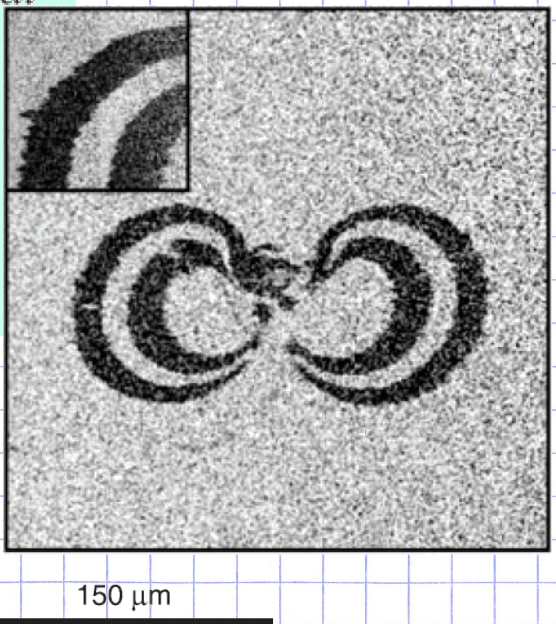
$$\gamma / 2\pi = 28\,\mathrm{GHz/T}$$

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

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

Demonstration: 1999

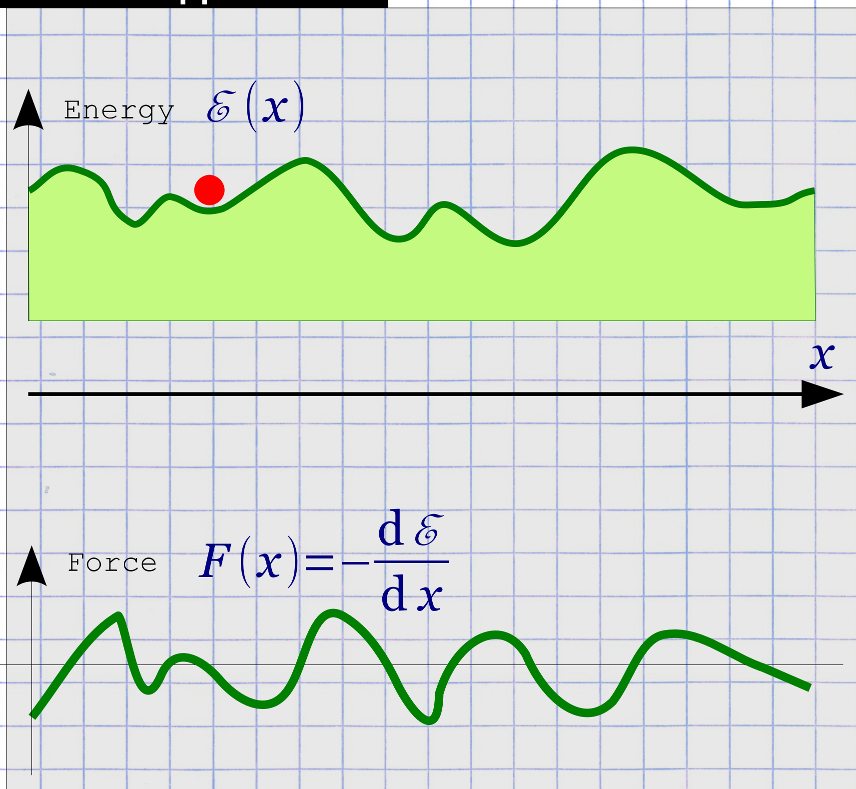




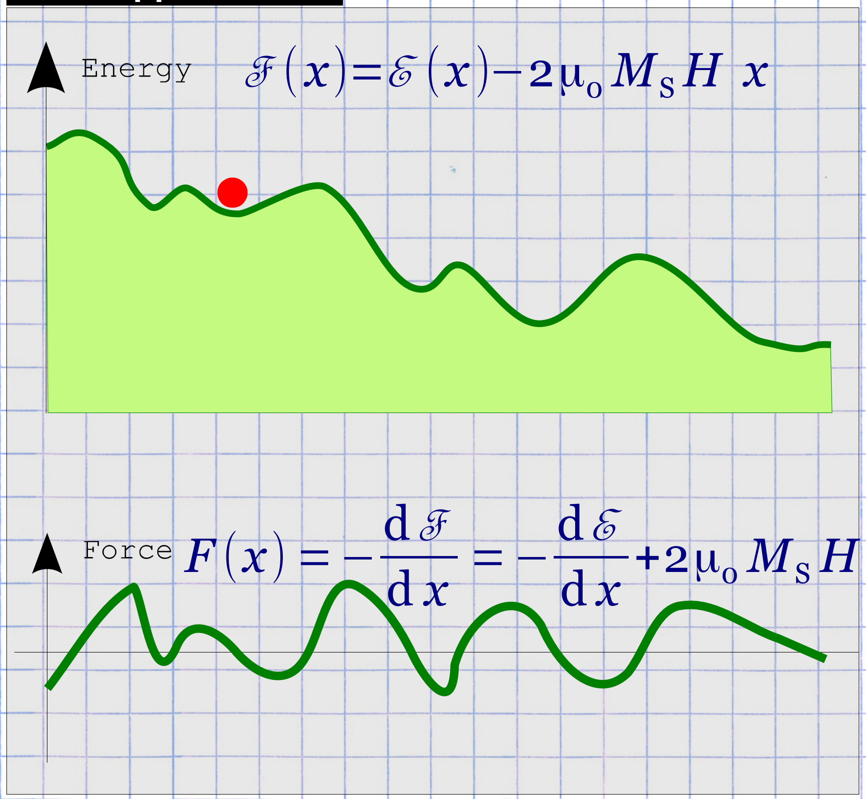
C. Back et al., Science 285, 864 (1999)

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

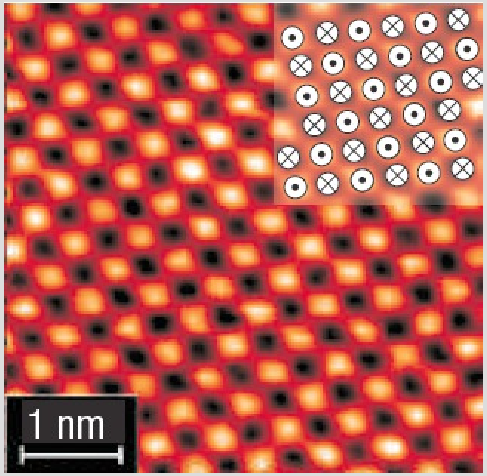
Many criteria to be balanced

See : slides on techniques for characterizing magnetic nano-objects :

http://perso.neel.cnrs.fr/olivier.fruchart/slides/tech/tech-fruchart-gdr2009.pdf

Spin-polarized STM

Fe(1ML)/W(001)

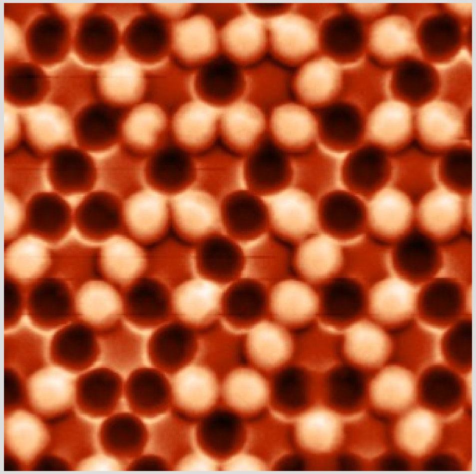


Antiferromagnetic domain

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

Magnetic Force Microscopy

Array of dots

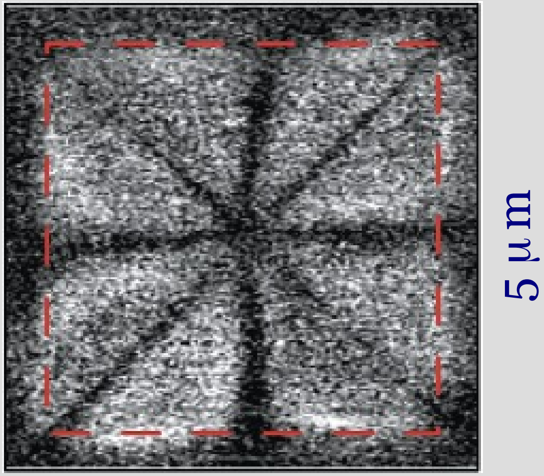


Up-and-down 'single-domains'

NEEL, sample courtesy: N. Rougemaille, I. Chioar

NV center microscopy

Square Fe20Ni80 dot



Signature of flux-closure

L. Rondin et al., arXiv:1302.7307

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

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

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

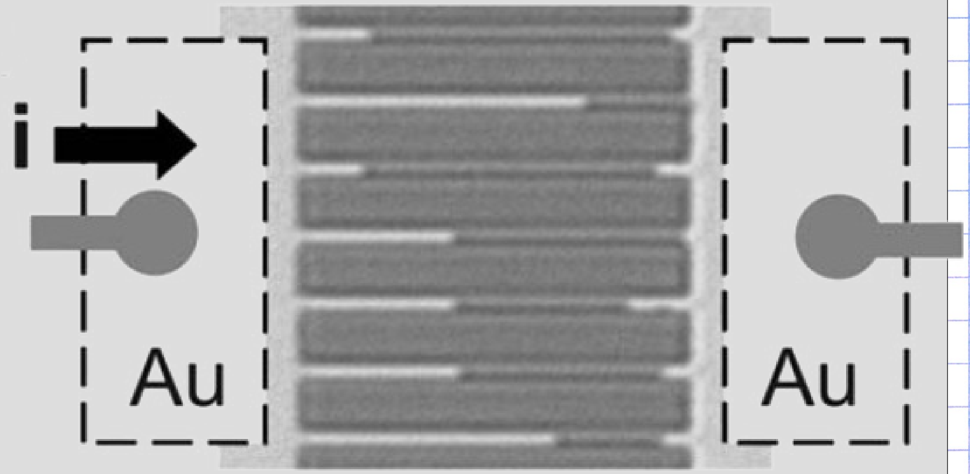
Overview
- Large variety
- Rather slow

Principle

- Polarization of light versus magnetic body
- Kerr : reflection geometry
- Faraday : transmission geometry

Example

Kerr microscopy of patterned Pt/Co/AlOx film with perpendicular magnetization



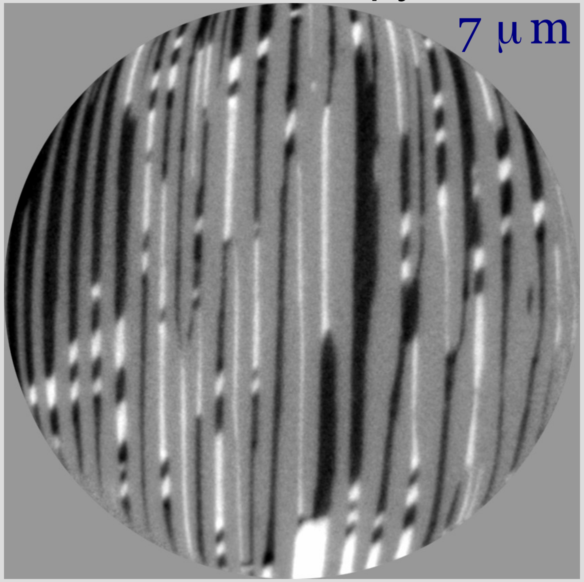
@NEEL : T. A. Moore et al., Appl. Phys. Lett 93, 262504 (2008)

Overview

- Quick (full field)
- Compatible with time resolution
- Limited spatial resolution

SPLEEM

Spin-Polarized Low Energy Electron Microscopy

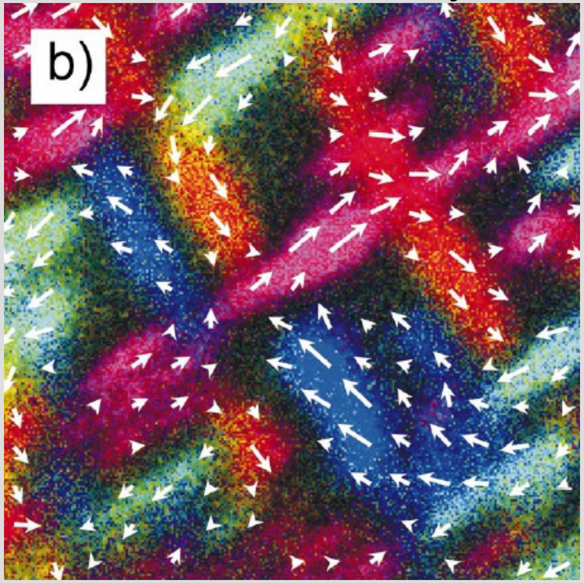


Stripes of Fe/W(110)

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

SEMPA

Scanning Electron Microsc. with Polarization Analysis

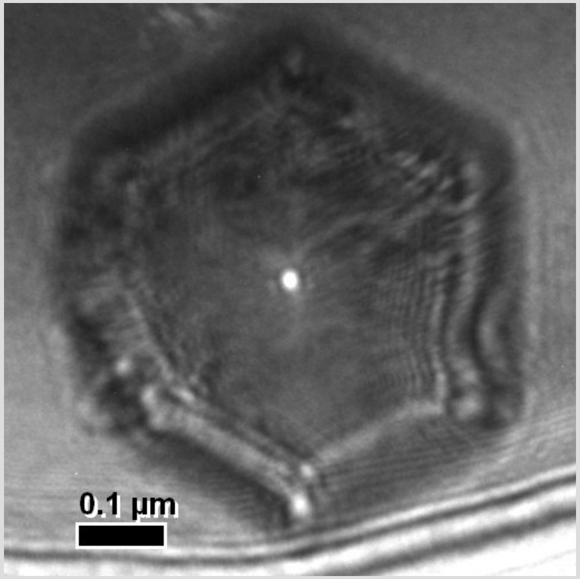


Maze of Fe/W(001) 1.5 µm

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

Lorentz, holography etc.

TEM - based



Self-assembled Co/W(110)

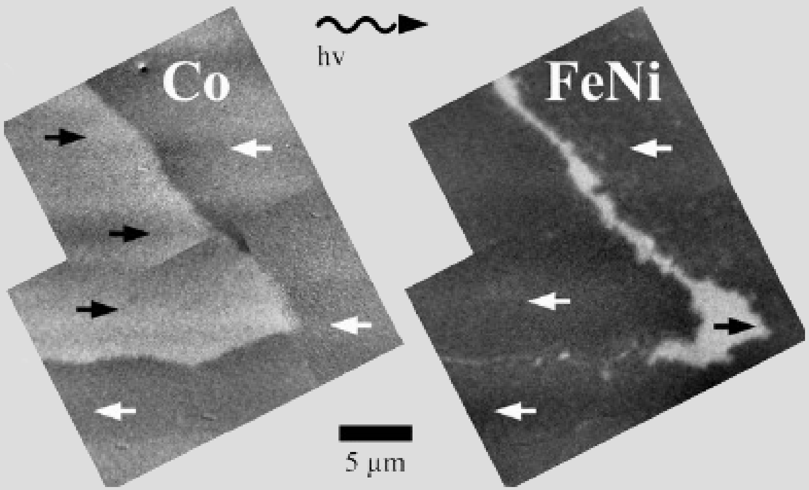
@NEEL :
O. Fruchart et al., in preparation

Overview

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

XMCD-PEEM

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



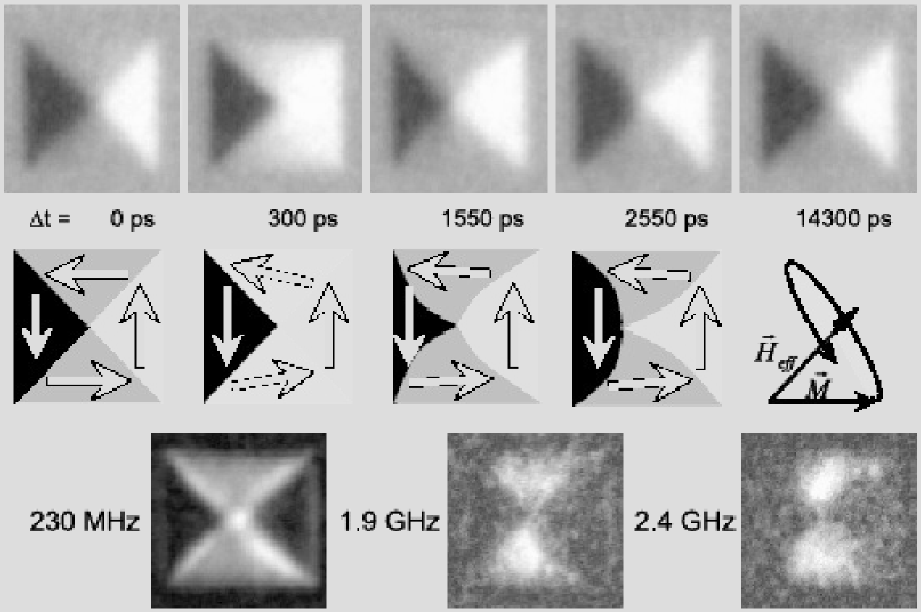
Co\Cu\FeNi trilayer

→ elemental resolution

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

TXM

Transmission X-ray Microscopy



FeNi 6µm square dot → time resolution

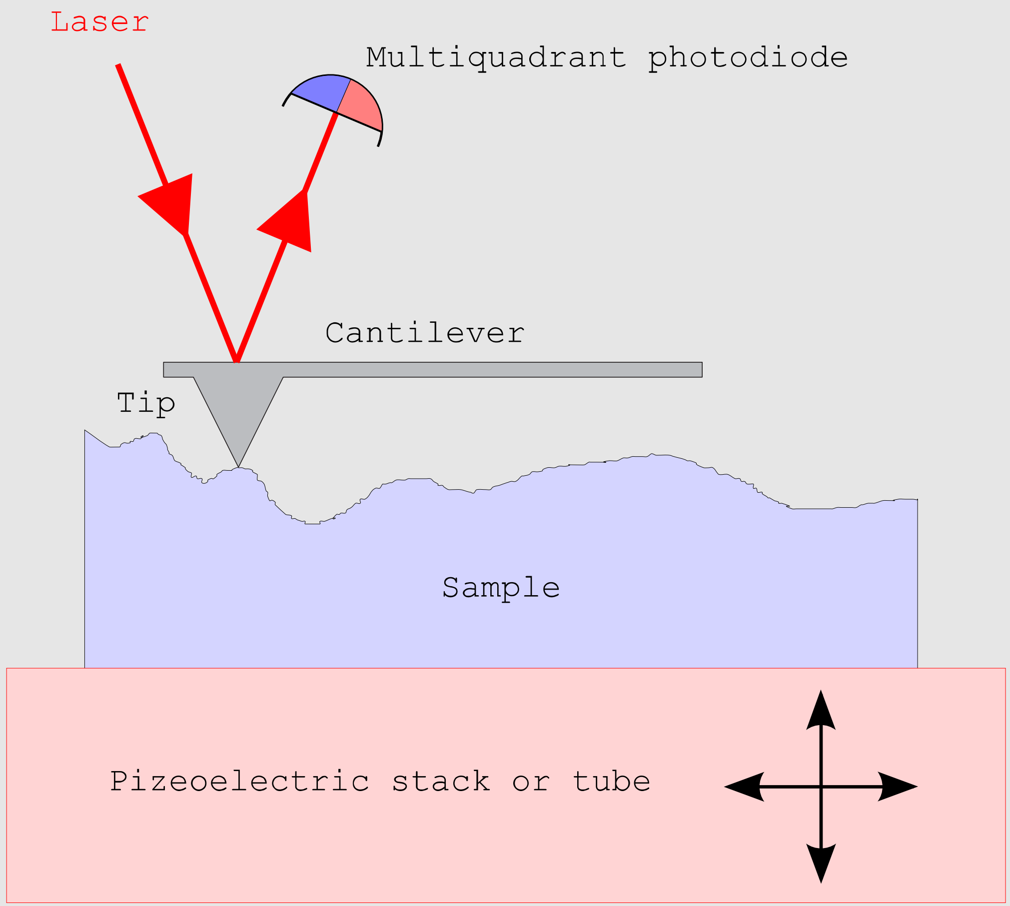
J. Raabe et al., Phys. Rev. Lett. 94, 217204 (2005)

Others : holography, sca

Overview
- Elemental sensitivity
- Compatible with time resolution
- Rather versatile

Table of contents

Key elements of an Atomic Force Microscope (AFM)

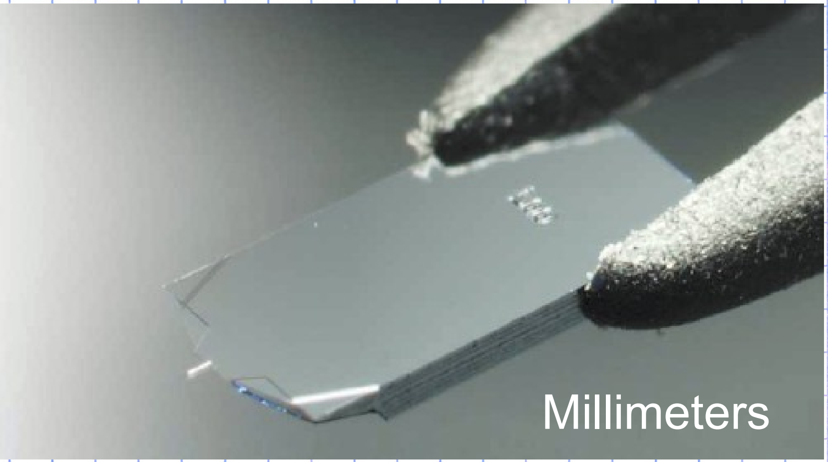


G. Binnig et al., Phys. Rev. Lett. 56, 930-933 (1986)

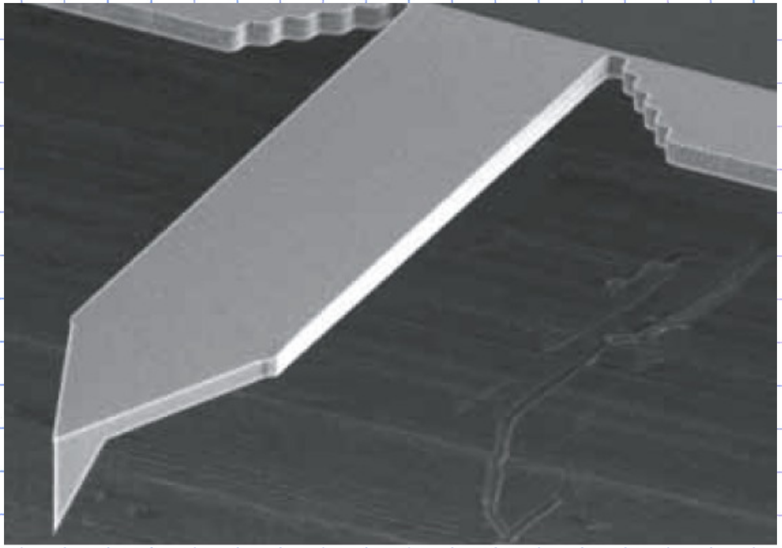
Overview

Measures forces (vertical and lateral) between sample and tip

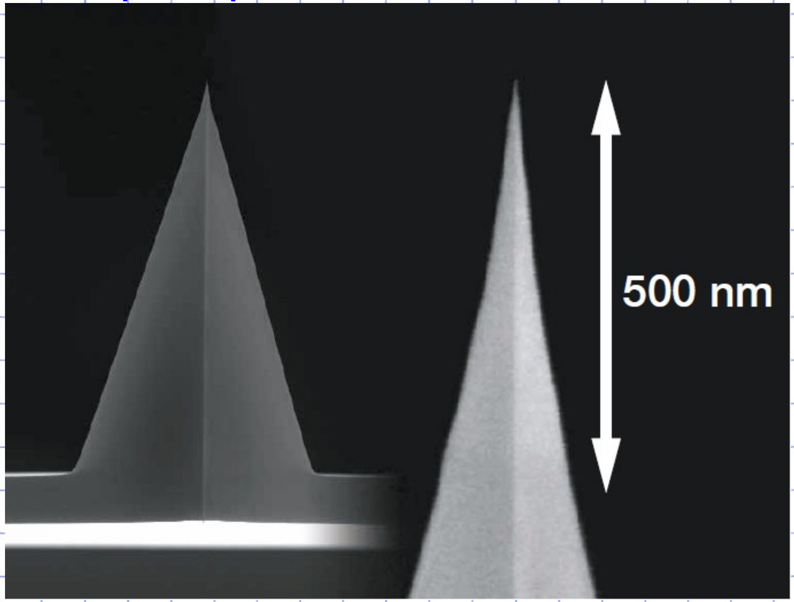
Chip – Batch fabrication



Cantilever



Full tip + apex

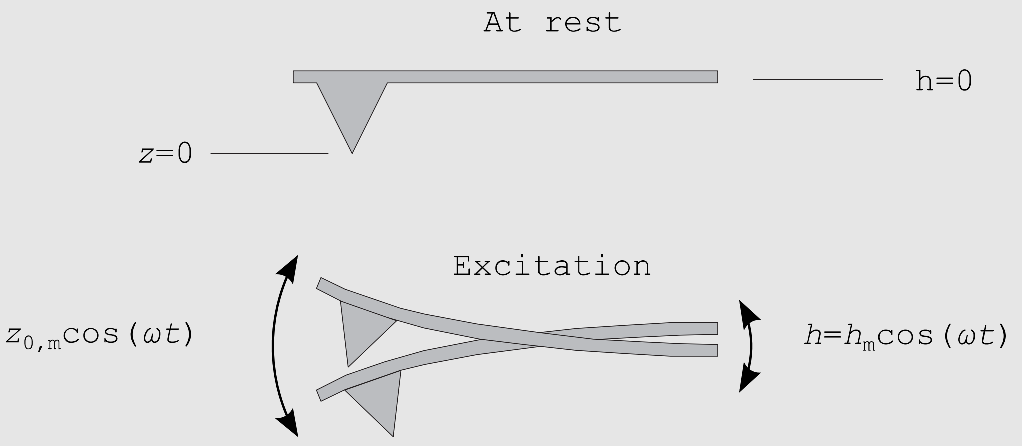


Overview

- Price 10-200eur/tip
- Radius of curvature ≈ 5nm

Images : Olympus catalog (http://www.olympus.co.jp/probe)

Mechanical excitation of cantilevers



$$m\ddot{z}+\Gamma\dot{z}+kz=F(z,t)$$

m	Inertia
Γ	Damping
k	Spring
$F(z,t)$	External force

Notations

Seek solutions for $F=0$ $\quad z(t)=z_0 e^{j\omega t}$

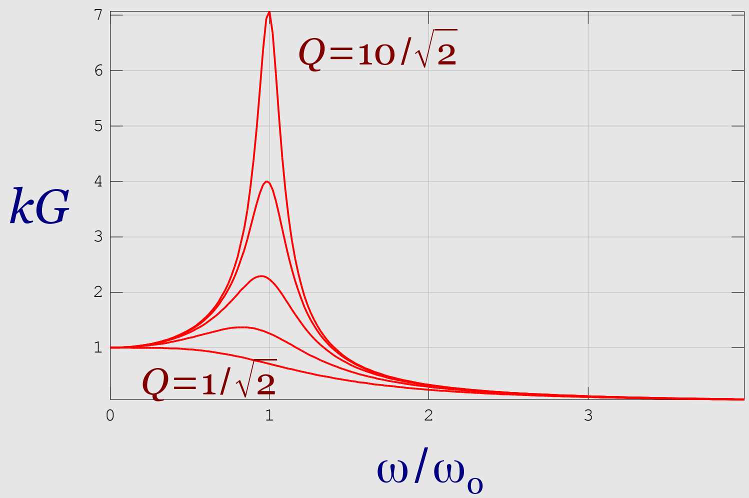
Reference angular velocity $\quad \omega_0=\sqrt{\frac{k}{m}}$

Quality factor $\quad Q=\frac{\sqrt{km}}{\Gamma}$

⇨ Transfert function

$$H=\frac{z}{F}=\frac{1}{k}\frac{1}{-\left(\frac{\omega}{\omega_0}\right)^2+\frac{j}{Q}\left(\frac{\omega}{\omega_0}\right)+1}$$

Gain



$$G=|H|=\frac{1}{k}\frac{1}{\sqrt{\left[1-\left(\frac{\omega}{\omega_0}\right)^2\right]^2+\frac{1}{Q^2}\left(\frac{\omega}{\omega_0}\right)^2}}$$

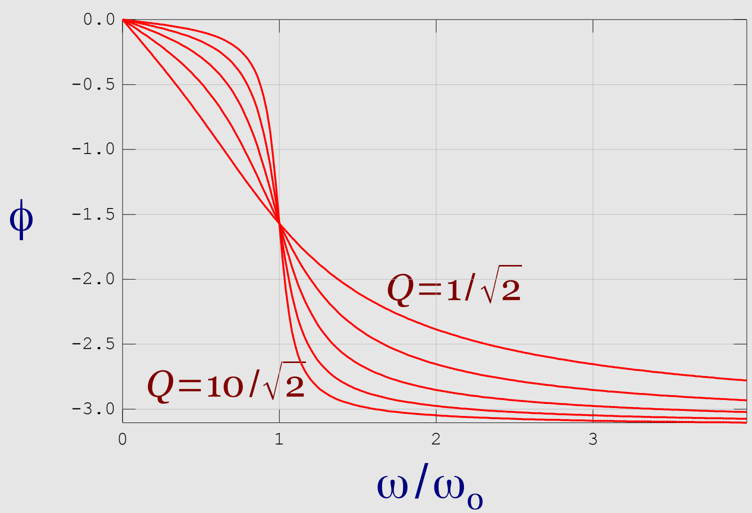
Peak at : $\omega_r=\omega_0\sqrt{1-\frac{1}{2Q^2}}$

$kG(0)=1$

$kG(\omega_r)=Q$

$kG(\infty)=0$

Dephasing



$$\cos\phi=\frac{1-\left(\frac{\omega}{\omega_0}\right)^2}{\sqrt{\left[1-\left(\frac{\omega}{\omega_0}\right)^2\right]^2+\frac{1}{Q^2}\left(\frac{\omega}{\omega_0}\right)^2}}$$

$\phi(0)=0$

$\phi(\infty)=-\pi$

Q>>1

$\omega_r\approx\omega_0$

$\phi(\omega_r)\approx-\pi/2$

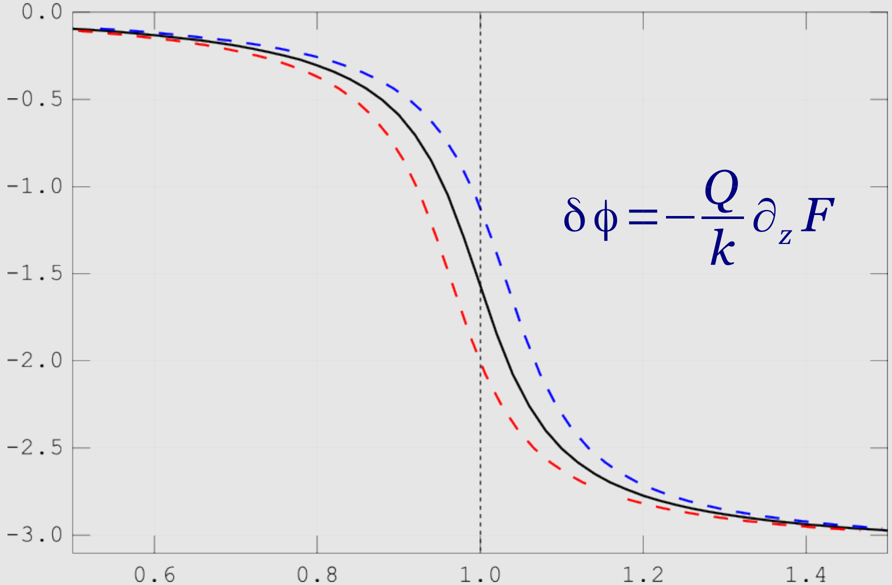
$\frac{\Delta\omega_r}{\omega_0}\approx\frac{\sqrt{3}}{Q}$

Tip-sample interaction treated as perturbation

$$m\ddot{z}+\Gamma\dot{z}+kz=F(z) \quad \text{with} \quad F(z)=F(z_o)+(z-z_o)\partial_z F$$

⇨ Mere renormalization : $\omega_{o,\mathrm{eff}}=\omega_o\left(1-\frac{1}{2k}\partial_z F\right)$

Phase shift



$$\delta\phi=-\frac{Q}{k}\partial_z F$$

$$\omega_{exc}=\omega_o$$

Attractive force

⇨ Red shift

Repulsive force

⇨ Blue shift

- Forces monitored through phase shift
- Notice my convention : decreasing phase (may be set in the software)

MFM tips : AFM tip + magnetic coating

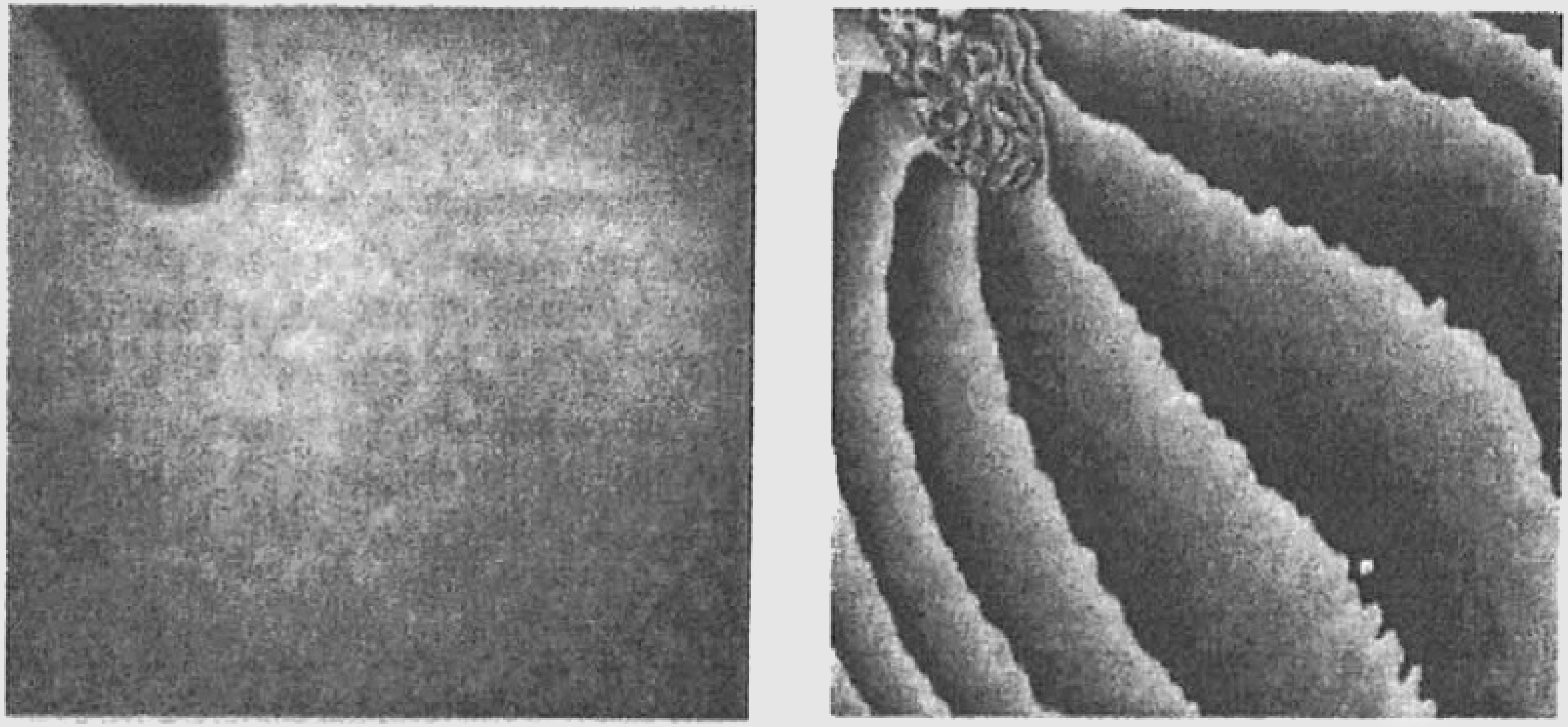
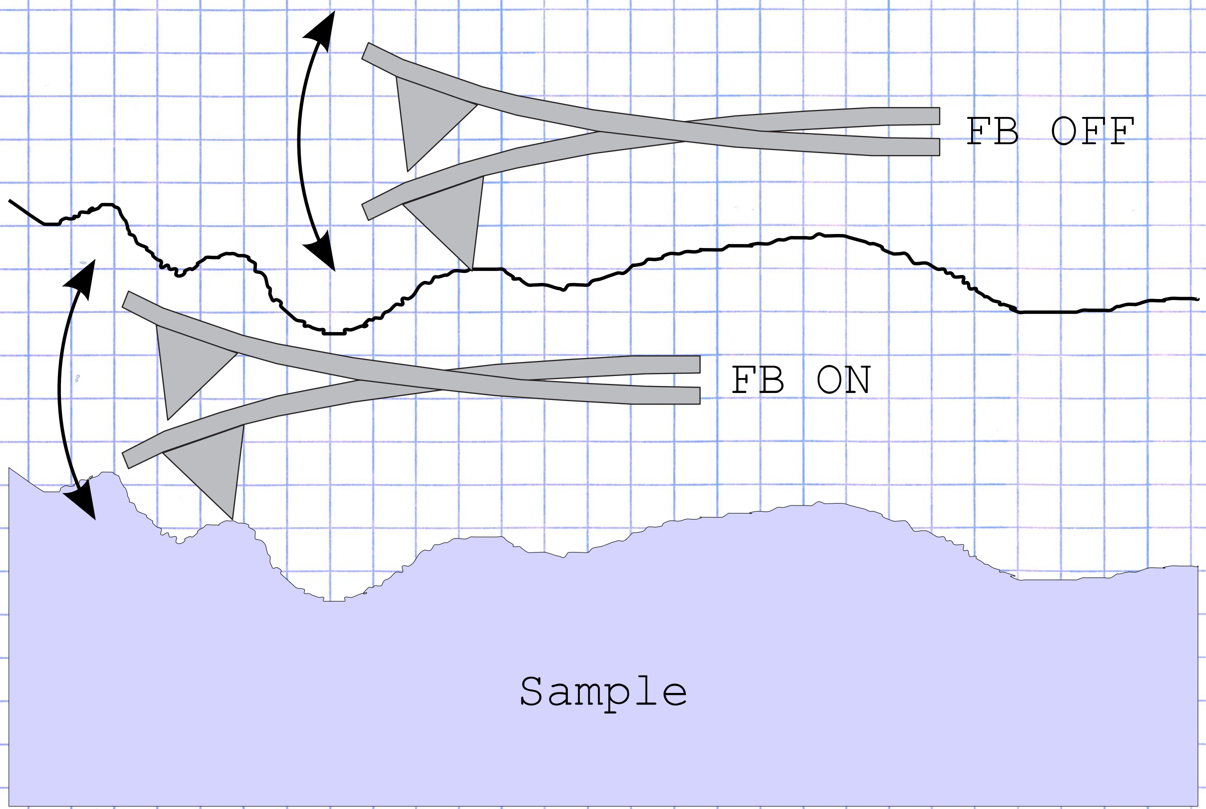
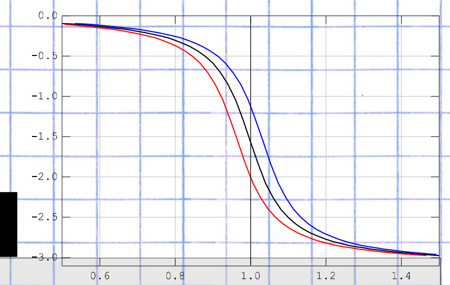


Figure 11-20: The electron amplitude (left) and phase (right) near an MFM tip visible as a dark shadow on the upper left corner of the left image.

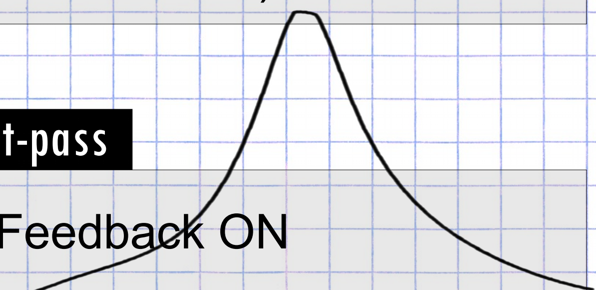
R. Proksch et al., Modern techniques for characterizing magnetic materials, Springer, p.411 (2005)





Second pass

⇨ Monitor long-range forces (magnetic, electrostatic)



First-pass

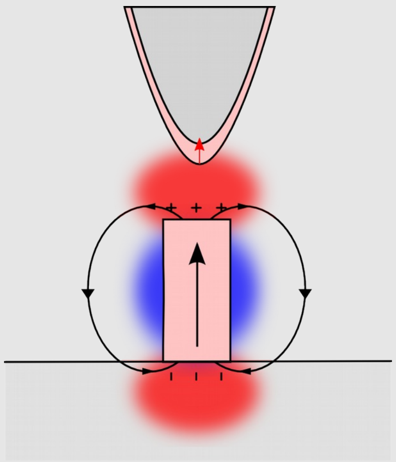
⇨ Feedback ON

⇨ Monitor topography (height) and any other signal (phase etc.)

First report : **Y. Martin et al., Appl. Phys. Lett. 50, 1455 (1987)**

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

Tip is a dipole



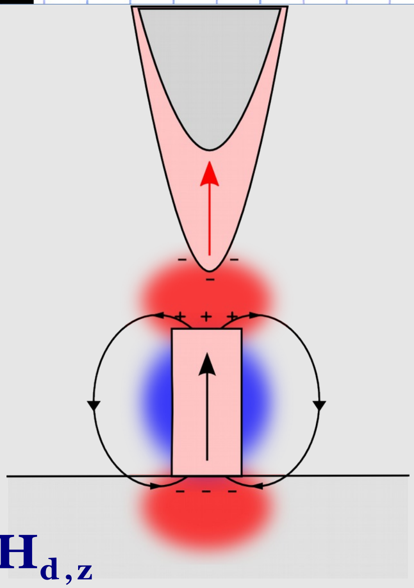
$$\mathcal{E}_{1,2} = -\mu_0 \boldsymbol{\mu_2} . \mathbf{H_d}$$

$$\mathcal{E}_{1,2} = -\mu_0 (\mu_x . H_{d,x} + \mu_y . H_{d,y} + \mu_z . H_{d,z})$$

$$\Rightarrow \delta\phi = \frac{Q}{k} \mu_0 \mu_i \partial_z^2 H_{d,i}$$

Tip is a monopole

$$\mathcal{E}_{1,2} = \mu_0 \sigma . \varphi$$

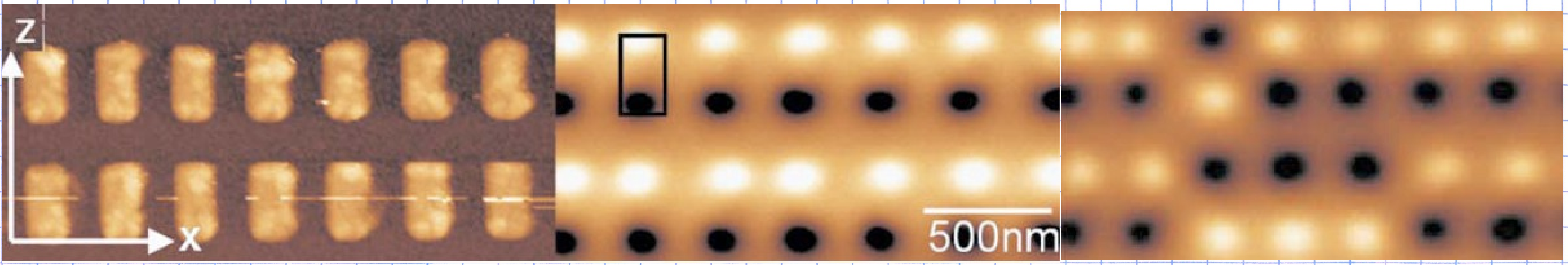


$$\mathbf{F_z} = -\mu_0 \sigma \mathbf{H_{d,z}}$$

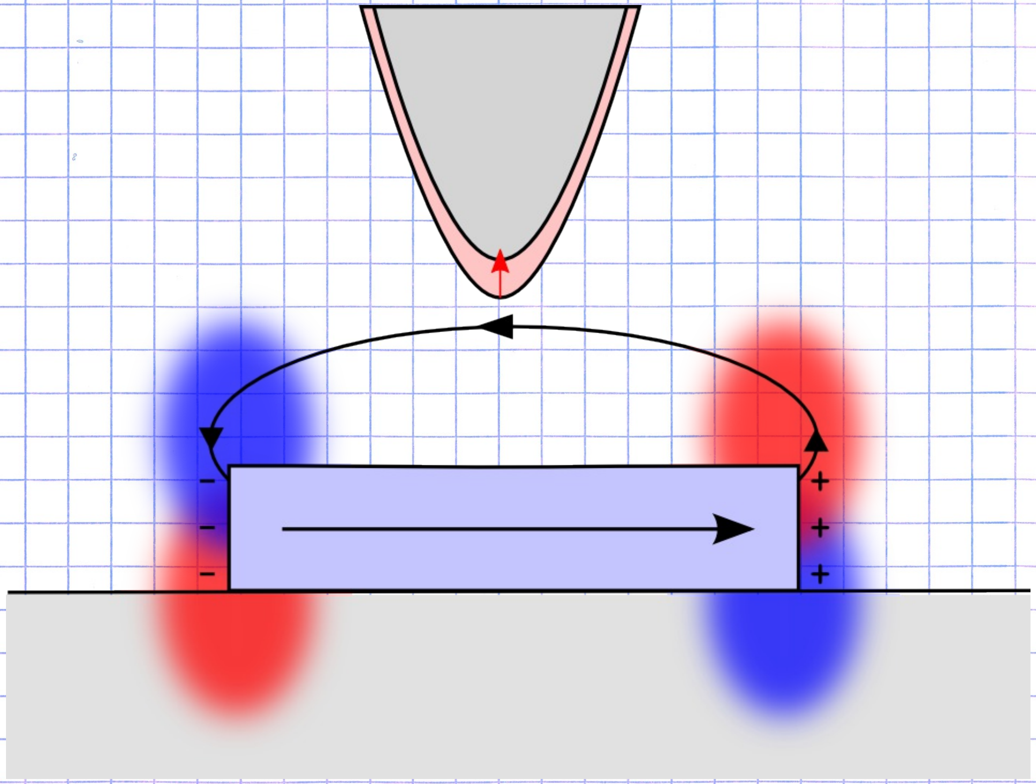
$$\Rightarrow \delta\phi = \frac{Q}{k} \mu_0 \sigma \partial_z H_{d,z}$$

- In practice, a combination of both models is best suited (dipole is more important)
- MFM is sensitive to some derivative(s) of the stray field from the sample
- MFM may be sensitive to in-plane field, depending on the tip magnetic moment

Topography MFM, saturated MFM, partly reversed



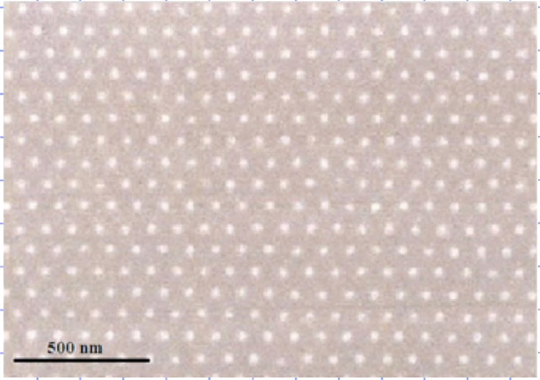
S. Y. Suck et al., APL95, 162503 (2009)

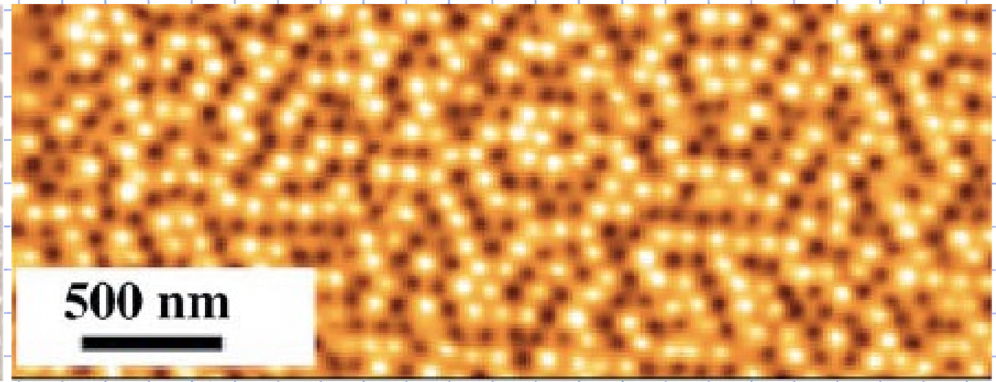


Single-domain in-plane magnetized dots appear as dipoles

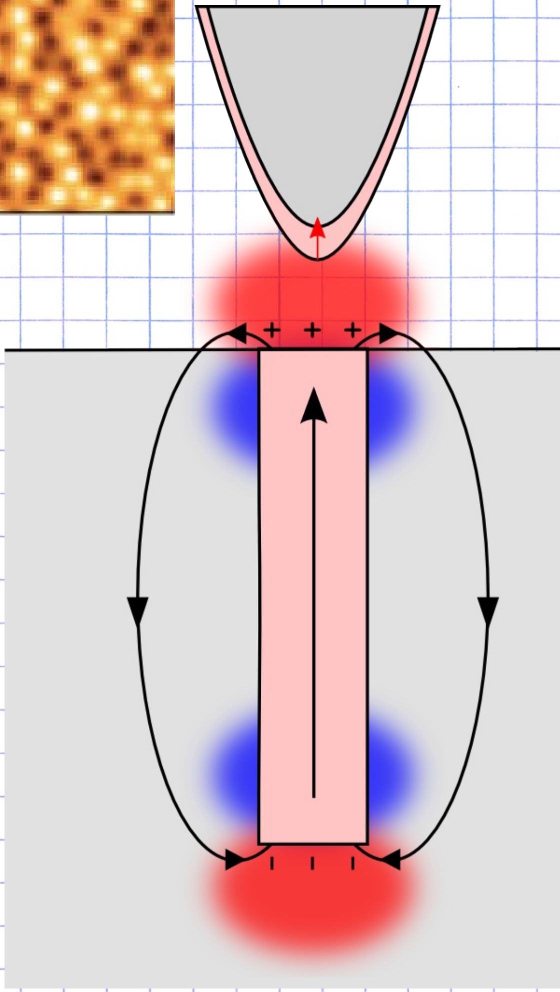
Structure (SEM)

MFM, partly reversed

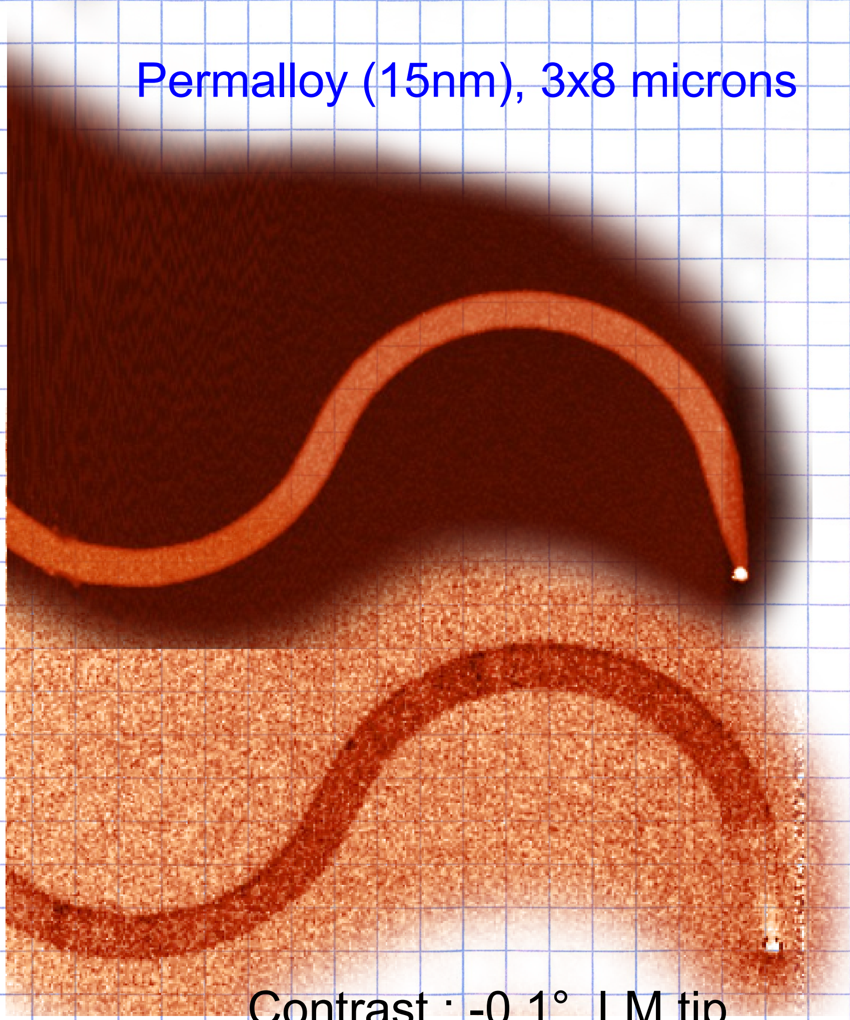




T. Wang et al., APL 92, 192504 (2008)

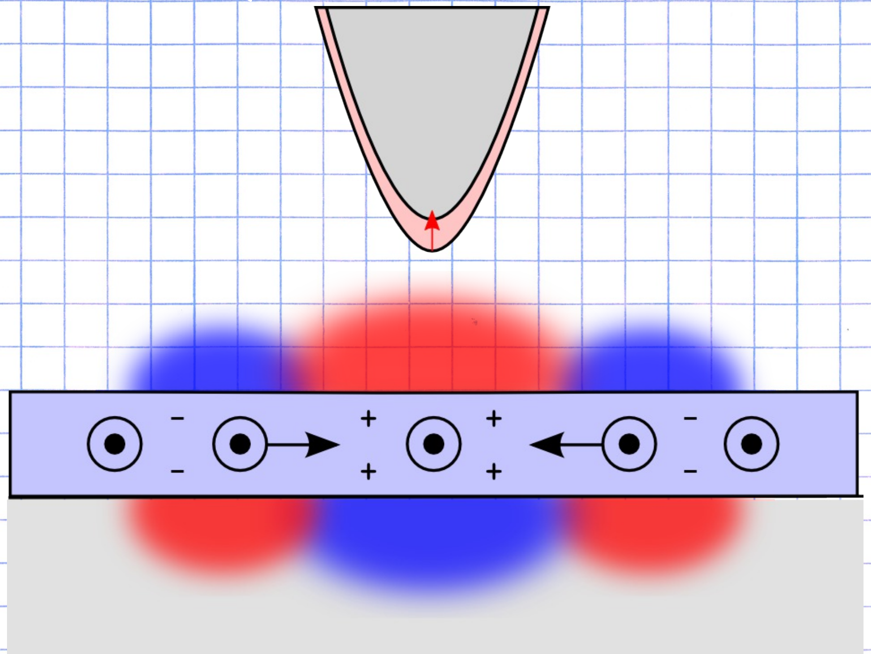


↳ Single-domain out-of-plane magnetized dots appear as monopoles



Lithography : S. Pizzini (Institut Néel)

Imaging : Z. Ishaque (Institut Néel)



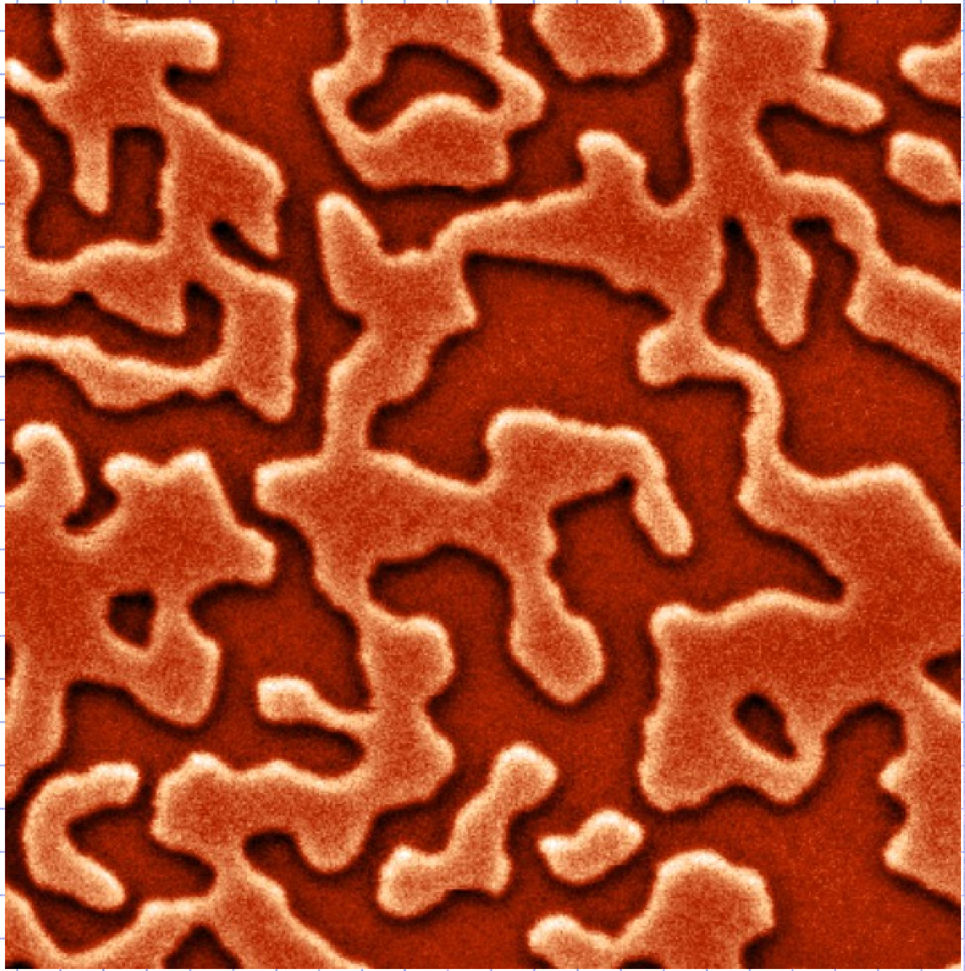
Principle :

1. Stray field magnetizes sample
2. Sample is non -uniform → stray field
3. Tip measures sample's stray field

- It is a DOMAIN contrast
- Interaction is ALWAYS attractive : red shift
- Contrast is proportionnal to the square of the tip moment

FePt (4nm)

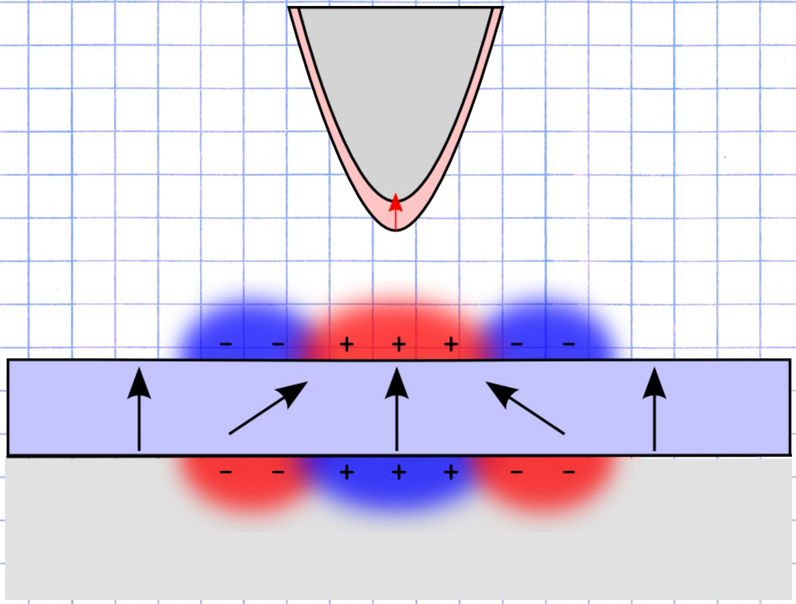
5x5 μm



Sample : A. Marty (CEA-Grenoble)

Imaging : M. Darques (Institut Néel)

Contrast : ±0.4°, LM tip

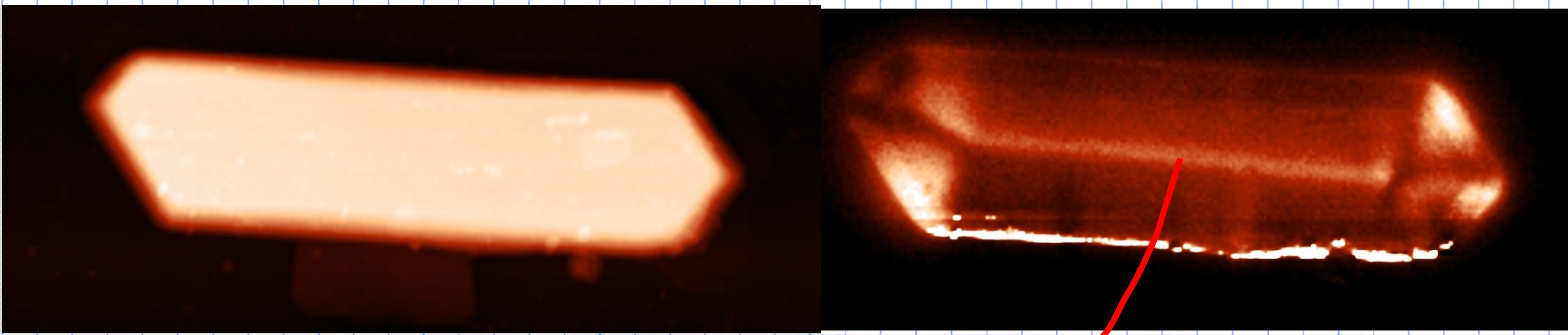


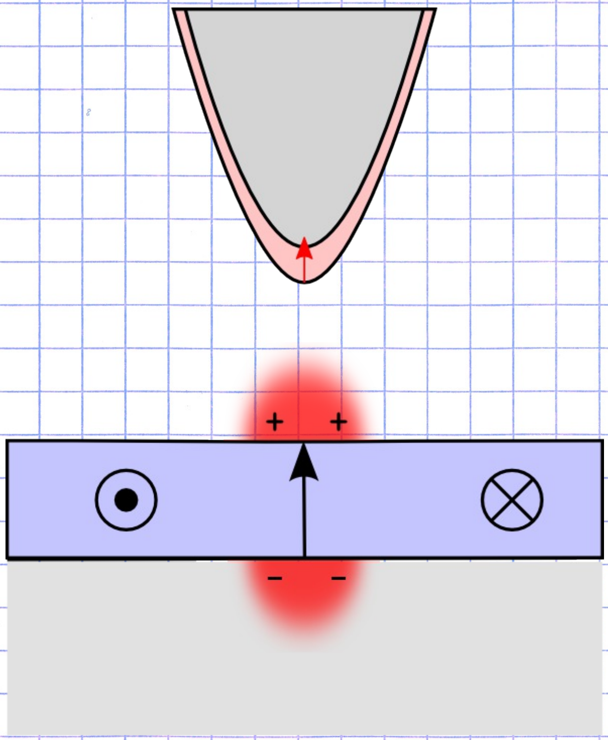
- It is a DOMAIN contrast
- The direction of magnetization is deduced

Quantitative analysis :

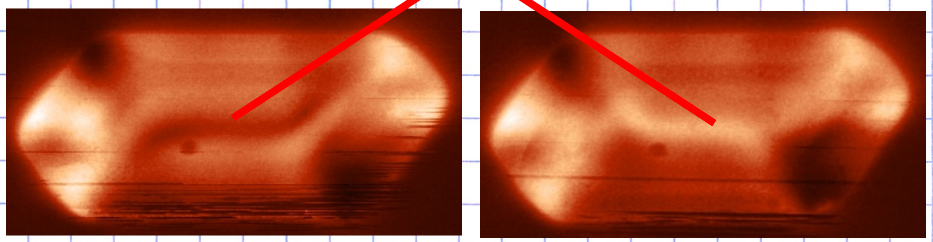
L. Belliard et al., J. Appl. Phys. 81, 3849 (1997)

Fe dot (25nm), 2.5x1 microns

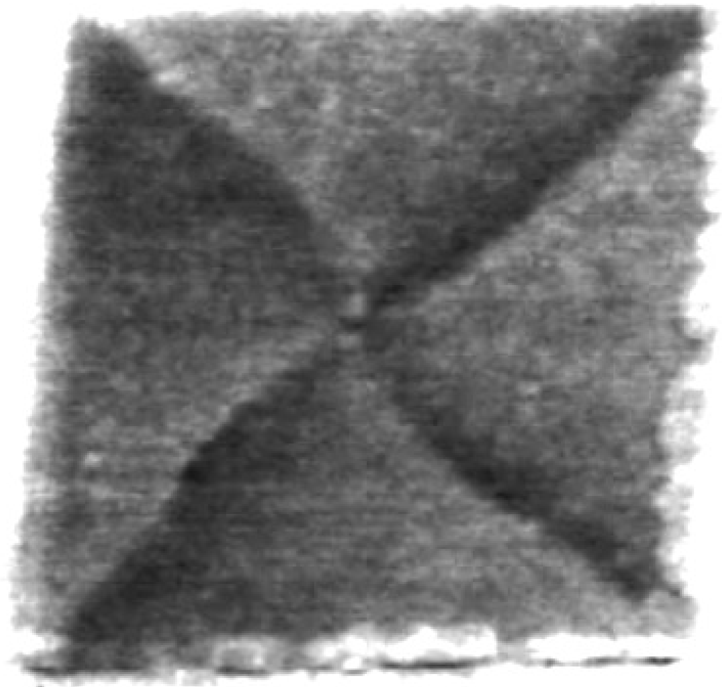




- Contrast is MONOPOLAR
- Informs about the polarity of the wall core

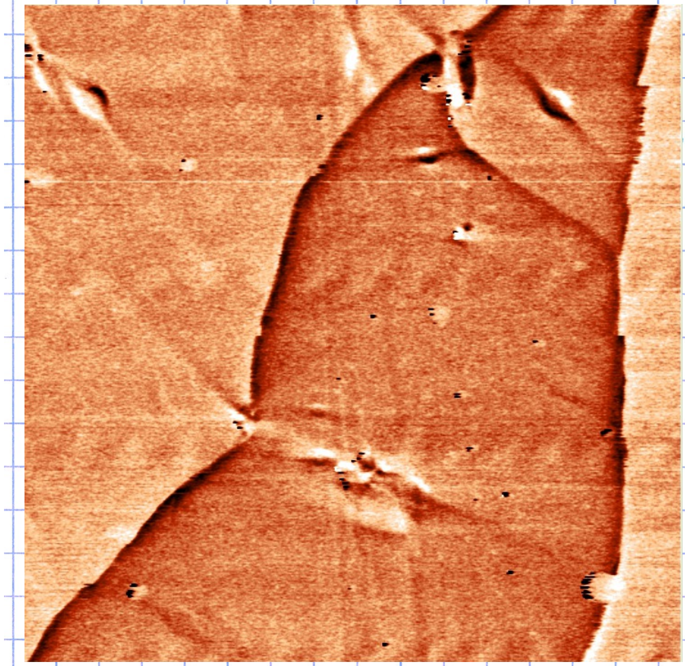


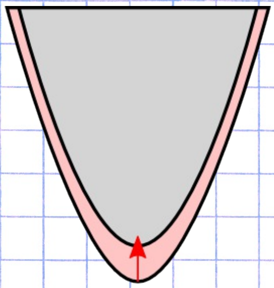
Permalloy dot (16nm)
2x2 microns

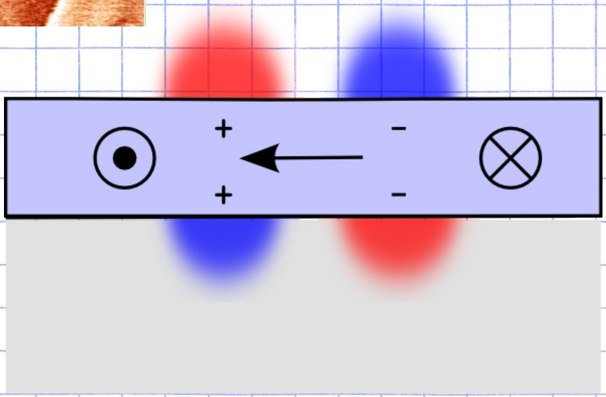


J. M. Garcia et al., APL 79, 656 (2001)

Permalloy film (20nm)
10x10 microns



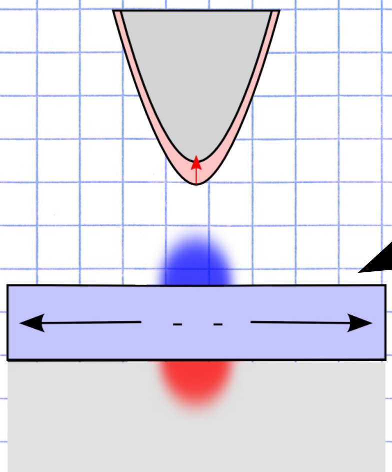


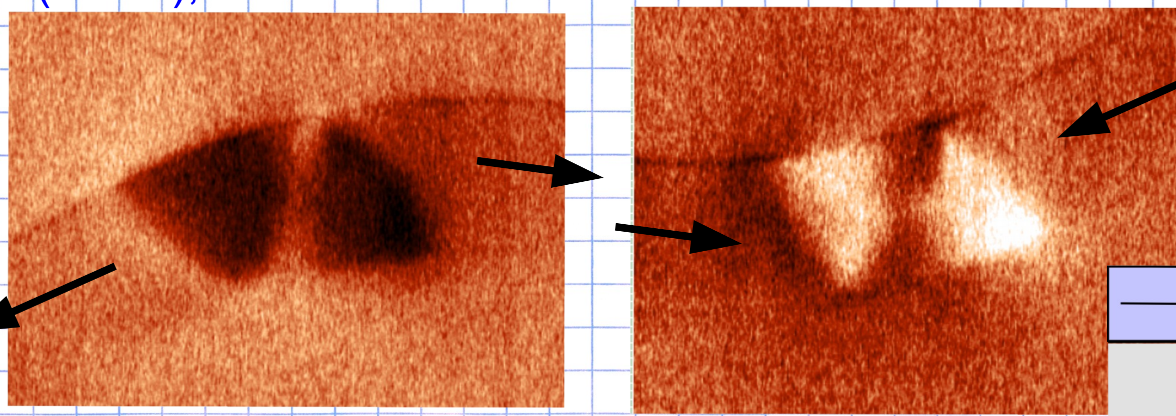


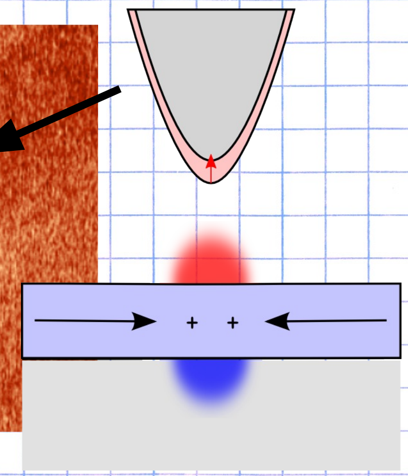
- Néel wall give rise to DIPOLAR contrast
- Informs about the chirality of the wall core

4. PRACTICE / Head-to-head domain walls

Permalloy strips (15nm), 250nm wide

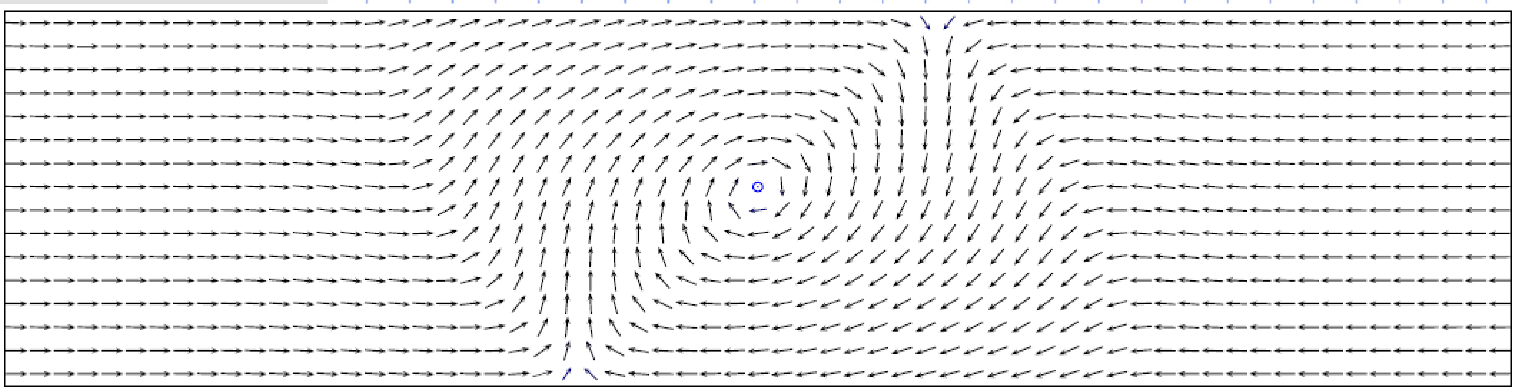






Contrast : ±0.3°, tip 5nm CoCr

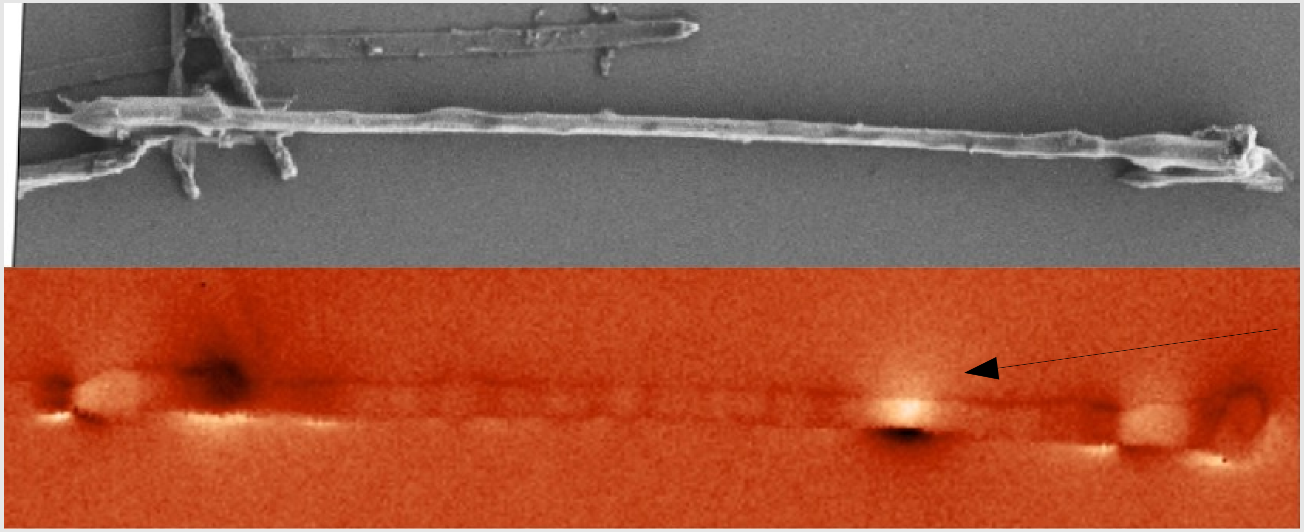
Known as vortex domain-wall

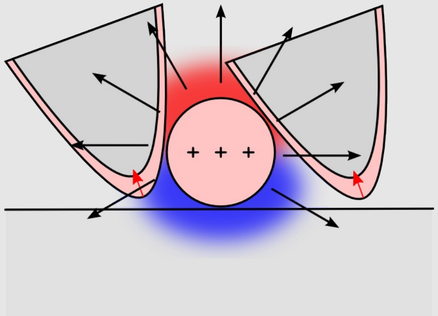


R. McMichael and M. Donahue, IEEE Trans. Magn. 33, 4167 (1997)

- Walls in in-plane magnetized stripes → MONOPOLAR
- Contrast informs about head-to-head ot tail-to-tail

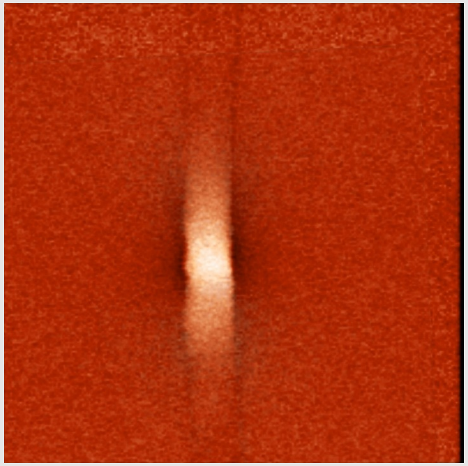
Tilted cantilever, across wire

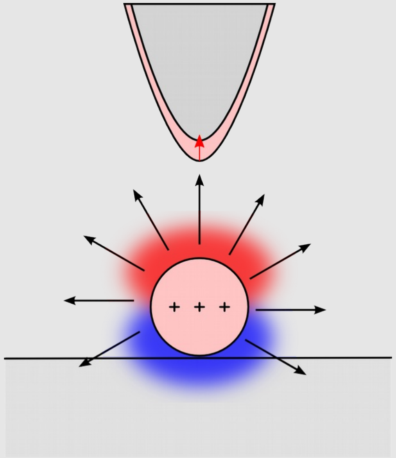




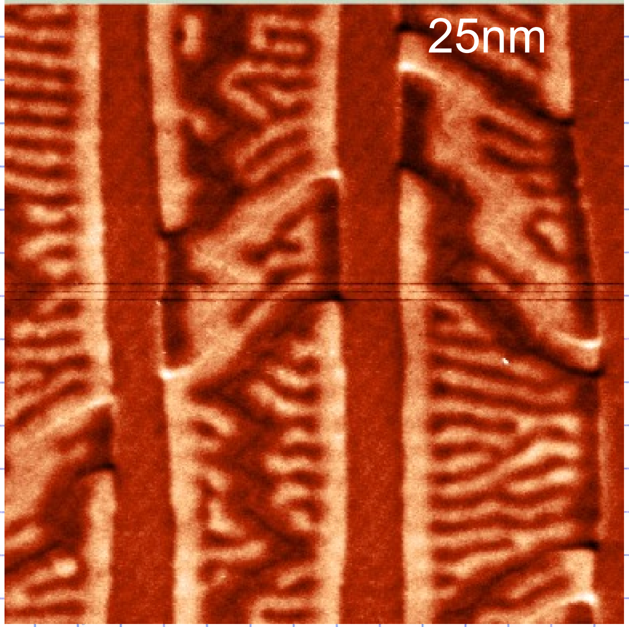
Tilted cantilever, along wire

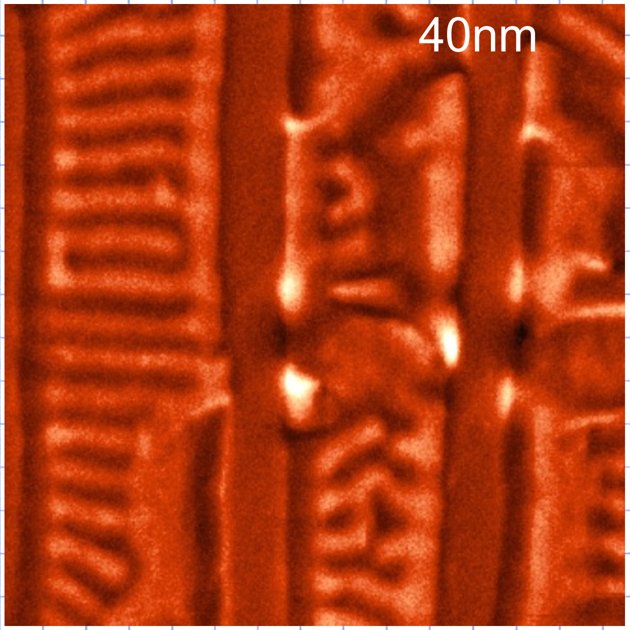
@NEEL : S. Da Col et al. (in preparation)

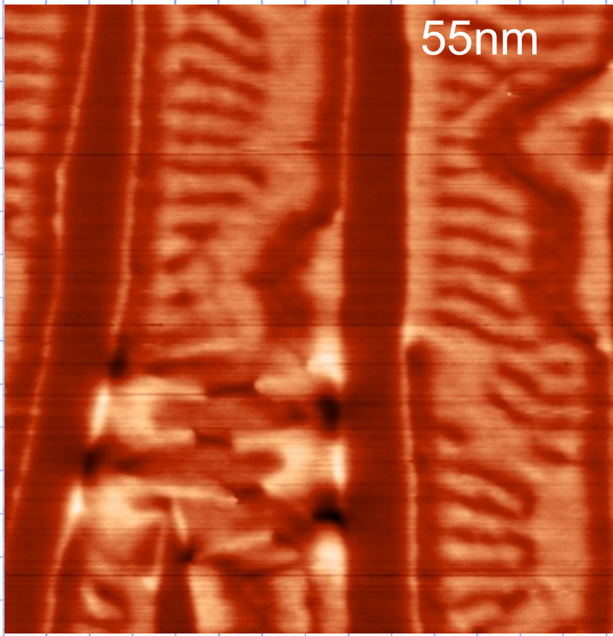


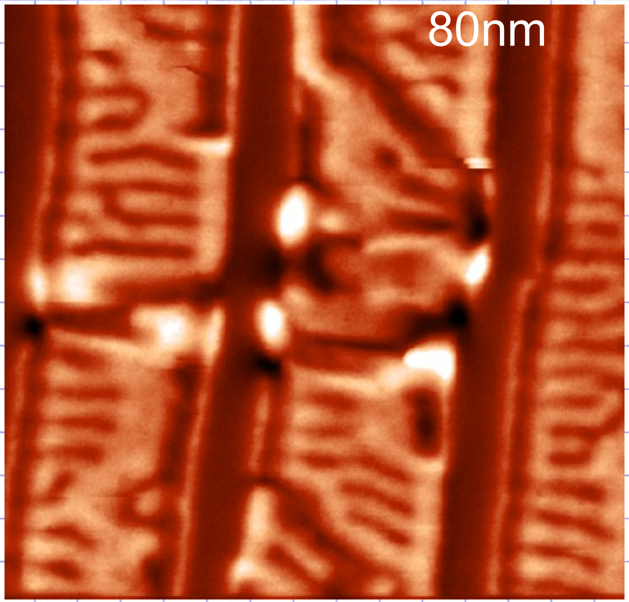


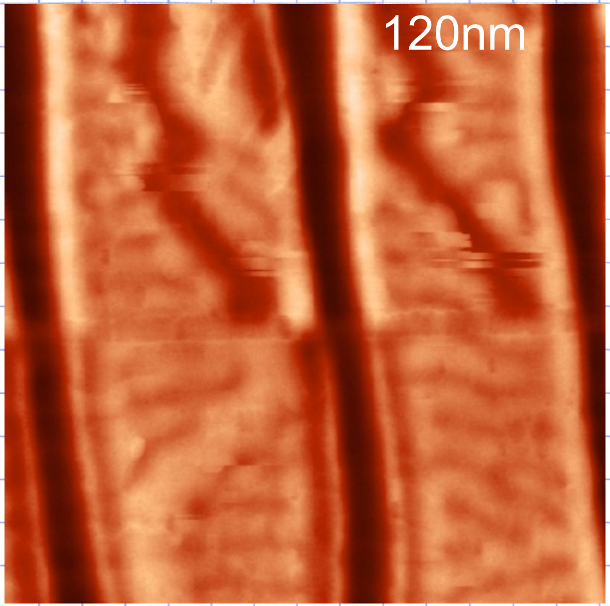
5. SOME DEVELOPMENTS / Calibration of tips and cantilevers (here : commercial)







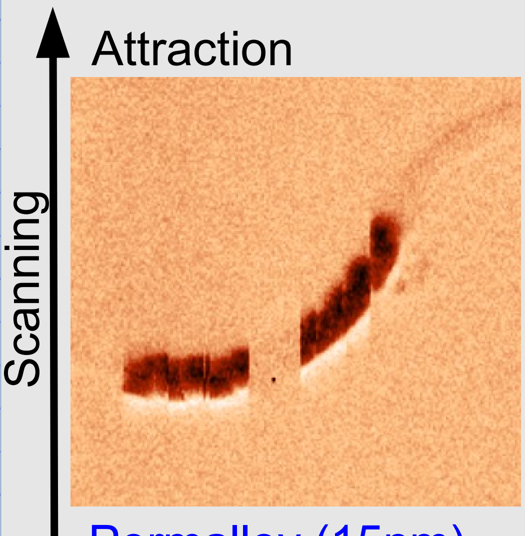




- Compare tips !
- Use identical sample and imaging parameters

Sample : MnAs(001)
R. Belkhou (Soleil)

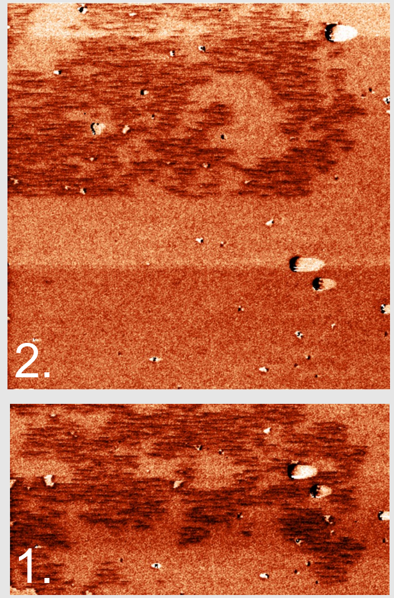
High



Permalloy (15nm)
500nm strips

Sample : S. Pizzini

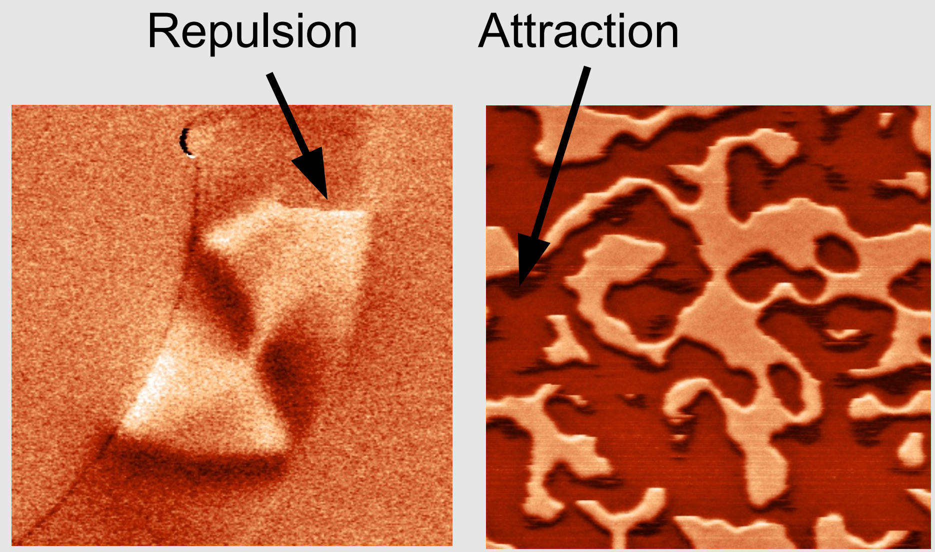
Imaging : Z. Ishaque



Co (0.6nm)/
graphene (20 mic)

C. Dieudonné

Moderate



Permalloy (15nm)
500nm wide

Sample : S. Pizzini

Imaging : Z. Ishaque

FePt (4nm)
Image 5 microns

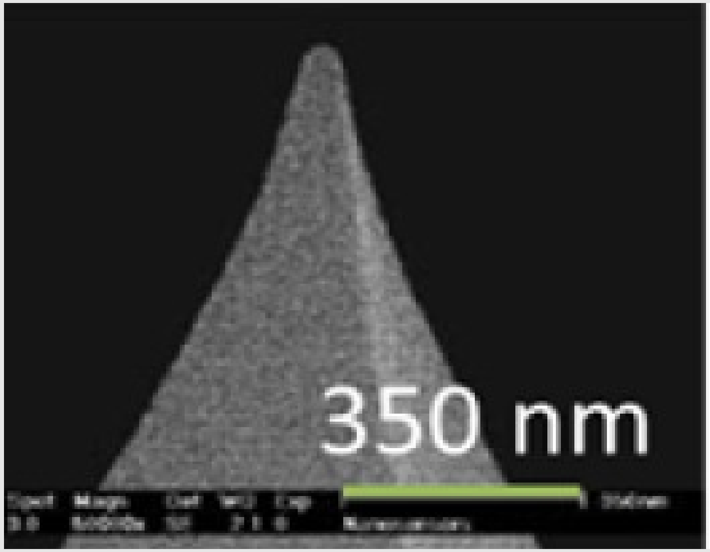
Sample : A. Marty

Imaging : M. Darques

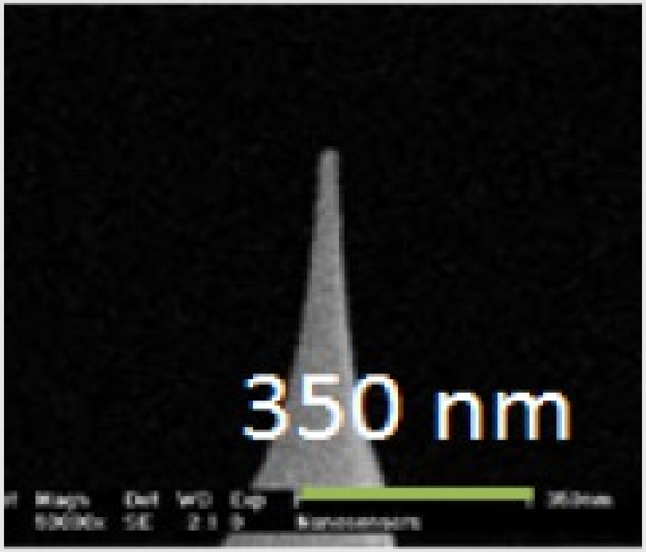
- Repeat measurement and/or change scanning direction
- Low-coercive samples require low-moment tips
- Commercial 'low-moment' may not be low enough

Improve resolution

From sharp to ultrasharp AFM tips



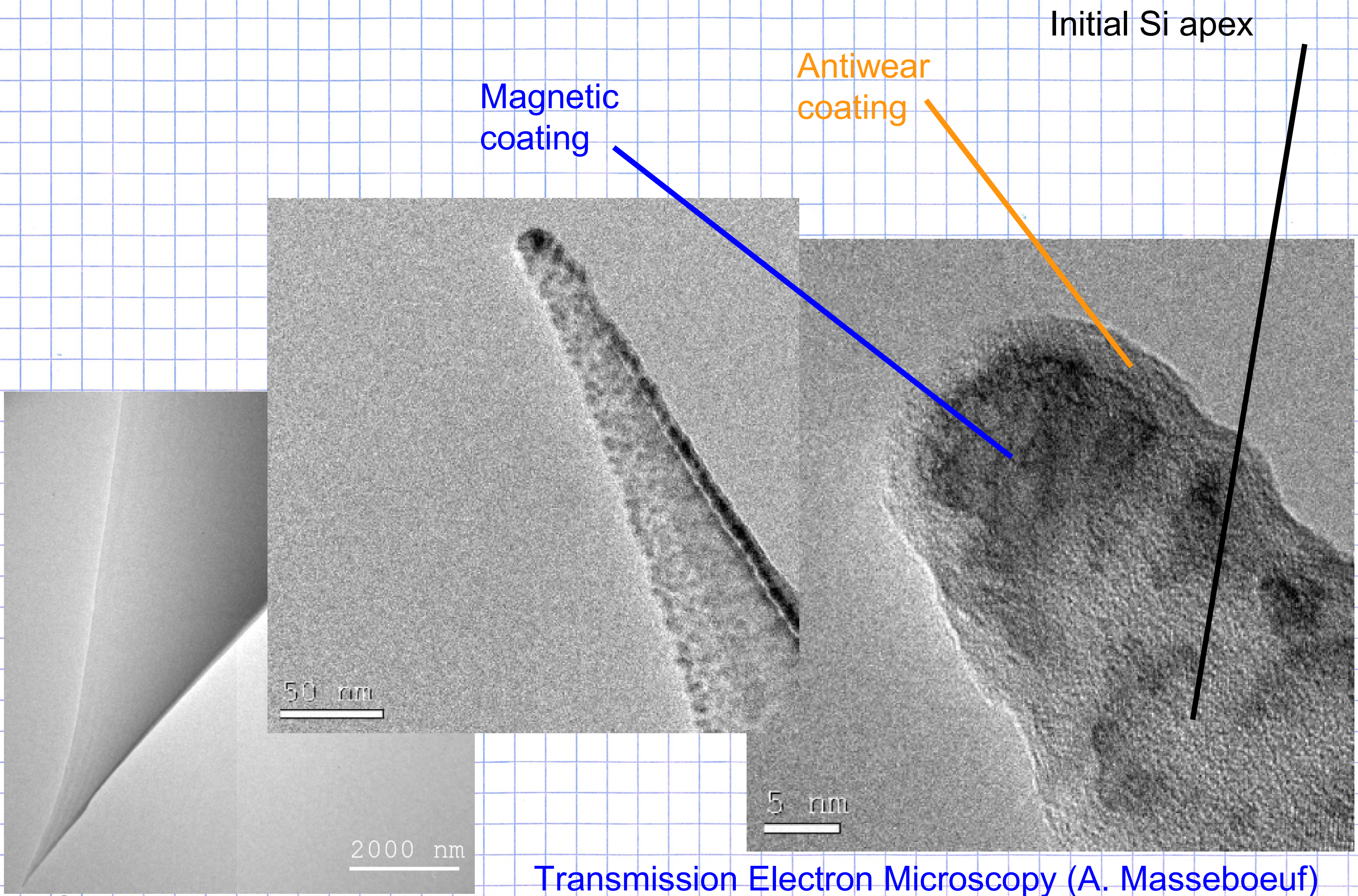
Asylum 240TS
Radius of curvature : 10 nm



Nanosensors PPP-SSS
Radius of curvature : 2-5 nm

Engineer magnetic coating

- Basis : $Co_{80}Cr_{20}$ (similar to hard disk media)
- Means : sputtering, DP850.
- Stacking : Based on CoCr [2-50 nm], various buffer and capping layers

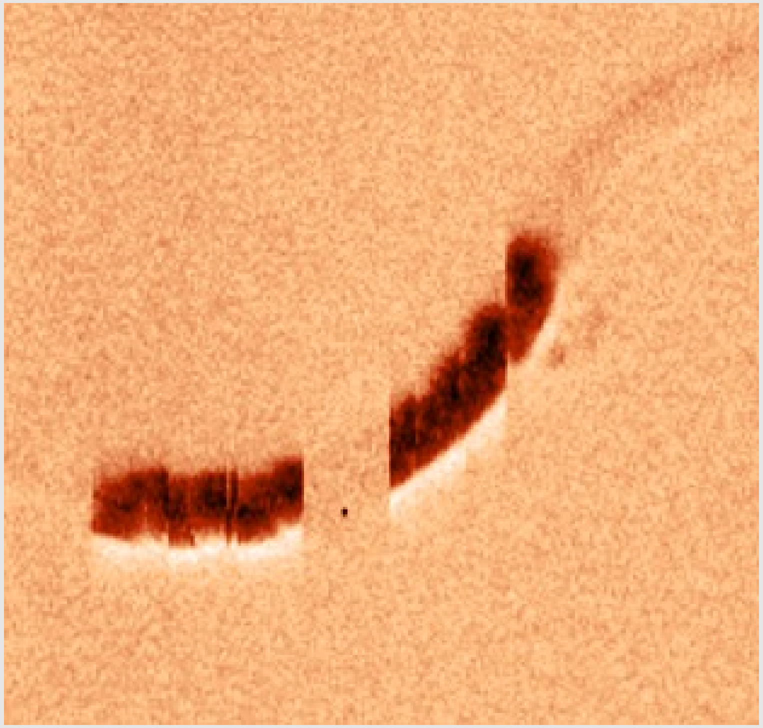


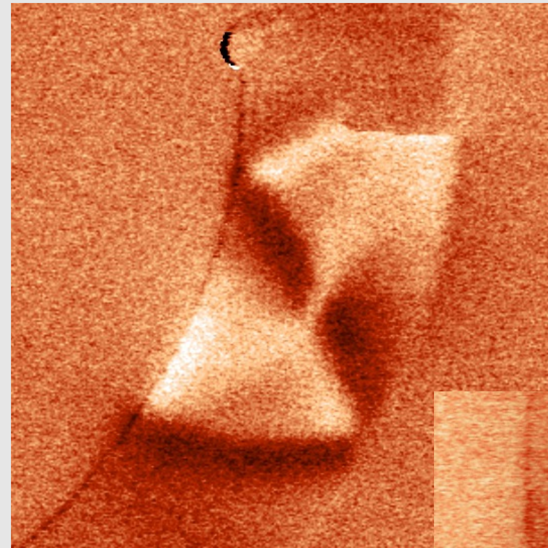
Transmission Electron Microscopy (A. Masseboeuf)

Commercial tips, 'low moment'

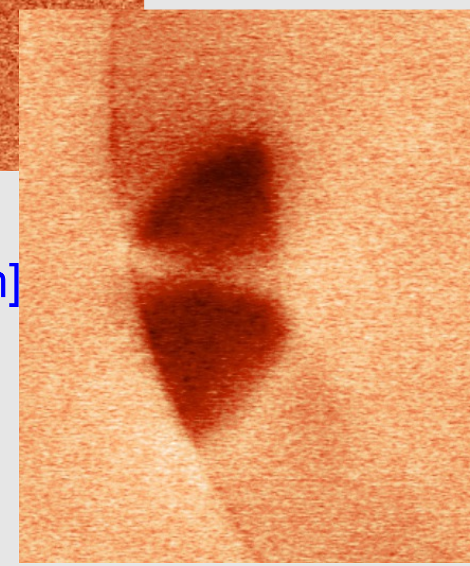
Permalloy strips [15nm]

Home-made tips, really low moment





Tip : CoCr[10nm]
500nm strips



Tip : CoCr[5nm]
300nm strips

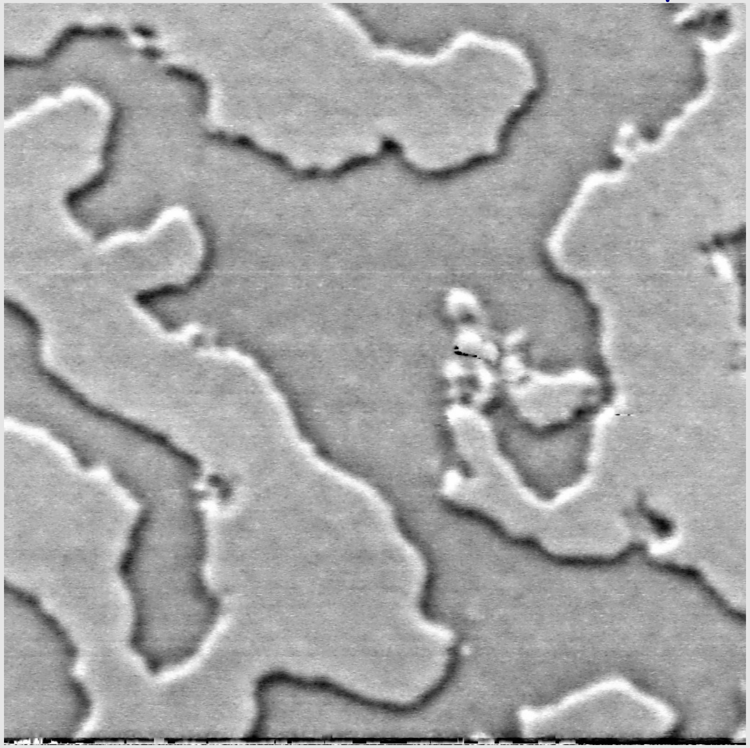
Sample : S. Pizzini
Imaging : Z. Ishaque

- Domain-wall motion under field or current
- Optimized tips for all topics

Spatial resolution 15nm

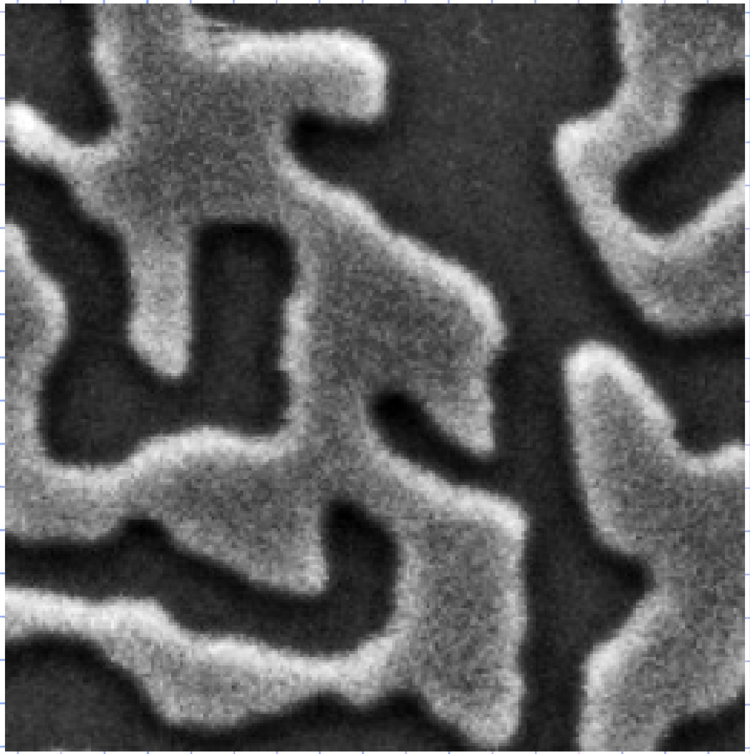
Test sample : FePt[4nm]. Perpendicular magnetization, narrow domain walls

2x2 μm



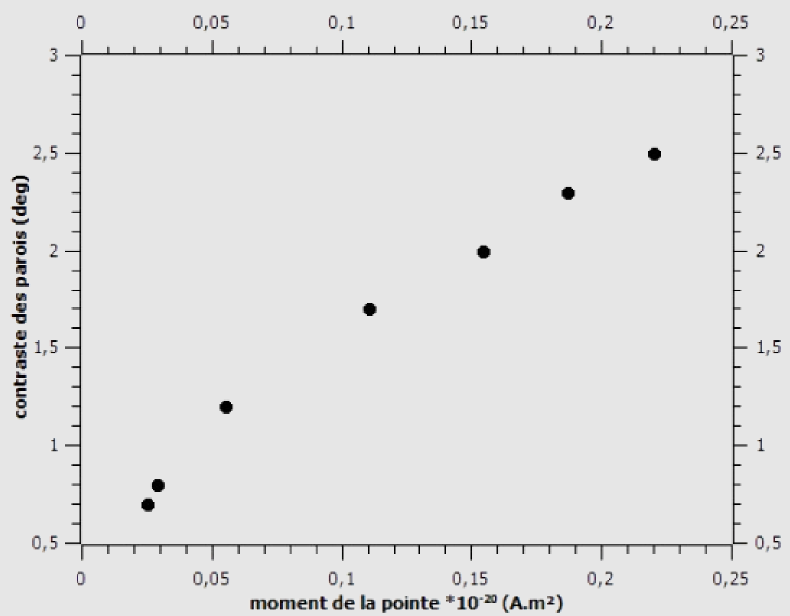
Tip : Nanosensors SSS \ 5nm CoCr
Fly height 0nm, amplitude 10nm

Commercial 'low moment' tip

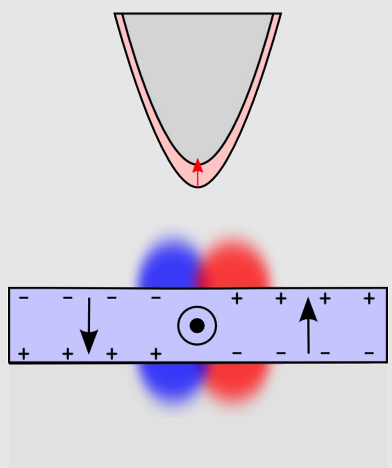


Spatial resolution : 20nm

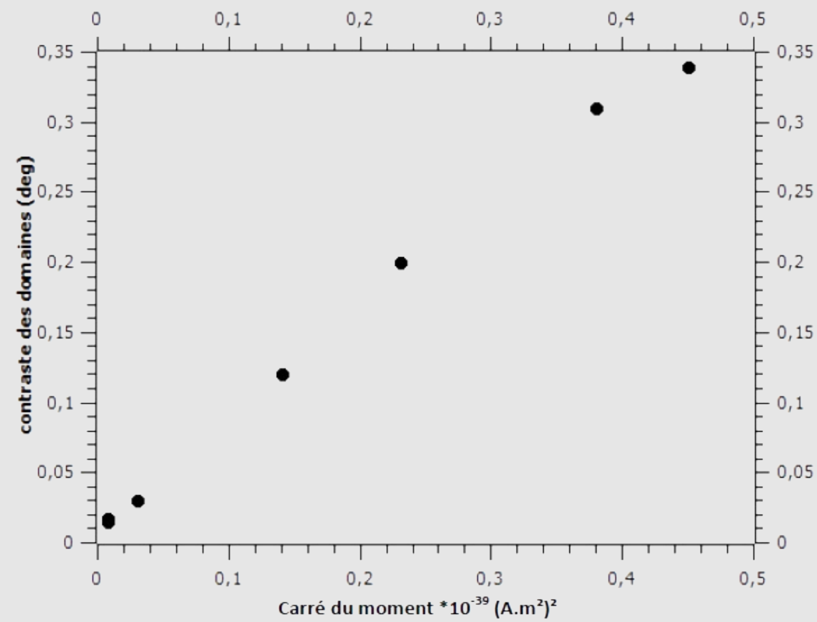
Domain wall contrast



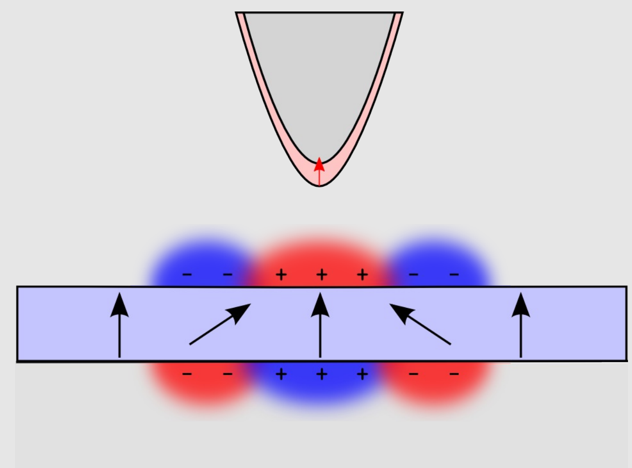
⇨ Linear with tip moment

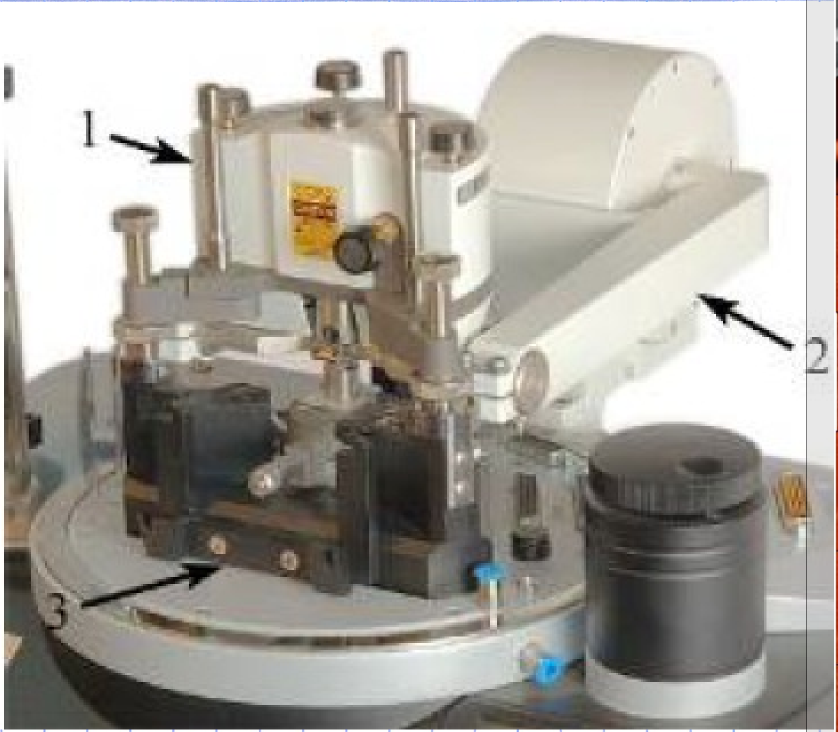


Domain contrast

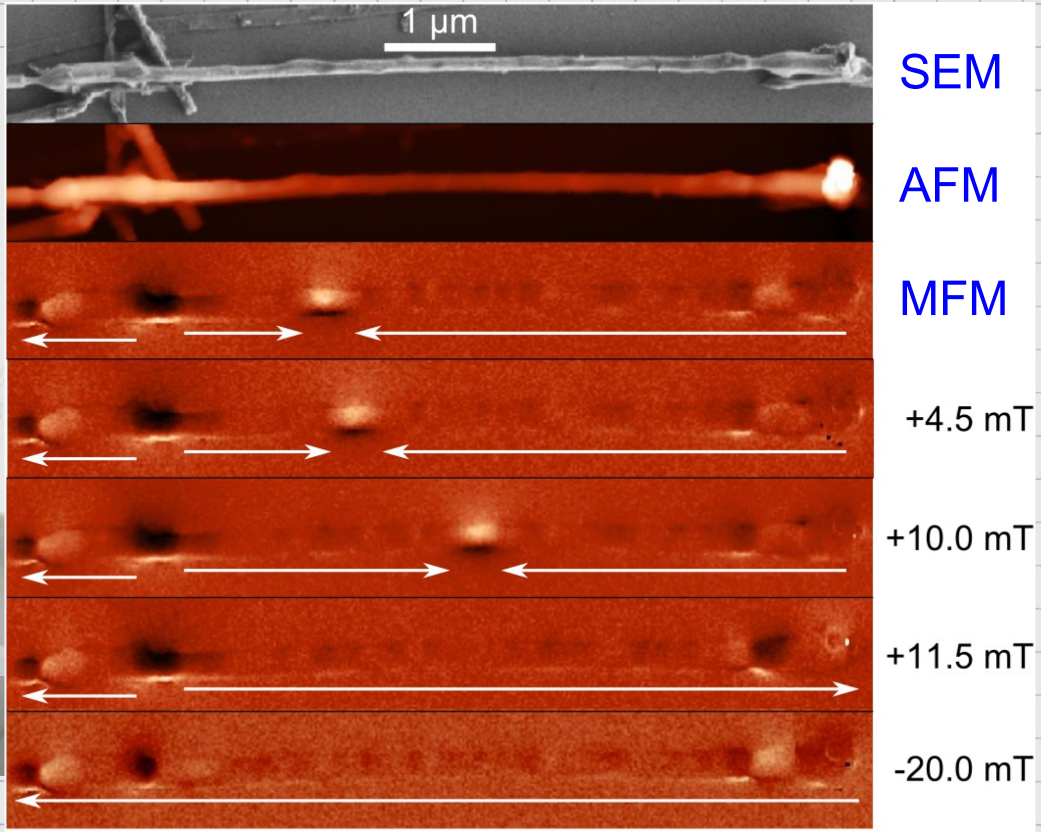


⇨ Linear with square of tip moment



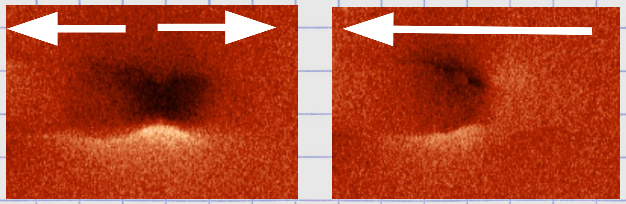


Domain wall motion



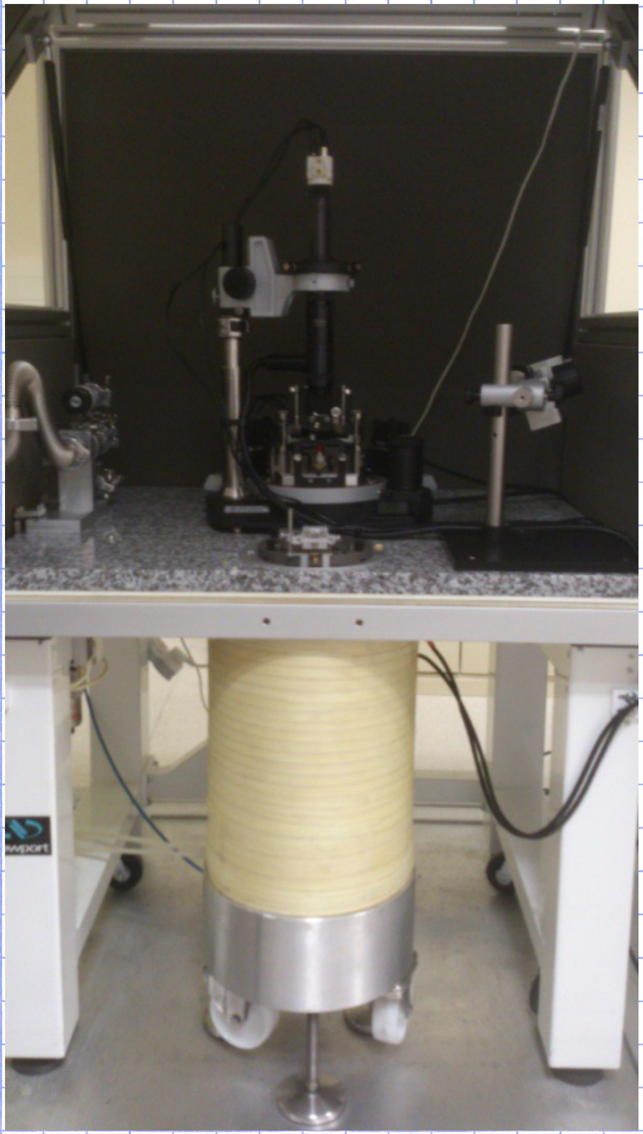
S. Da-Col et al., unpublished

Protrusions and constrictions

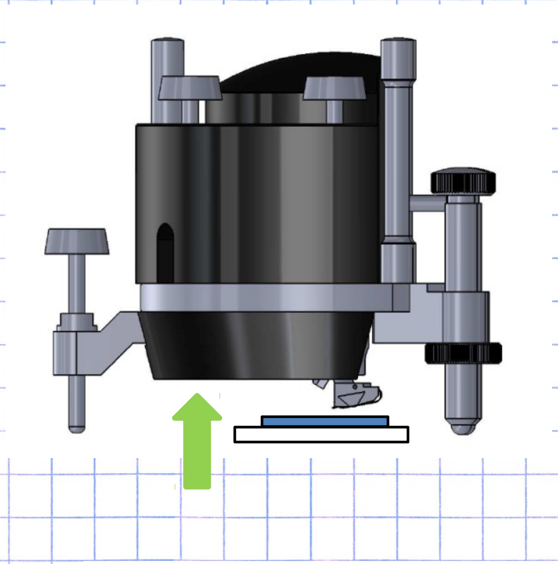


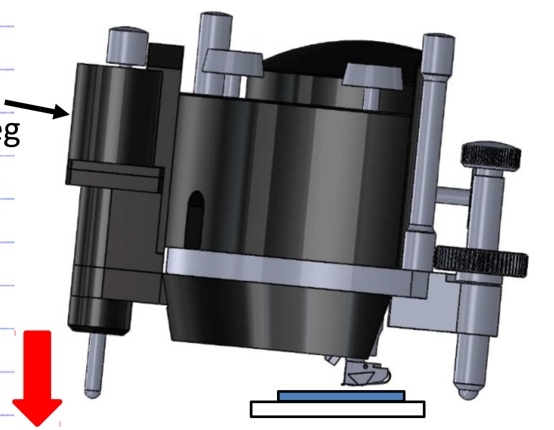
⇨ Pinning field ~30mT

- Imaging under field
- Magnetization processes

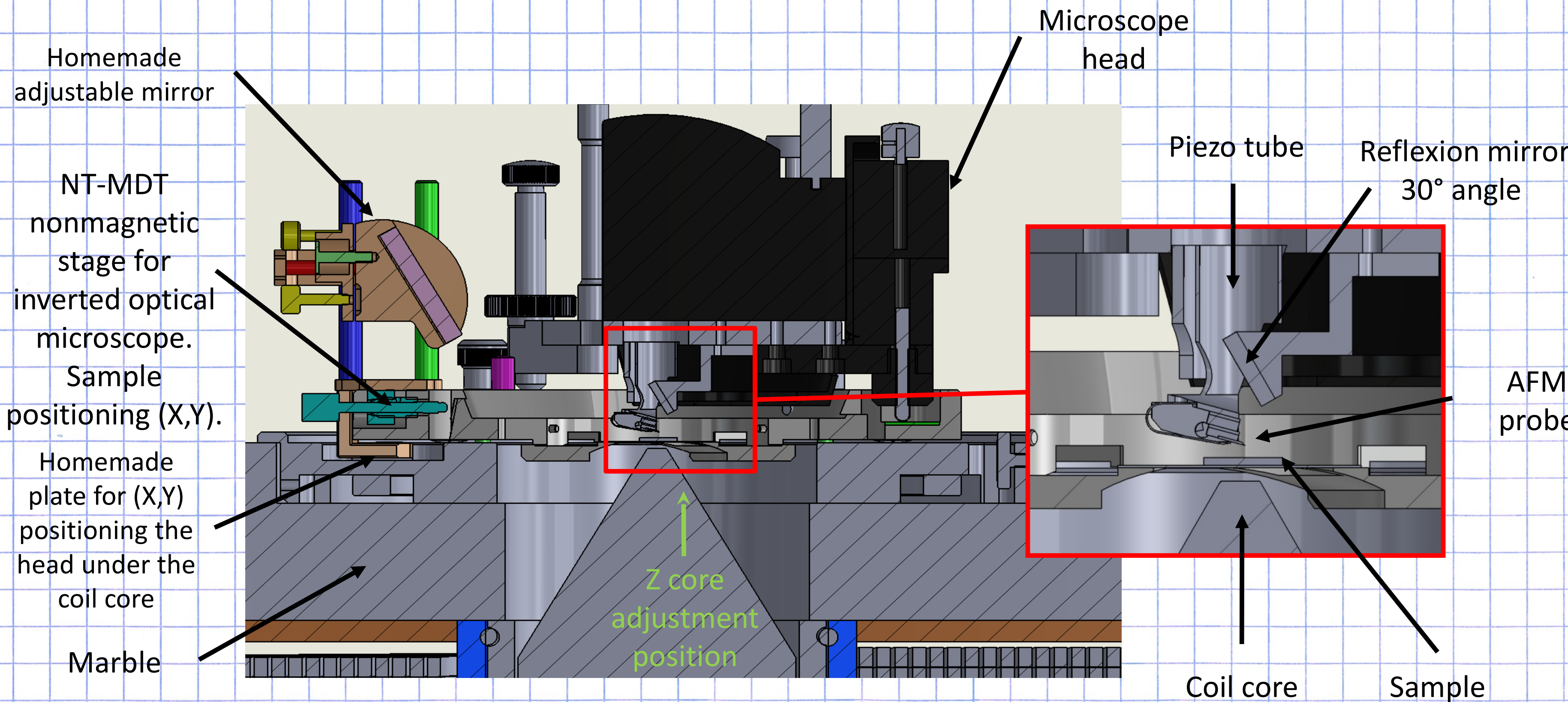


Field >1T (custom-made)
Optimized cooling





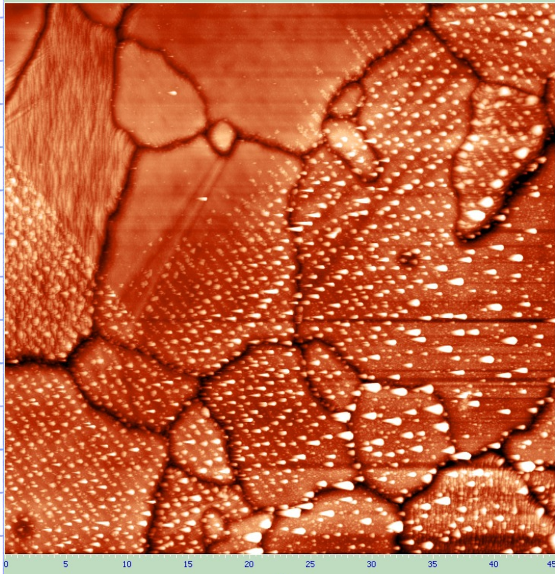
Approach by head (motorized leg)



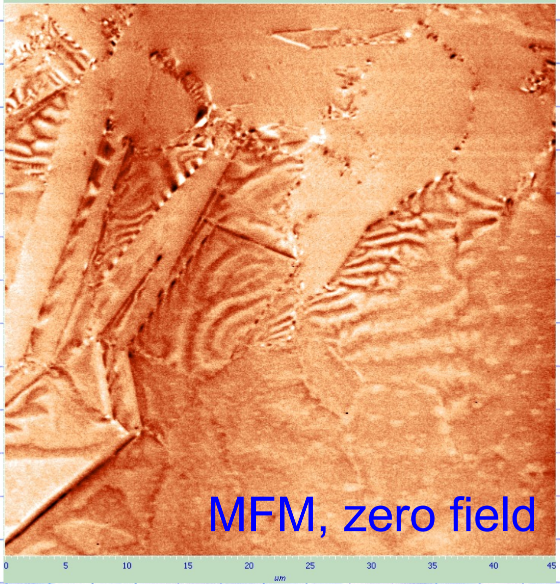
- Combines NT-MDT and custom-made designs
- High stability thanks to decoupling head and sample from the coil

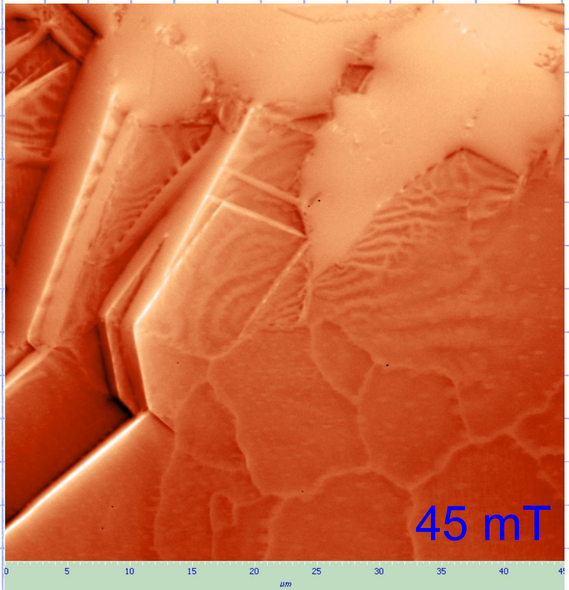
Magnetic shape-memory alloy

G. Crouigneau et al.

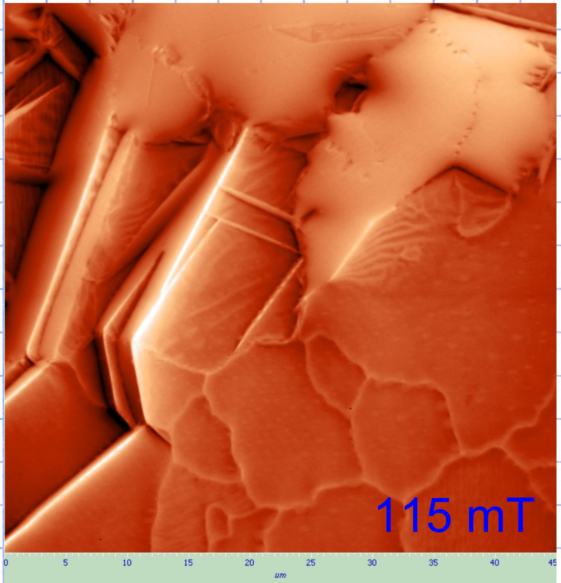


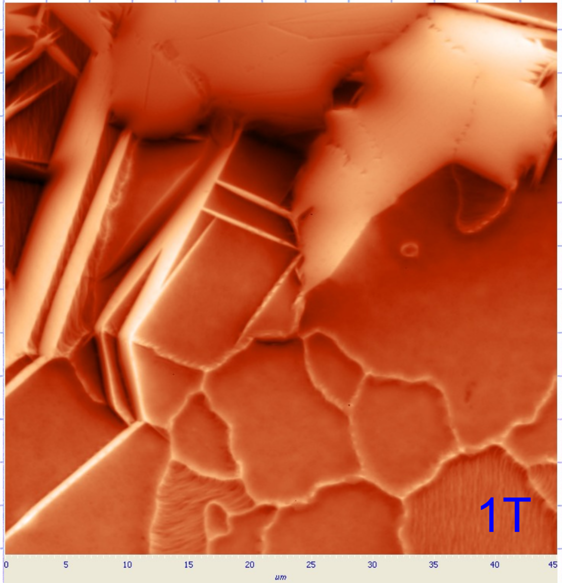
Topography (grains)





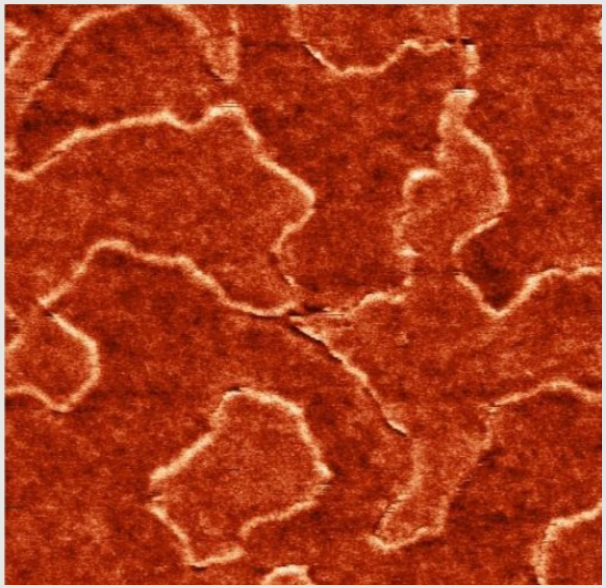
- Perturbation-free measurements (non-magnetic head)
- High stability (sample and coil decoupled)





Keep developing tips

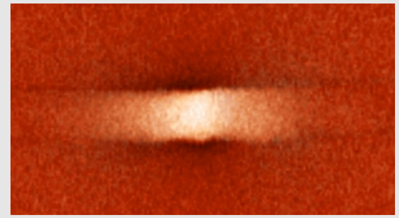
- Superparamagnetic tips (reduced effect on samples : ultrasoft, skyrmions etc)

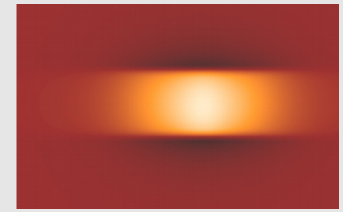


- Hard magnetic tips (imaging permanent magnets)

Towards quantitative analysis

- Simulations



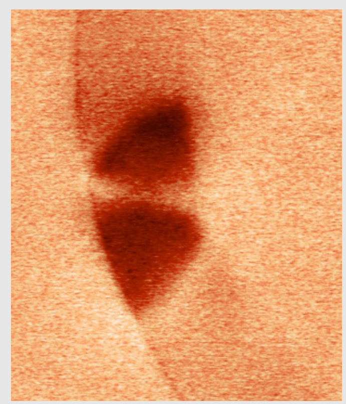


S. Jamet, JC Toussaint

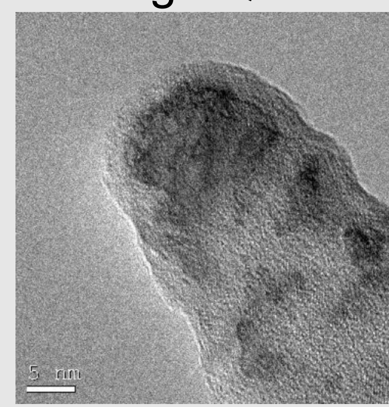
- Special tips (eg filled carbon nanotube)

Pushing further sensitivity

- Work under vacuum → High Q



<10nm film



<5nm tip

Measurements

Fadhel Abedi, Ioan Chioar, Geta Ciuta, Guillaume Crouigneau, Sandrine Da Col, Michael Darques, Christophe Dieudonné, Alexander Grimm, Zahid Ishaque, Keita Ito, Simon Le Denmat, Svenja Perl, Jérémy Tillier

Tip development

S. Le Denmat, Ph. David, A. Masseboeuf (CEMES Toulouse)

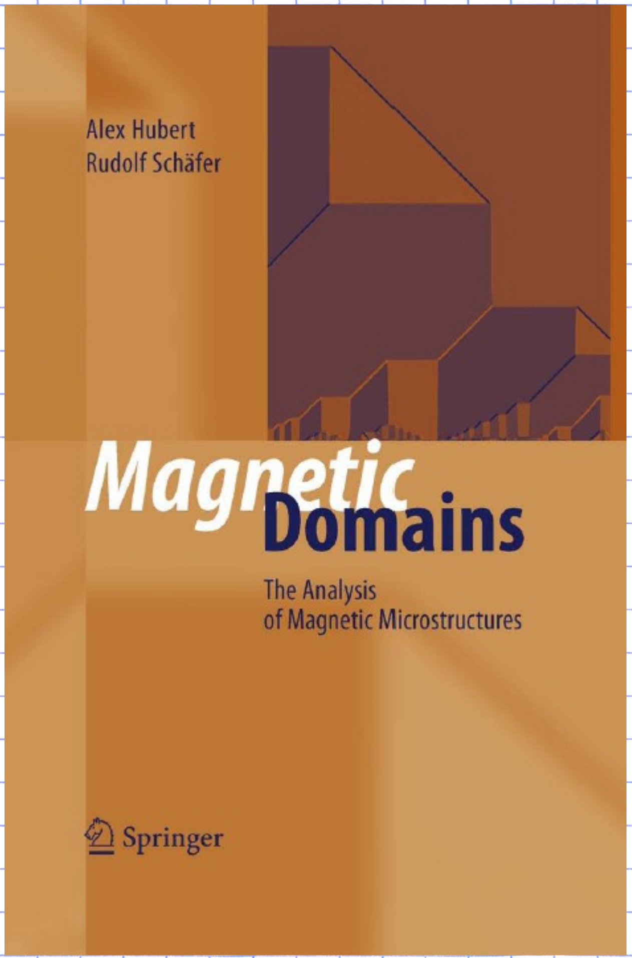
Simulations

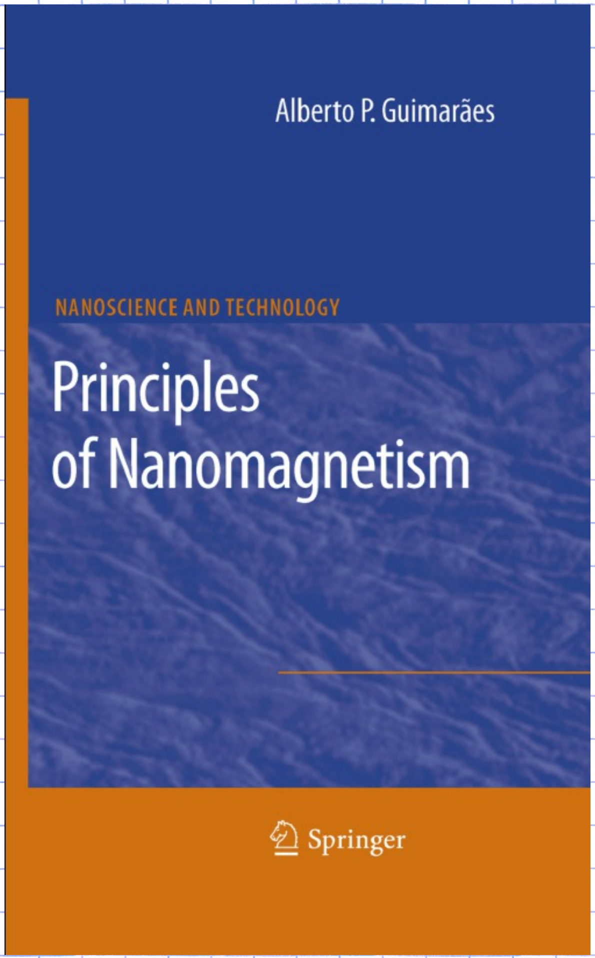
S. Jamet, JC Toussaint

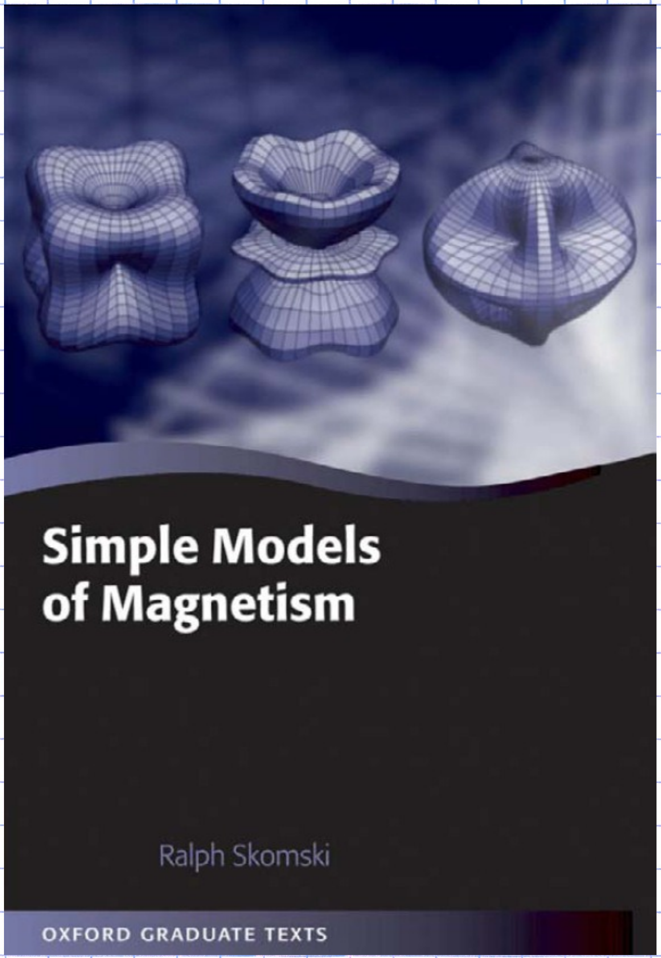
Instrumental development and maintenance

S. Le Denmat, E. Wagner

- Magnetic Force Microscopy of hard magnetic films, G. Ciuta, F. Dumas-Bouchiat, N. M. Dempsey, O. Fruchart, **submitted**
- Third type of magnetic domain wall in permalloy nanostrips, D. N'Guyen, O. Fruchart, S. Pizzini, J. Vogel, J. C. Toussaint and N. Rougemaille, **submitted**
- Manipulating domain wall chirality by current pulses in Permalloy/Ir nanostrips, M. Z. Ishaque, V. D. Nguyen, O. Fruchart, S. Pizzini, N. Rougemaille, S. Perl, J. C. Toussaint, J. Vogel, **submitted**
- Non-universality of artificial frustrated spin systems, I. A. Chioar, N. Rougemaille, A. Grimm, O. Fruchart, E. Wagner, M. Hehn, D. Lacour, F. Montaigne, B. Canals, **Phys. Rev. B** 90, 064411 (2014) (http://fr.arxiv.org/abs/1407.7416)
- Growth and micromagnetism of self-assembled epitaxial fcc(111) cobalt dots, O. Fruchart, A. Masseboeuf, J. C. Toussaint, P. Bayle-Guillemaud, **J. Phys. Condens. Matter** 25, 496002 (2013). (http://fr.arxiv.org/abs/1309.0793)
- Tunning micro-twinned domain sizes and the b-variants content of the adaptative 14-modulated martensite in epitaxial Ni-Mn-Ga films by co-sputtering, J. Tillier, D. Bourgault, Ph. Odier, L. Ortega, S. Pairis, O. Fruchart, N. Caillault, L. Carbone, **Acta Mater.** 59 (1), 75 (2011) (http://fr.arxiv.org/abs/1011.2303)


Alex Hubert
Rudolf Schäfer
Magnetic
Domains
The Analysis
of Magnetic Microstructures
Springer


Alberto P. Guimarães
NANOSCIENCE AND TECHNOLOGY
Principles
of Nanomagnetism
Springer


Simple Models
of Magnetism
Ralph Skomski
OXFORD GRADUATE TEXTS