spintec

SPIN IN ELECTRONICS

An overview on …

www.spintec.fr

email olivier.fruchart@cea.fr

Slides http://fruchart.eu/slides

Measurements using magnetic force microscopy

Olivier FRUCHART

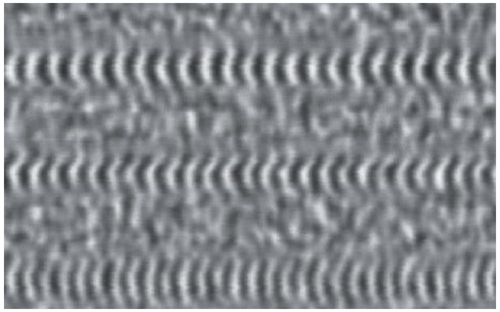
Univ. Grenoble Alpes / CNRS / CEA-INAC, France

Univ. Grenoble Alpes / CNRS, France

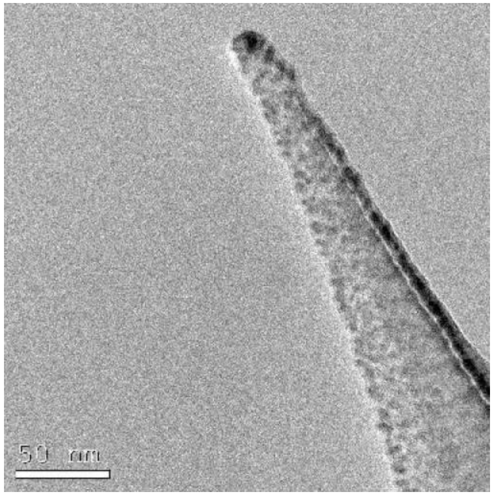
LOCATIONS IN GRENOBLE

TABLE OF CONTENTS

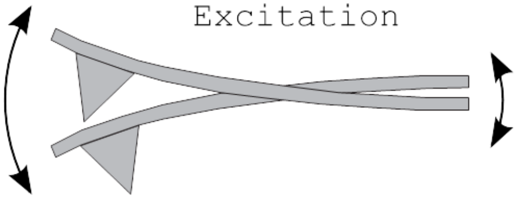
- Motivation and criteria



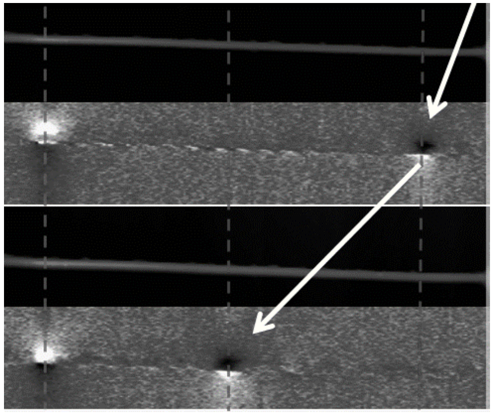
- Choice of tips



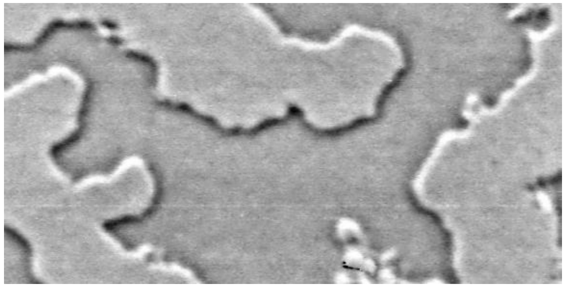
- Working principle



- Operando imaging



- Image analysis



- Panorama of other microscopies

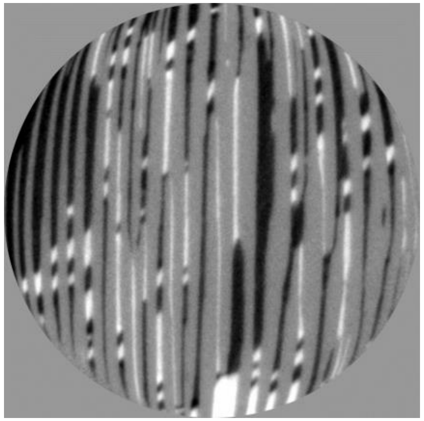
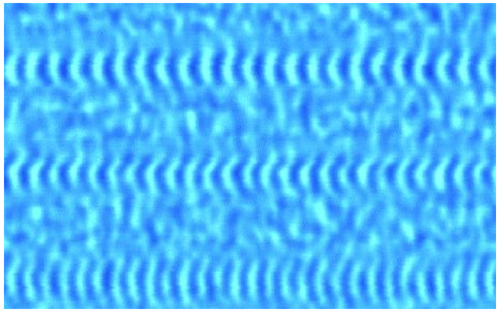
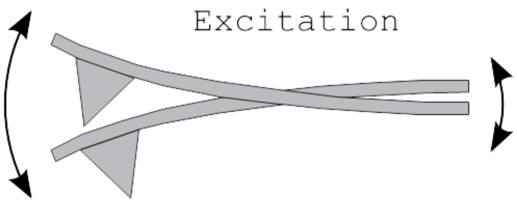


TABLE OF CONTENTS

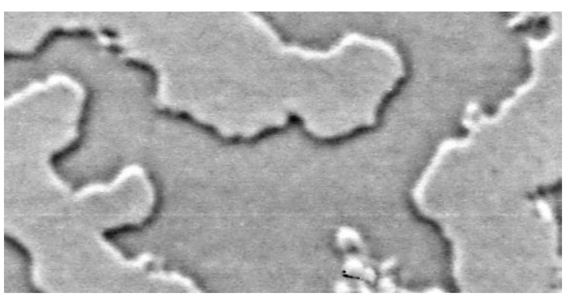
- Motivation and criteria



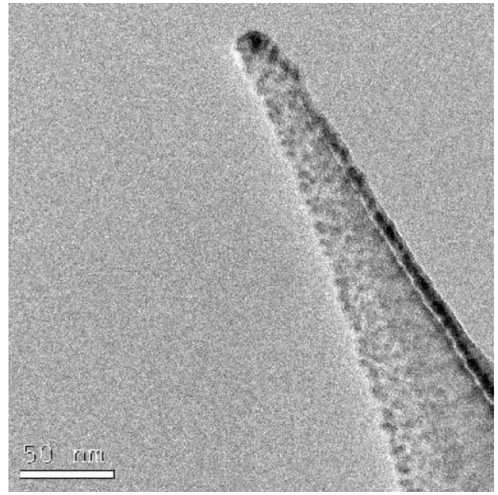
- Working principle



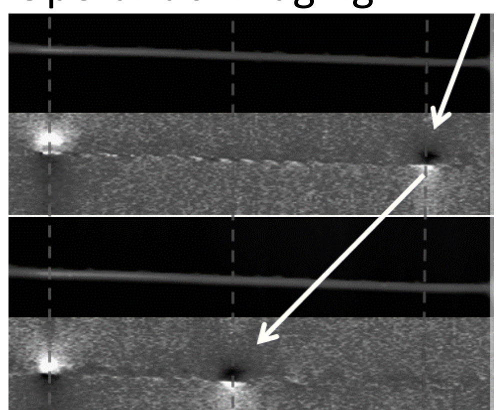
- Image analysis



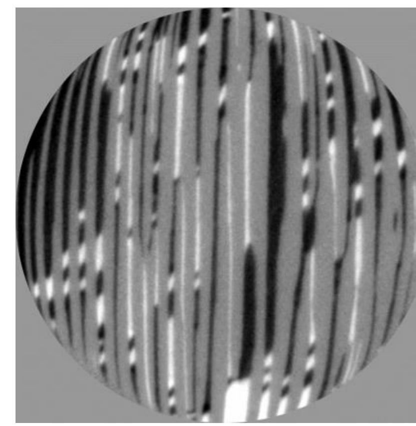
- Choice of tips



- Operando imaging

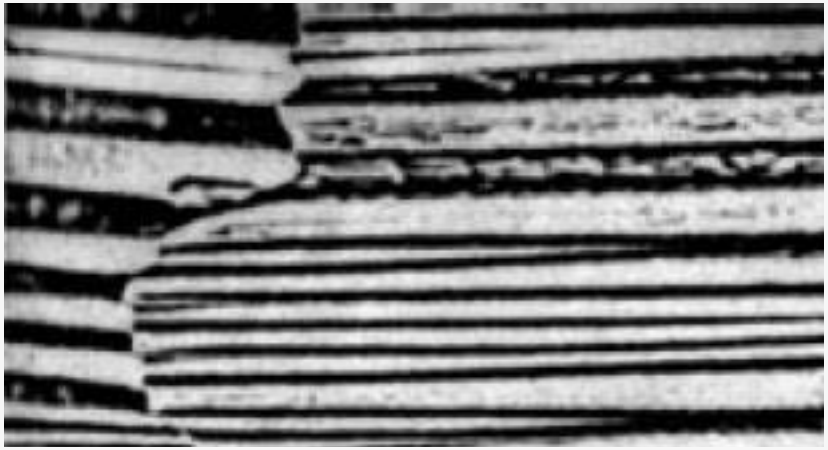


- Panorama of other microscopies



Magnetic domains

Numerous and complex magnetic domains



(History : Weiss domains)

Anisotropy exchange length

(domain wall width)

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

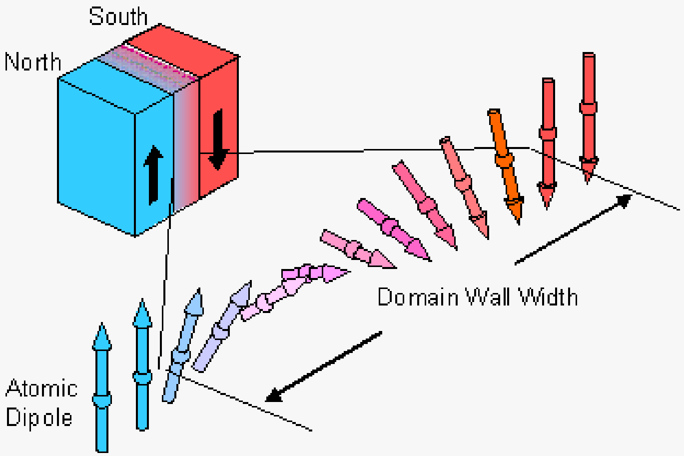
Exchange → $\mathrm{J/m}$

Anisotropy → $\mathrm{J/m^3}$

Anisotropy exchange length: $\Delta_\mathrm{u} = \sqrt{A/K}$

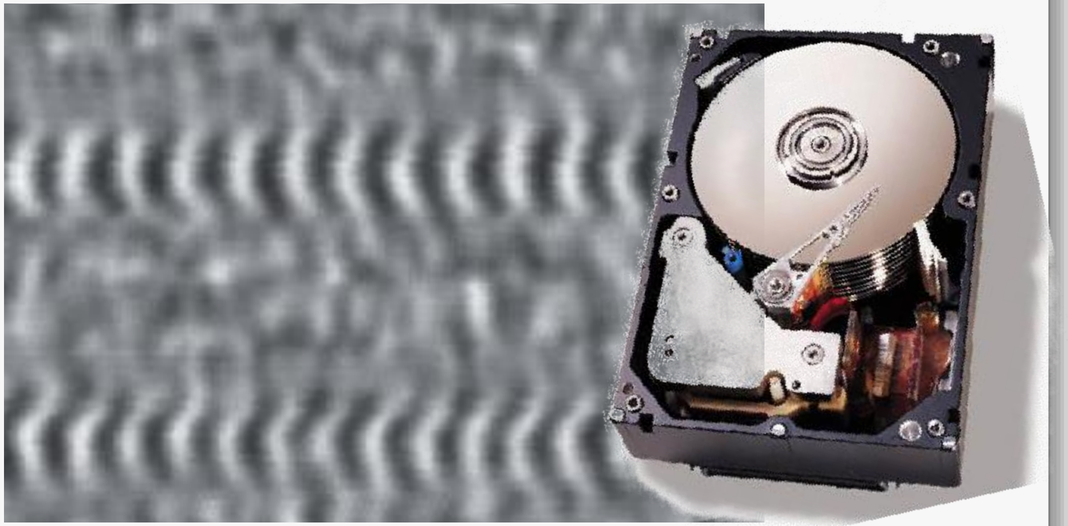
$\Delta_\mathrm{u} \approx 1\,nm \rightarrow \Delta_\mathrm{u} \geq 100\,nm$

Hard Soft



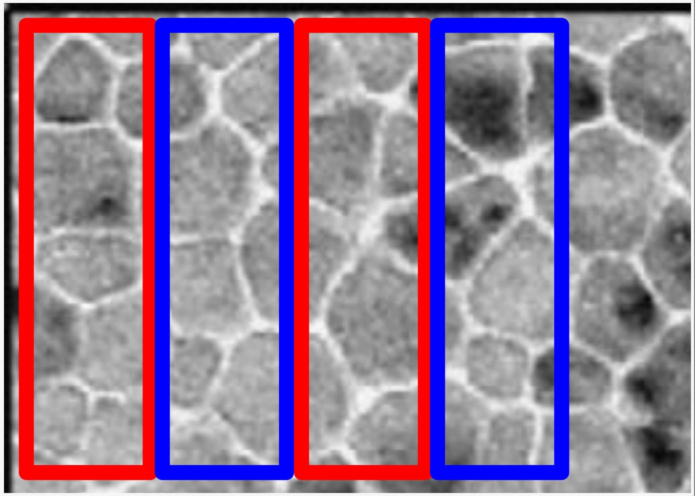
Magnetic bits on hard disk drive

Co-based hard disk media : bits 20nm in length



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

Underlying microscotructure



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 dynamics

Magnetization dynamics:

Landau-Lifshitz-Gilbert equation:

$$\frac{dM}{dt} = -\gamma_0 \left[M \times H_{\mathrm{eff}}\right] + \frac{\alpha}{M_s}\left[M \times \frac{dM}{dt}\right]$$

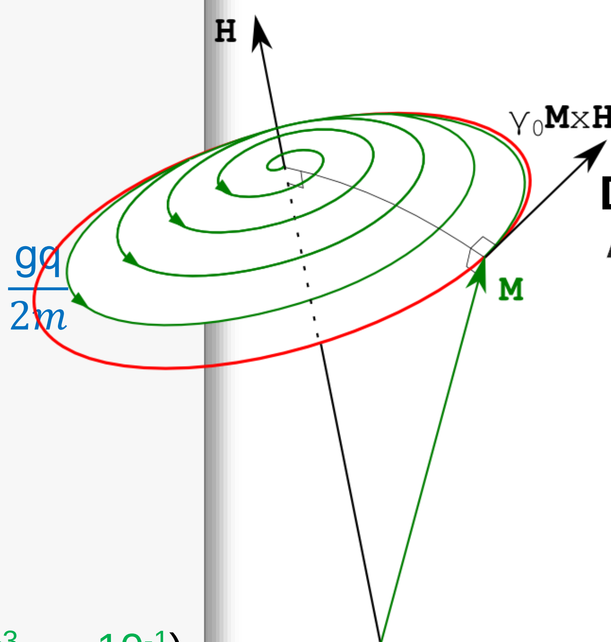
Gyromagnetic factor

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

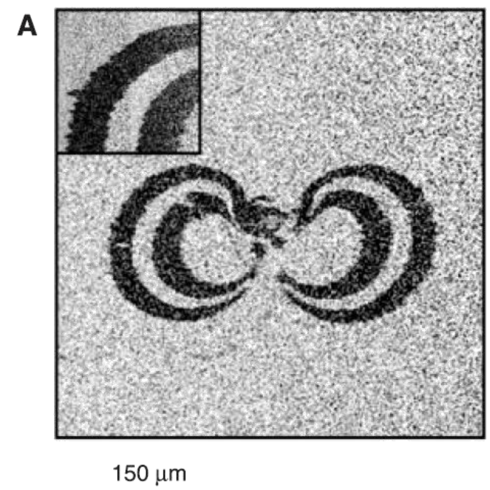
$$\gamma / 2\pi = 28\ \mathrm{GHz/T}$$

H_{eff} Effective field (including applied)

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



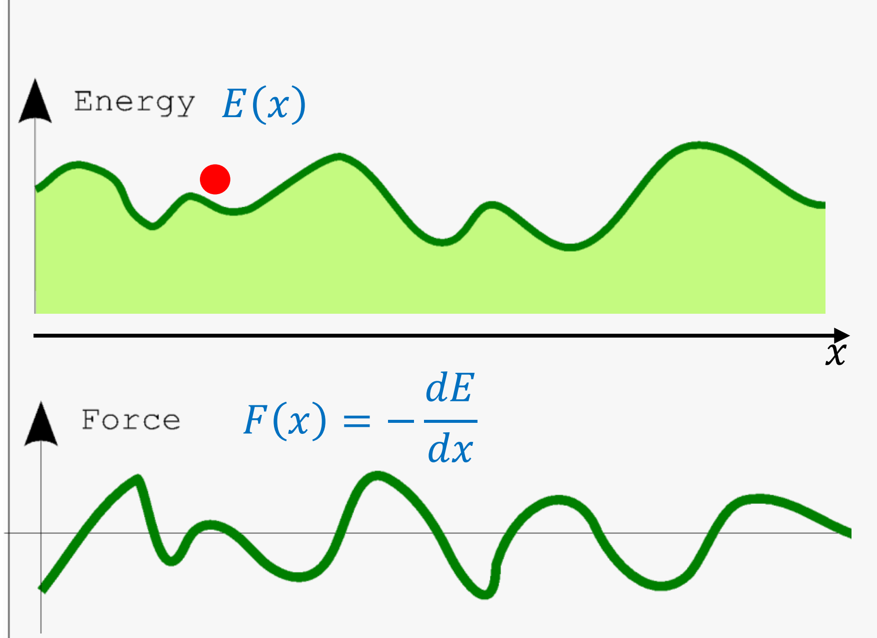
Demonstration: 1999



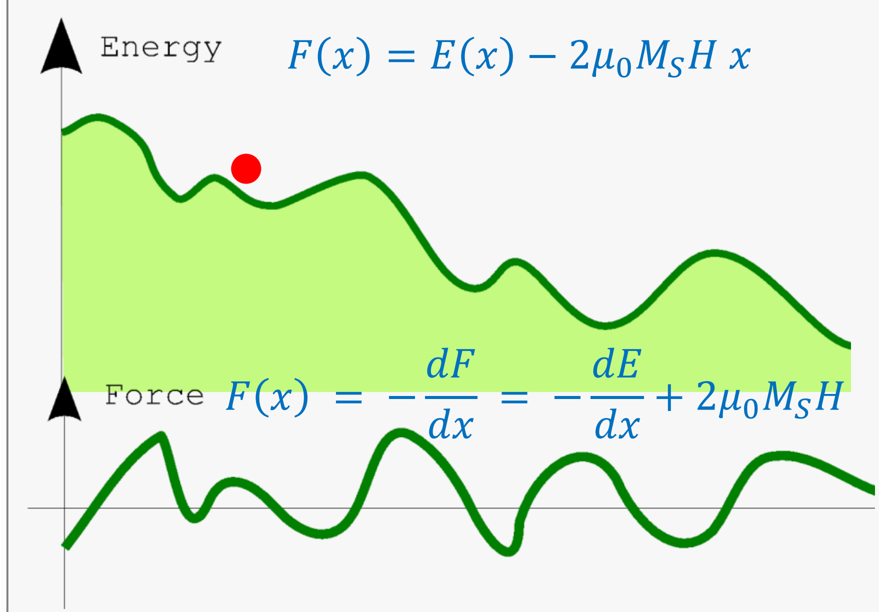
C. Back et al., Science 285, 864 (1999)

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.

MOTIVATION / Practical considerations

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

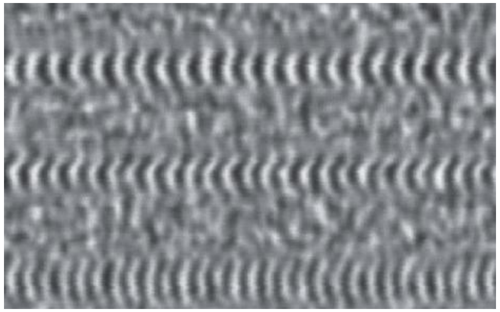
- Large-scale instrument or in-lab ?
- Expensive or cheap ?

Measured quantity

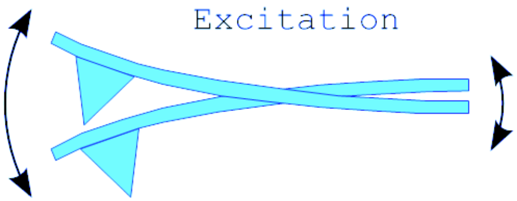
- Surface or volume technique ?
- Sensitivity ?
- Magnetization, stray field, other ?

- No universal technique
- Many criteria to be balanced

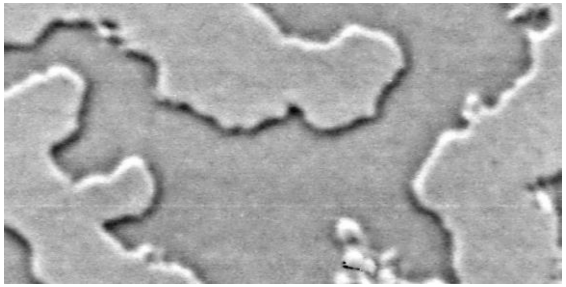
- Motivation and criteria



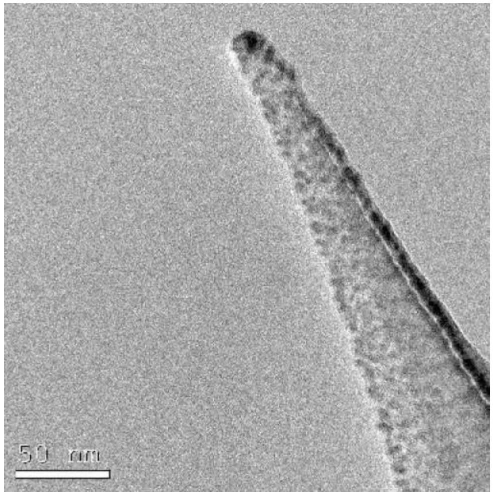
- Working principle



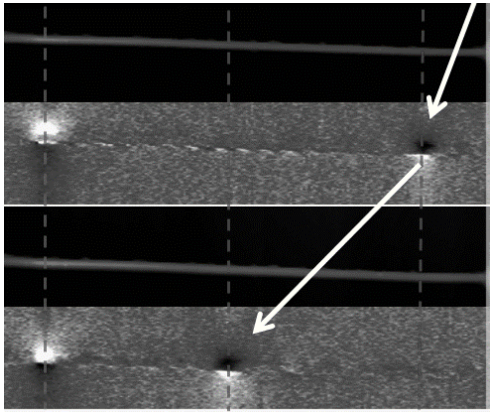
- Image analysis



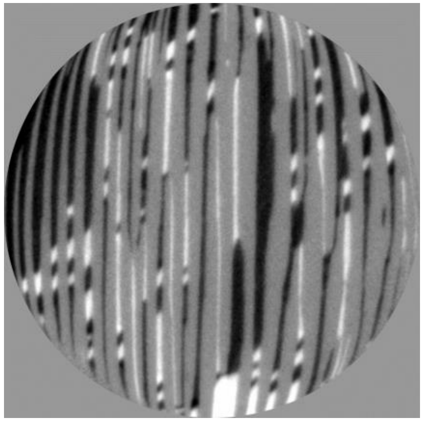
- Choice of tips



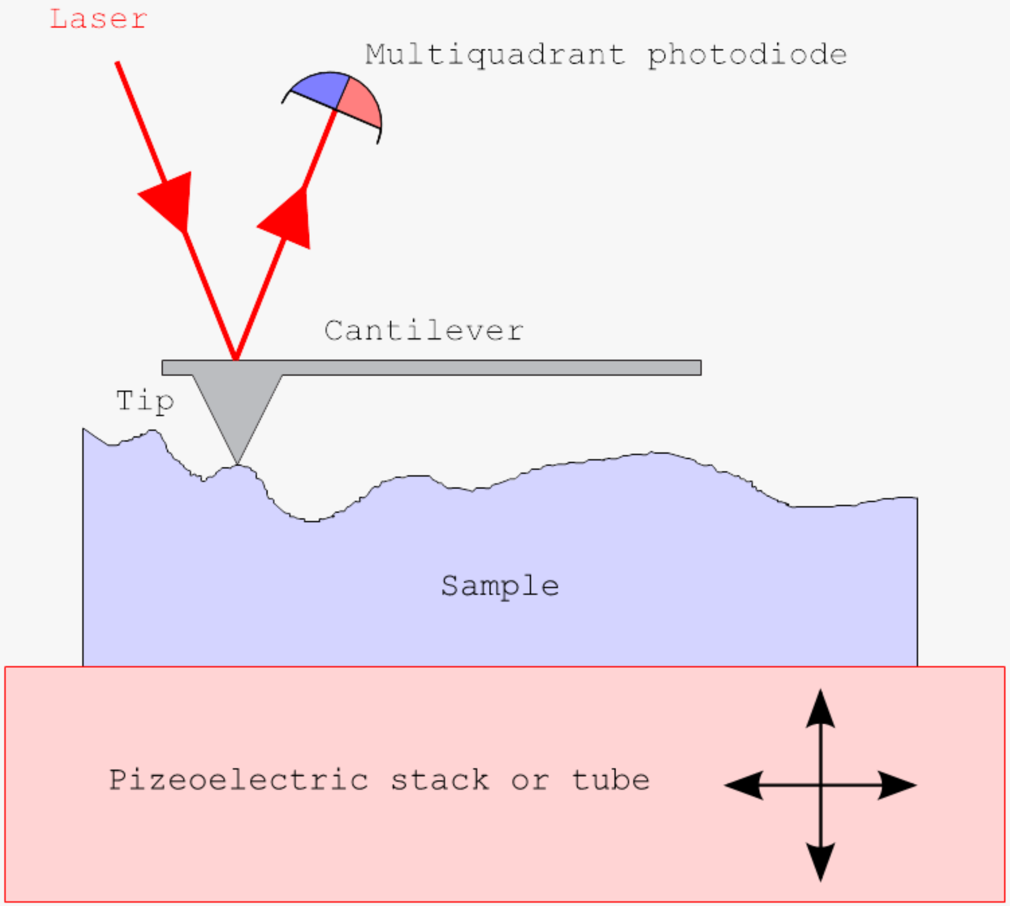
- Operando imaging



- Panorama of other microscopies



Key elements of an Atomic Force Microscope (AFM)

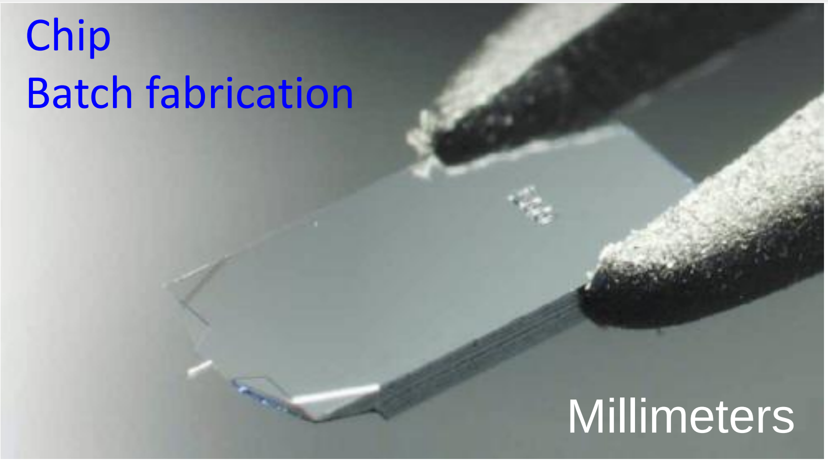


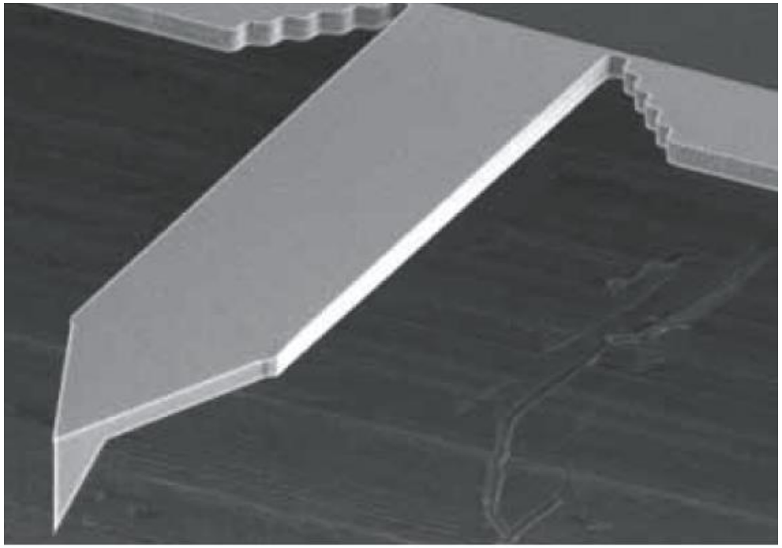
G. Binnig et al., Phys. Rev. Lett. 56, 930-933 (1986)

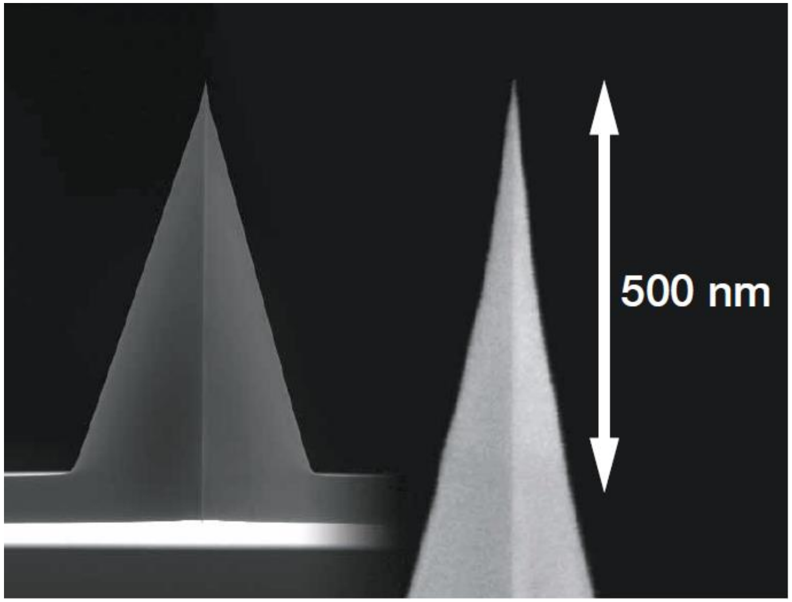
Overview

- Measures forces (vertical and lateral) between sample and tip

MFM / Conventional cantilevers and tips





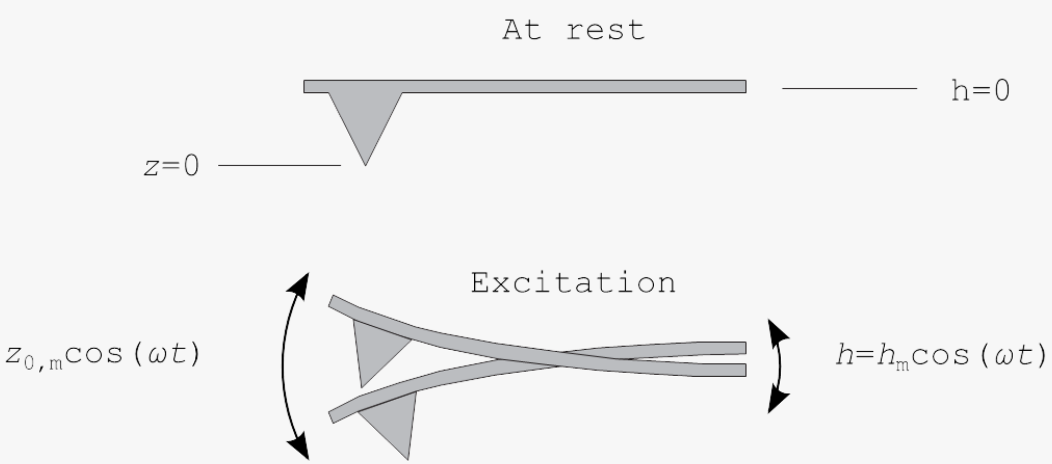


- Price 10-200€ / tip
- Radius of curvature ≈ 5nm

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

MFM / Equations for a harmonic oscillator

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

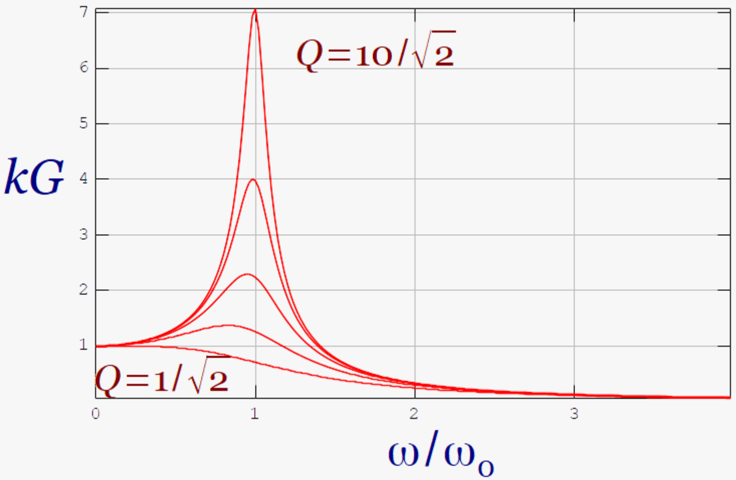
Reference angular velocity $\quad \omega_0=\sqrt{\dfrac{k}{m}}$

Quality factor $\quad Q=\dfrac{\sqrt{k\,m}}{\Gamma}$

→ Transfer 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



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

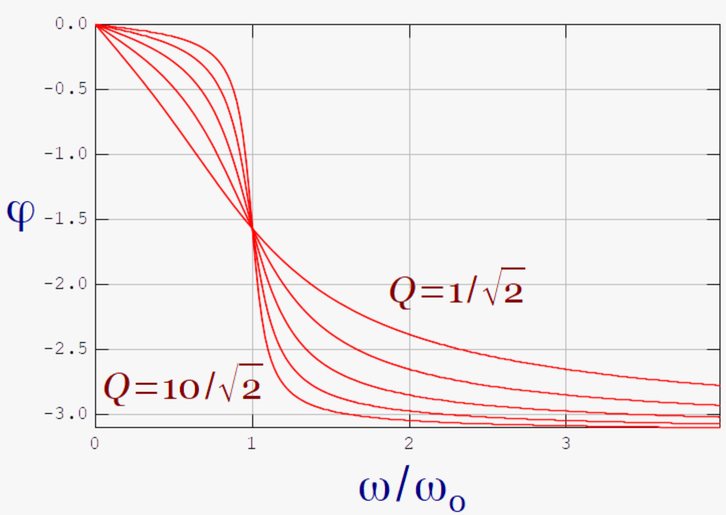
Peak at : $\omega_r=\omega_0\sqrt{1-\frac{1}{2Q^2}}$

$kG(0)=1$

$kG(\omega_r)=Q$

$kG(\infty)=0$

Dephasing



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

$\varphi(0)=0$

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

Q>>1

$\omega_r\approx\omega_0$

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

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

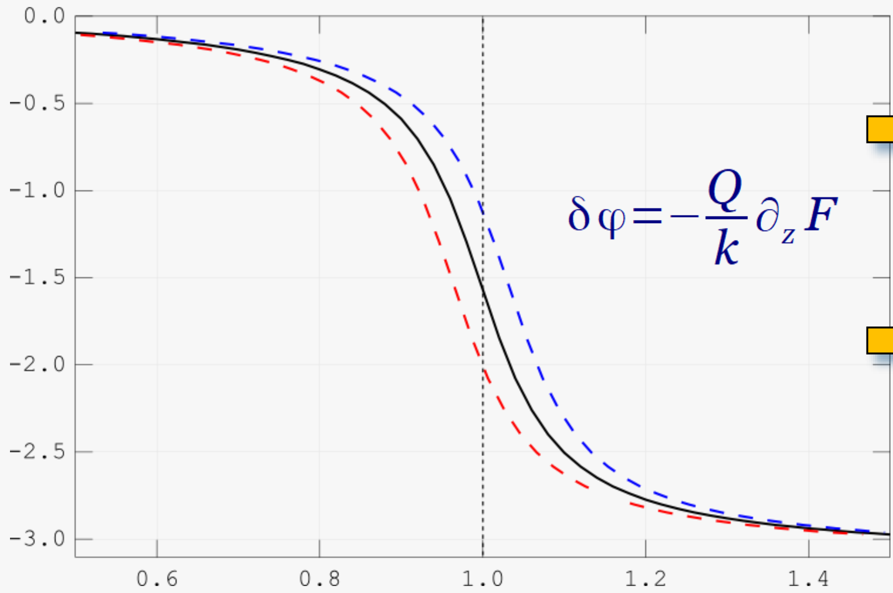
MFM / Detecting forces on the phase shift

Tip-sample interaction treated as perturbation

$m\ddot{z}+\Gamma\dot{z}+kz=F(z)$ with $F(z)=F(z_0)+(z-z_0)\partial_z F$

➡ Mere renormalization: $\omega_{0,\mathrm{eff}}=\omega_0\left(1-\frac{1}{2k}\partial_z F\right)$

Phase shift



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

$\omega_{exc}=\omega_0$

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 / Standard tips

MFM tips: AFM tip + magnetic coating

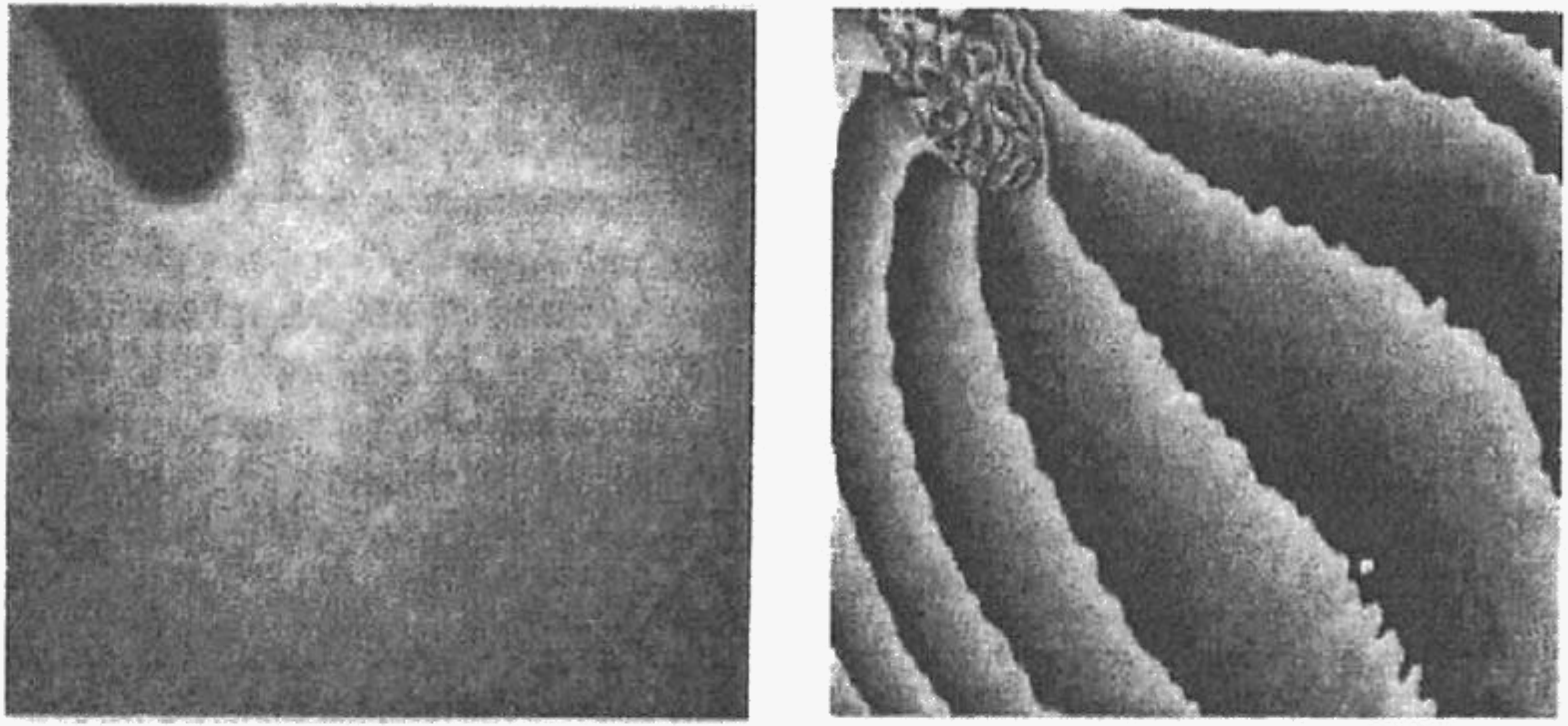
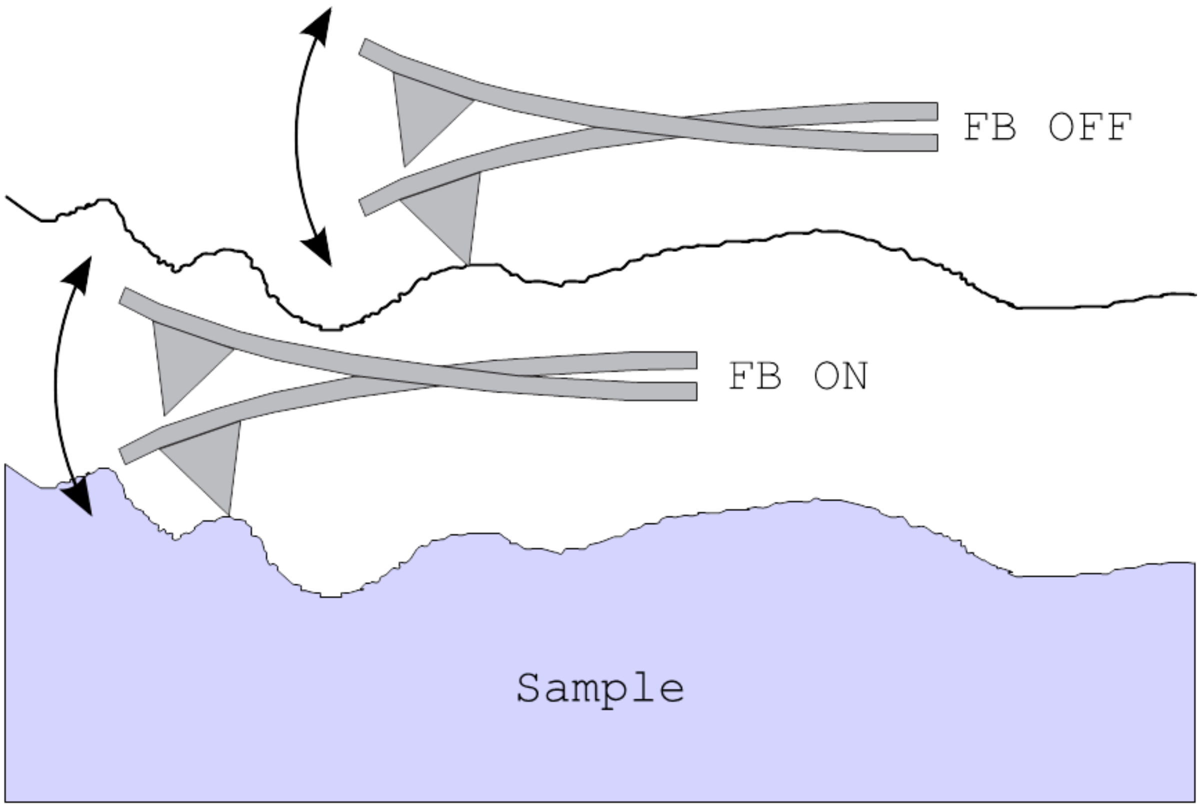


Figure 11-20: The electron amplitude (left) and phase (right) near an MFM tip visible as a dark shadow on the upper left corner of the left image.

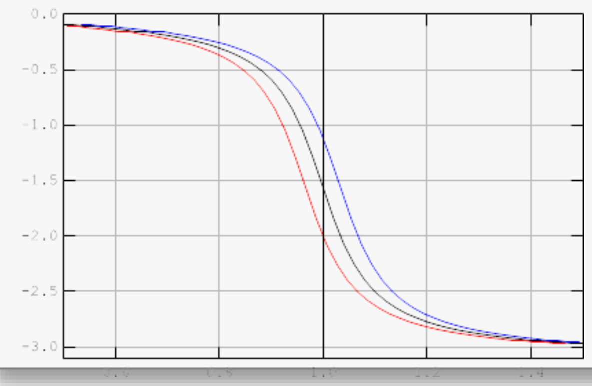
R. Proksch et al., Modern techniques for characterizing magnetic materials, Springer, p.411 (2005)

MFM / Two-pass technique



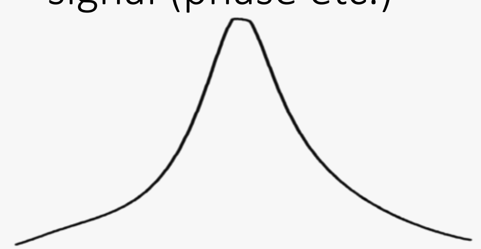
Second pass

- Monitor long-range forces (magnetic, electrostatic)



First pass

- Feedback ON
- Monitor topography (height) and any other signal (phase etc.)

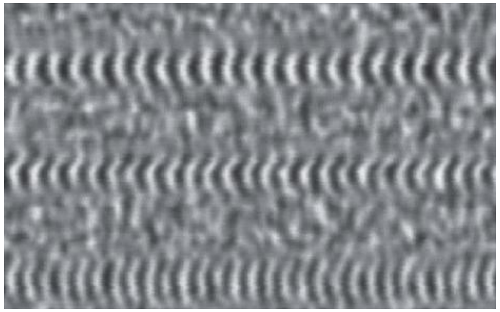


First report : Y. Martin et al., Appl. Phys. Lett. 50, 1455 (1987)

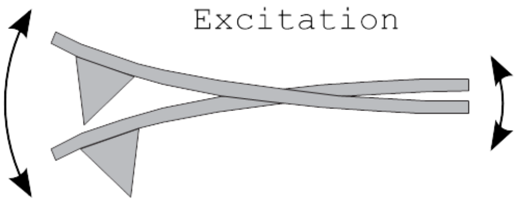
Review : R. Proksch et al., Modern techniques for characterizing magnetic materials, Springer, p.411 (2005)

TABLE OF CONTENTS

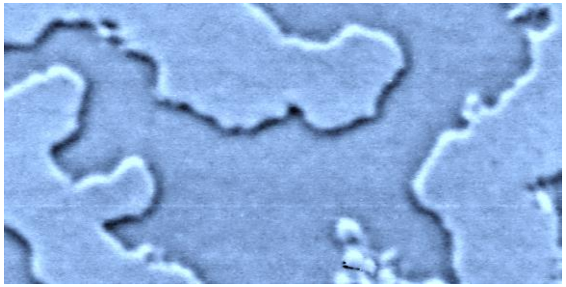
- Motivation and criteria



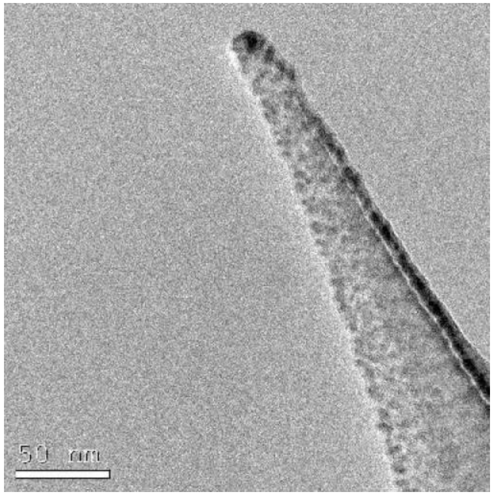
- Working principle



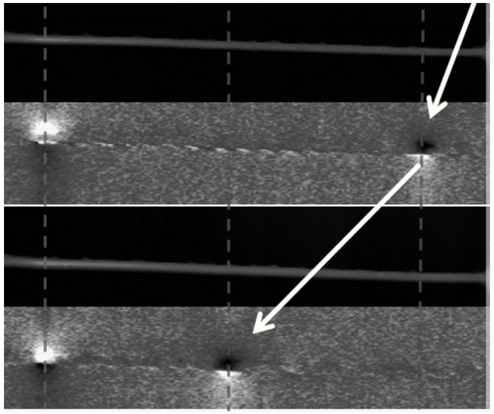
- Image analysis



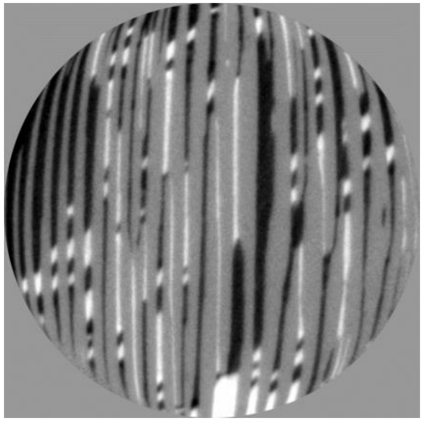
- Choice of tips



- Operando imaging

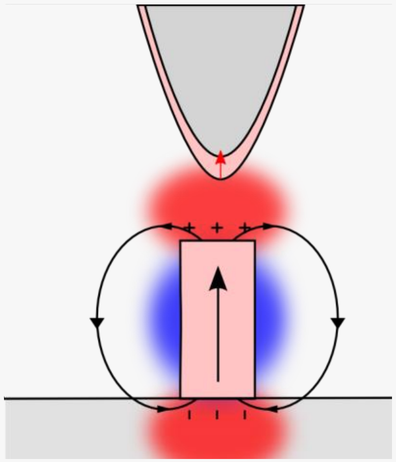


- Panorama of other microscopies



PRACTICE / MFM – tip/sample interaction

Tip is a dipole



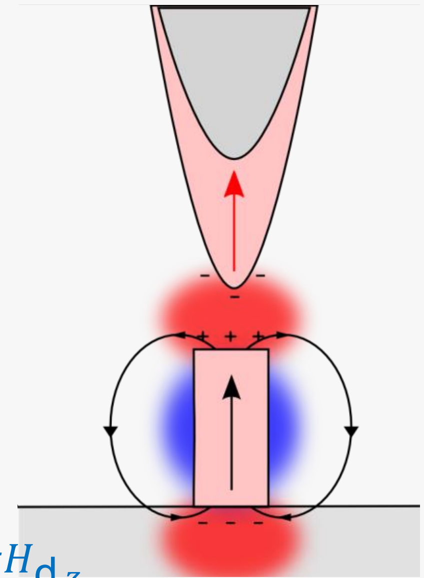
$$E_{1,2} = -\mu_0 \mu_2 . H_{\mathrm{d}}$$

$$E_{1,2} = -\mu_0 \left(\mu_x . H_{\mathrm{d},x} + \mu_y . H_{\mathrm{d},y} + \mu_z . H_{\mathrm{d},z} \right)$$

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

Tip is a monopole

$$E_{1,2} = \mu_0 \sigma . \phi$$



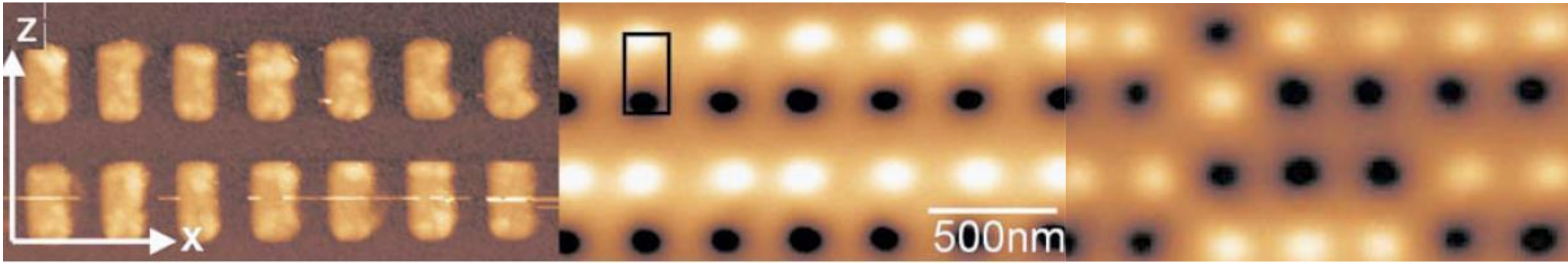
$$F_z = -\mu_0 \sigma H_{\mathrm{d},z}$$

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

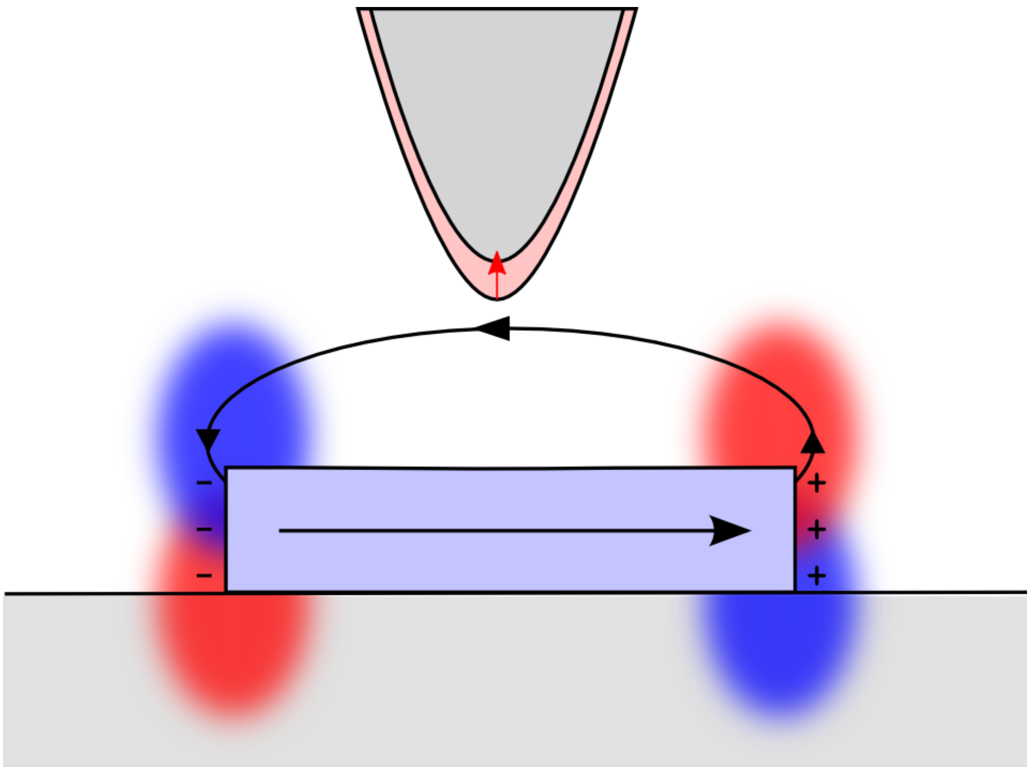
- In practice, a combination of both models is best suited (dipole is more important)
- MFM is sensitive to some derivative(s) of the stray field from the sample
- MFM may be sensitive to in-plane field, depending on the tip magnetic moment

PRACTICE / Single-domain (planar)

Topography | MFM, saturated | MFM, partly reversed

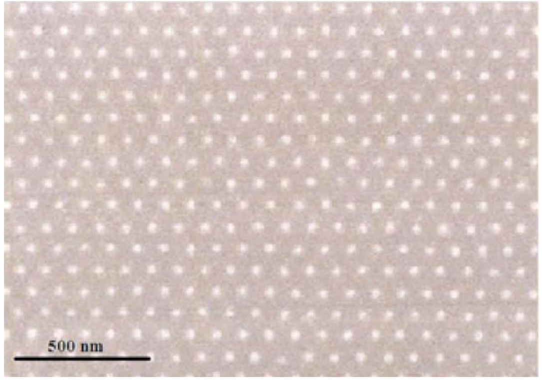


S. Y. Suck et al., APL95, 162503 (2009)

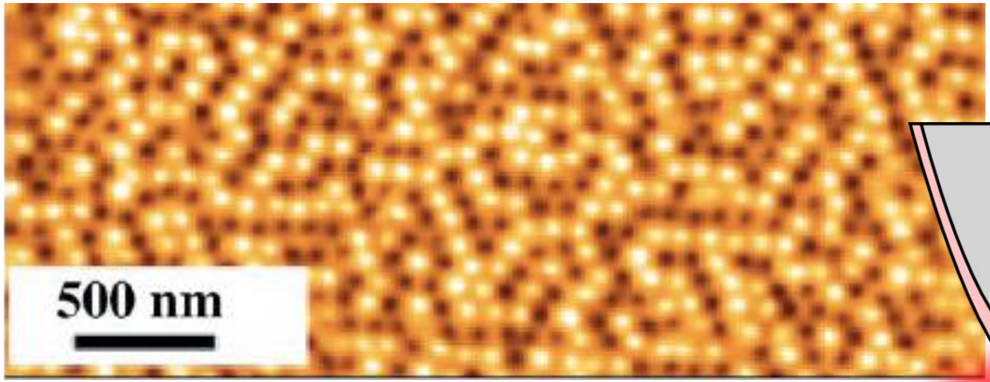


- Single-domain in-plane magnetized dots appear as dipoles

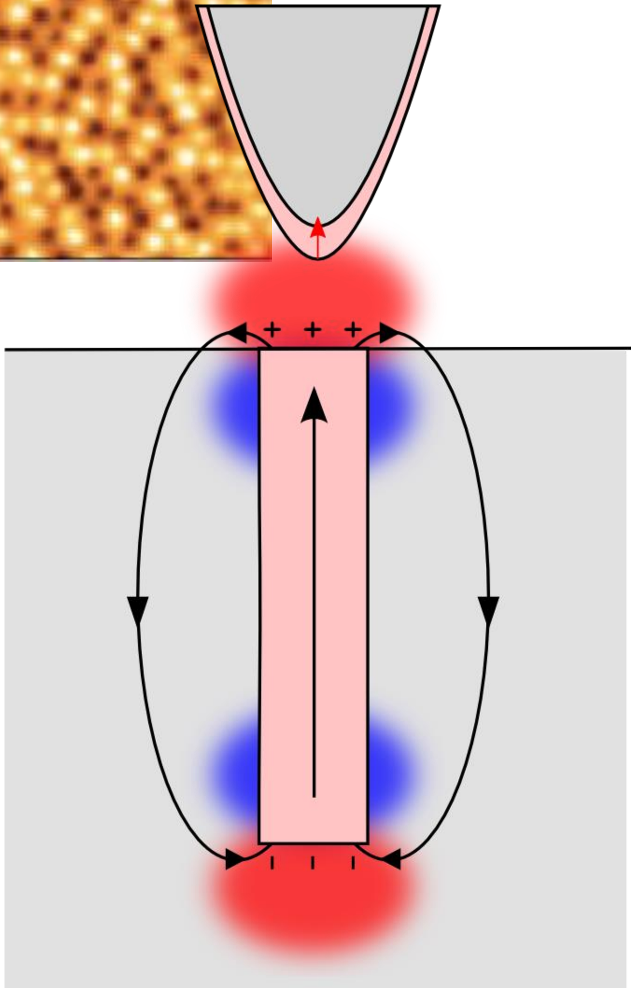
Structure (SEM)



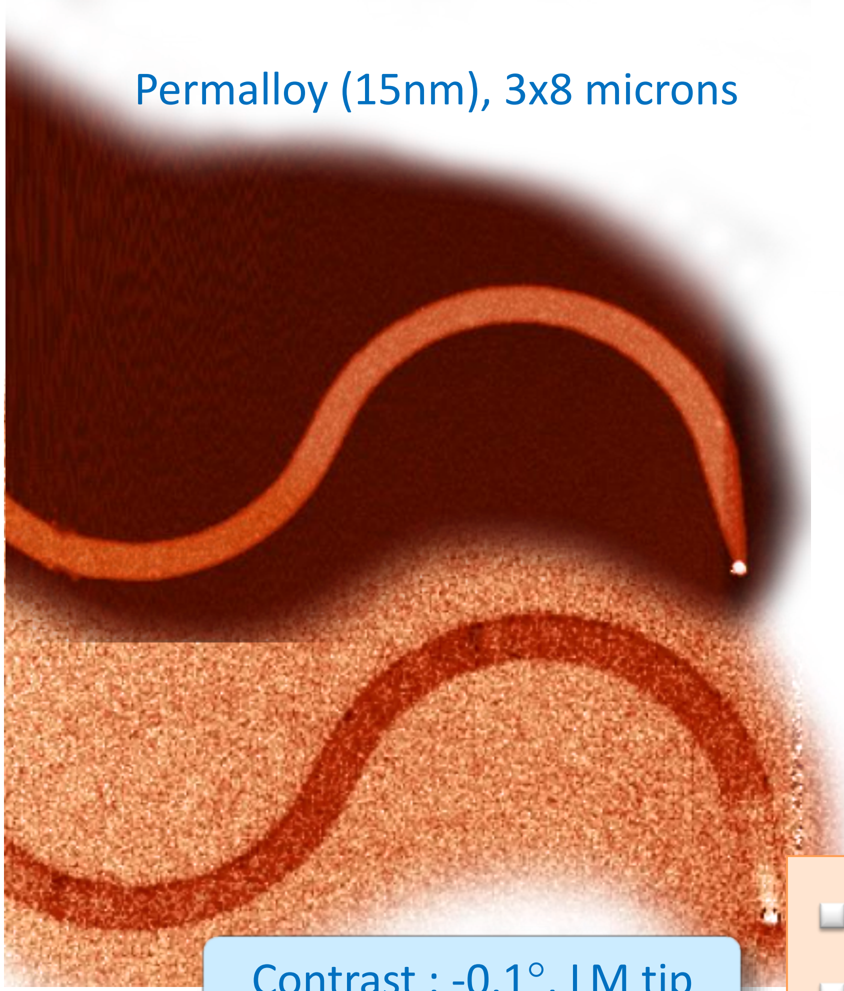
MFM, partly reversed



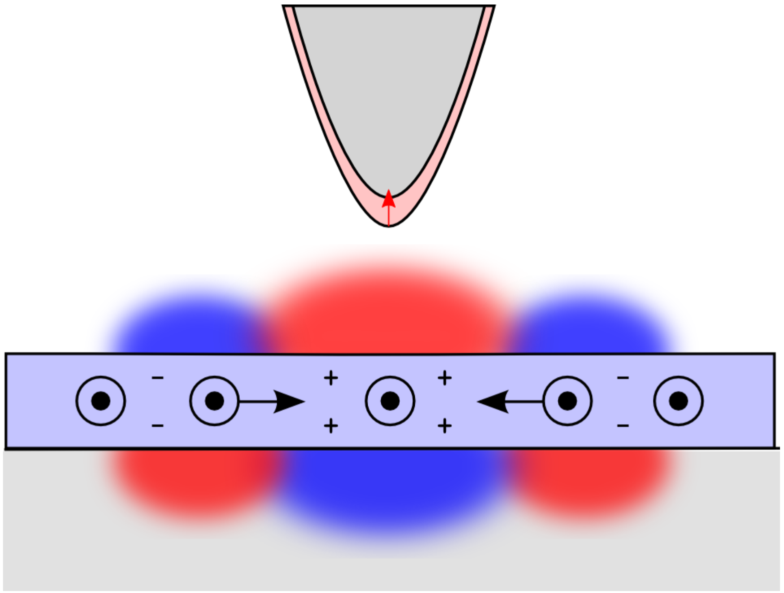
T. Wang et al., APL 92, 192504 (2008)



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



Lithography : S. Pizzini (Institut Néel)
Imaging : Z. Ishaque (Institut Néel)

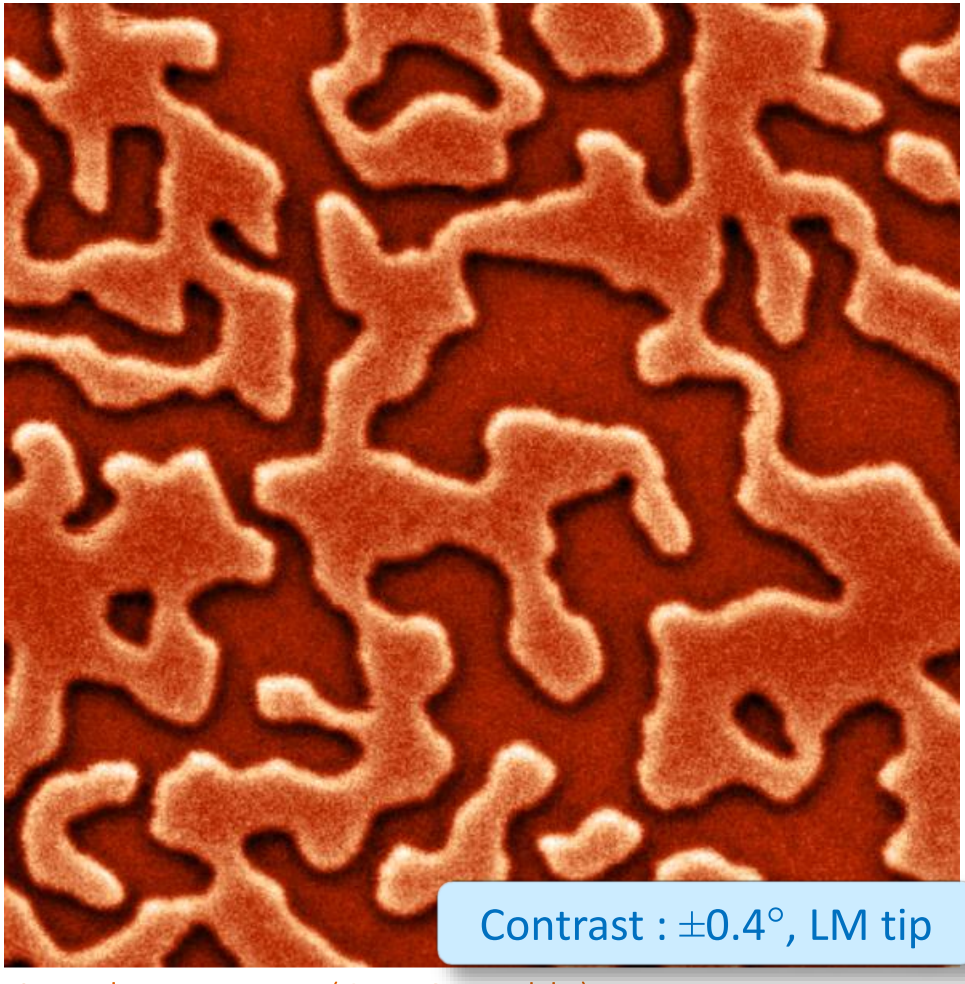


Principle :
1. Stray field magnetizes sample
2. Sample is non -uniform → stray field
3. Tip measures sample's stray field

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

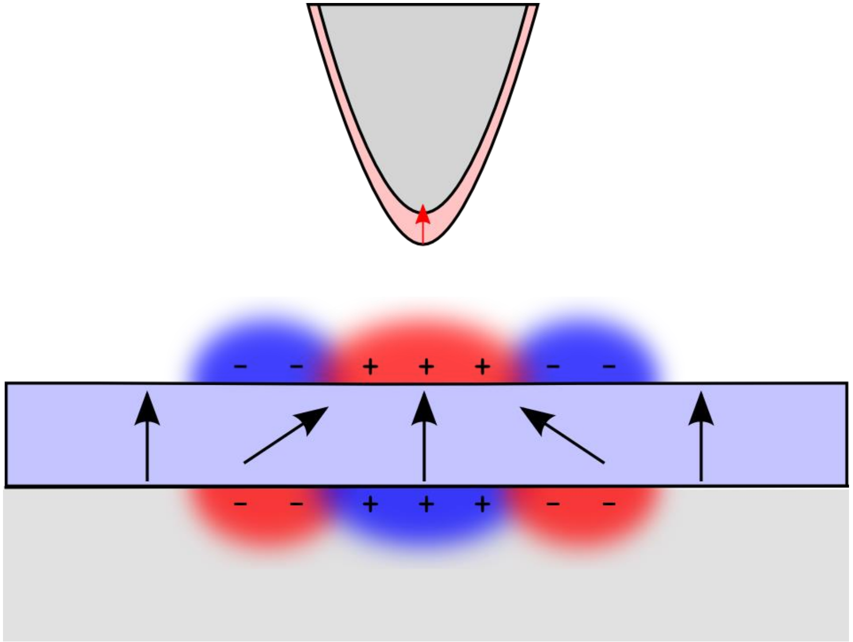
FePt (4nm)

5x5 μm



Contrast : ±0.4°, LM tip

Sample : A. Marty (CEA-Grenoble)
Imaging : M. Darques (Institut Néel)

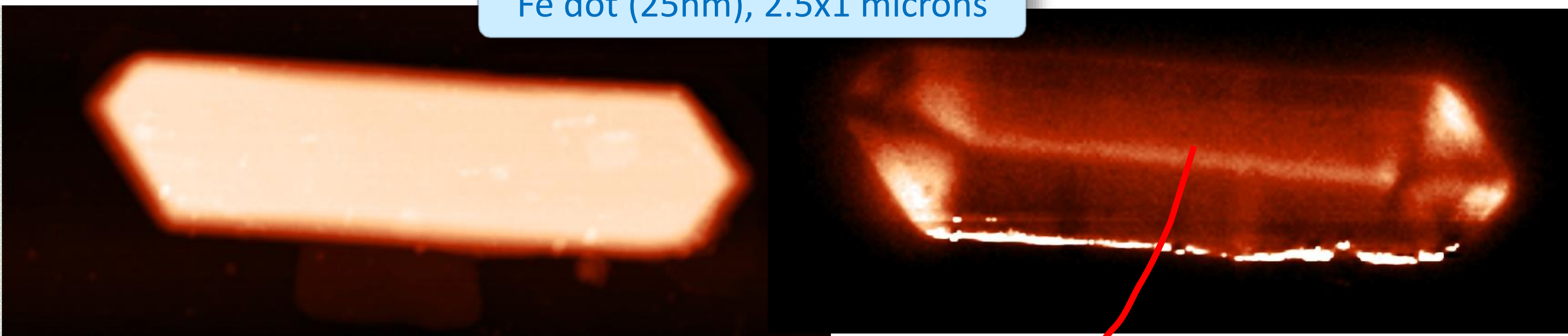


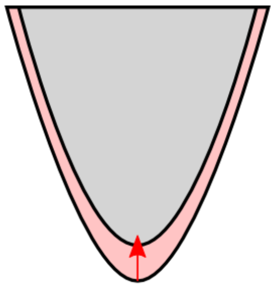
- It is a DOMAIN contrast
- The direction of magnetization is deduced

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

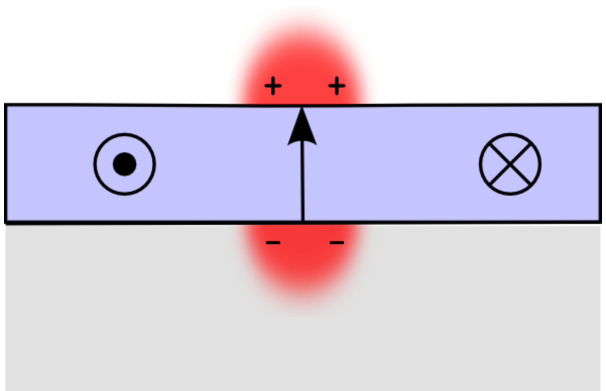
PRACTICE / Imaging domain walls (Bloch)

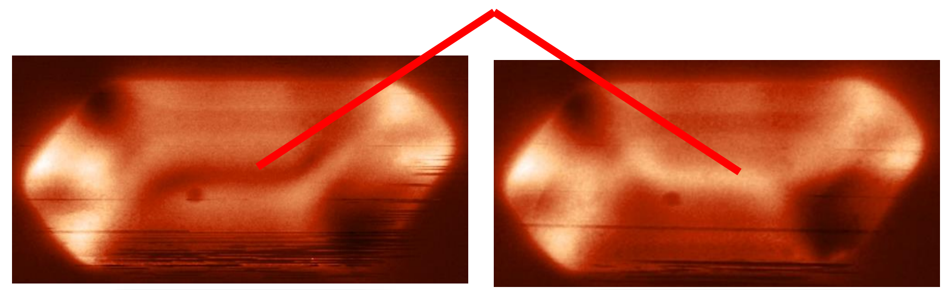
Fe dot (25nm), 2.5x1 microns





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

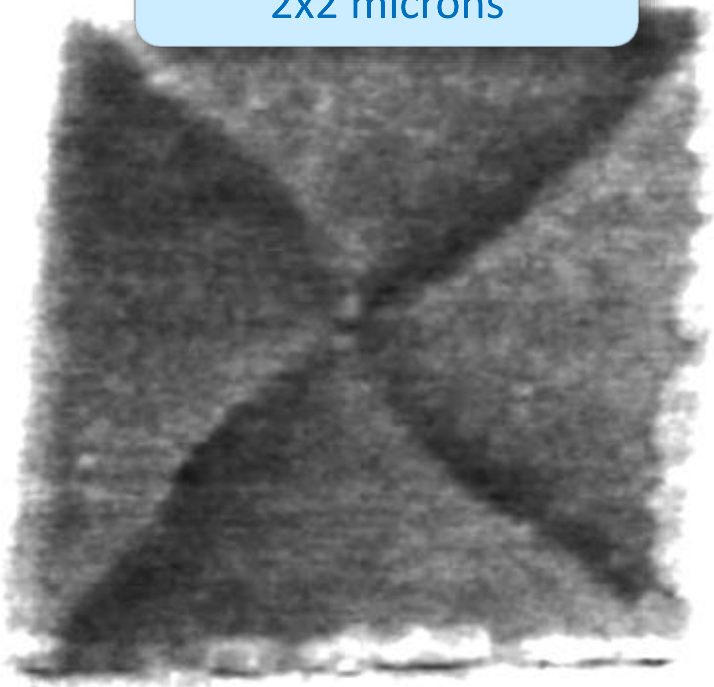




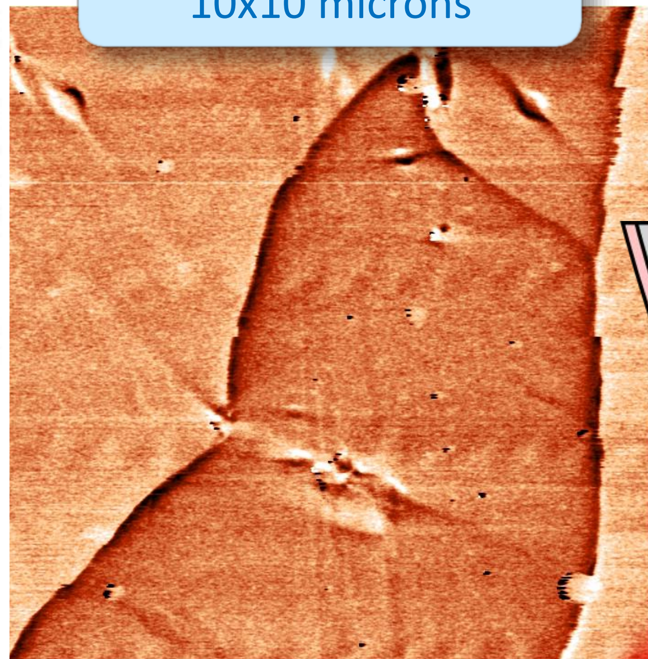
Down core

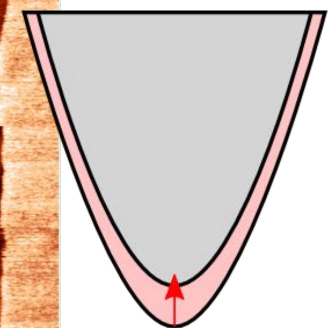
Up core

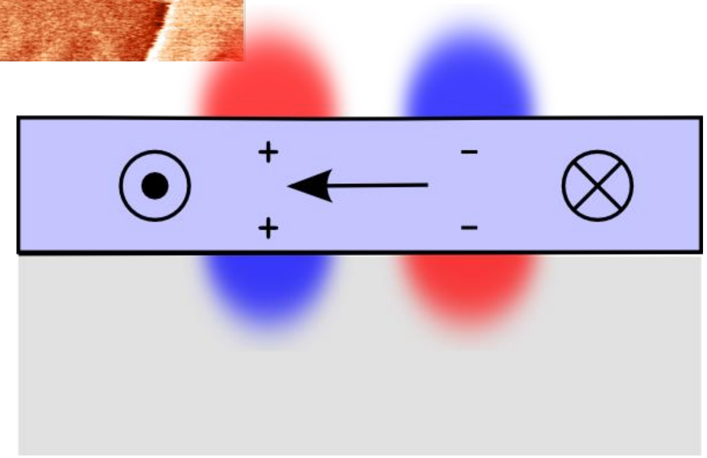
Permalloy dot (16nm)
2x2 microns



Permalloy film (20nm)
10x10 microns





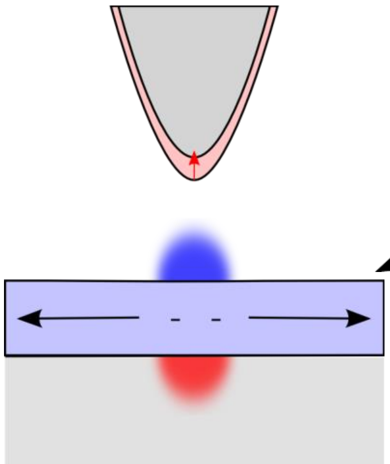


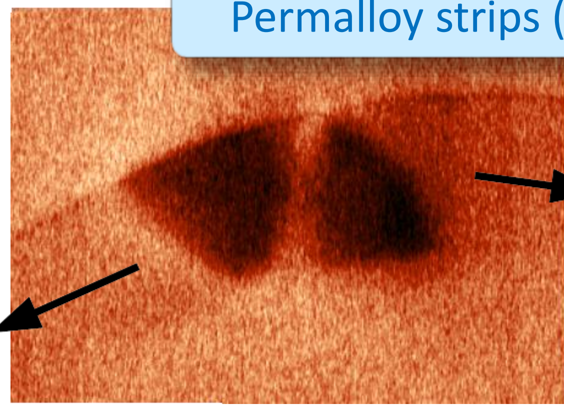
J. M. Garcia et al., APL 79, 656 (2001)

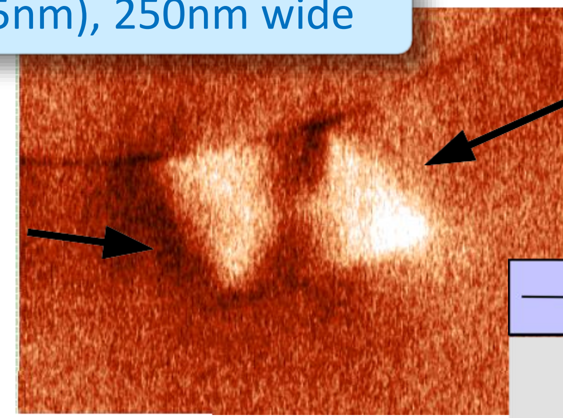
- Néel wall give rise to DIPOLAR contrast
- Informs about the chirality of the wall core

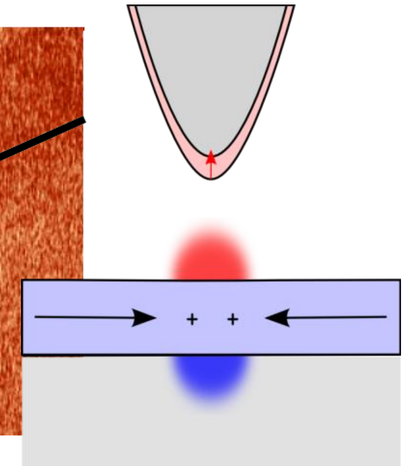
PRACTICE / Head-to-head domain walls

Permalloy strips (15nm), 250nm wide



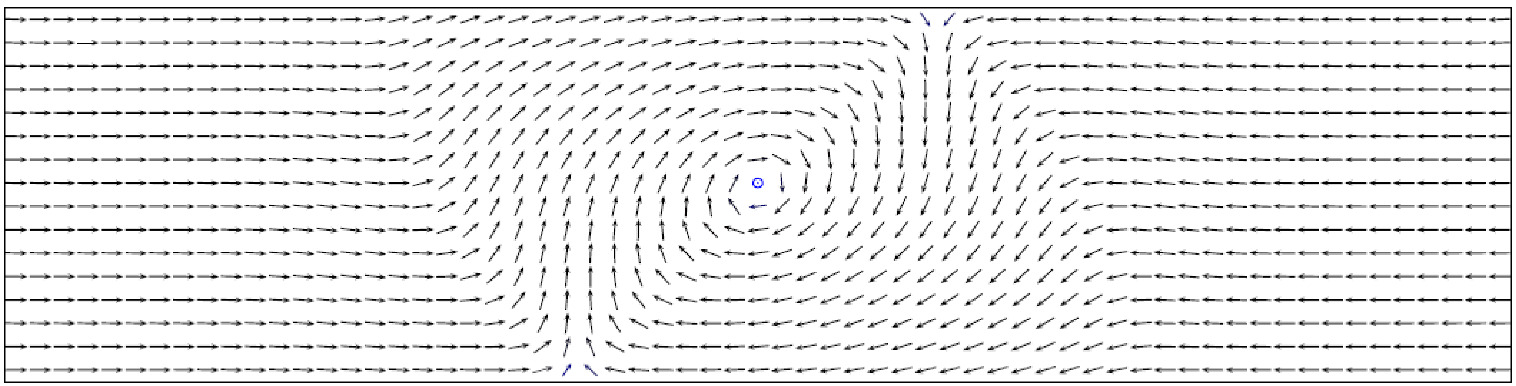






Contrast : ±0.3°,
tip 5nm CoCr

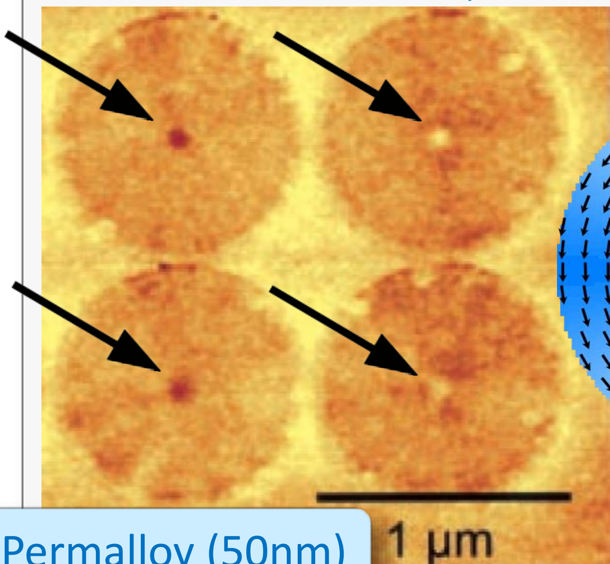
Known as vortex domain wall

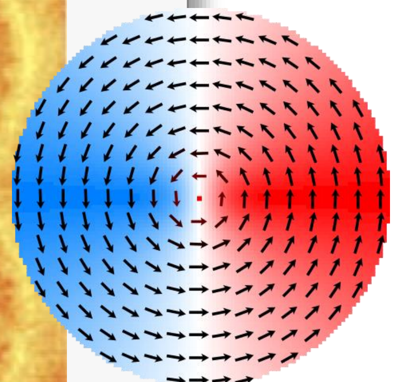


R. McMichael and M. Donahue, IEEE Trans. Magn. 33, 4167 (1997)

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

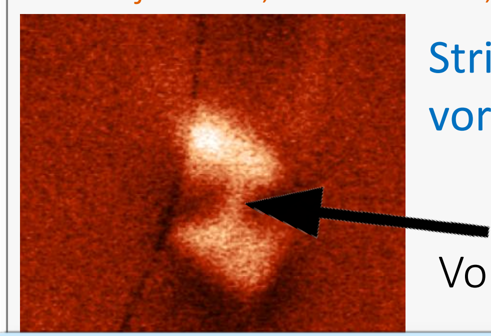
Observation Disk, vortex state





Permalloy (50nm)

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

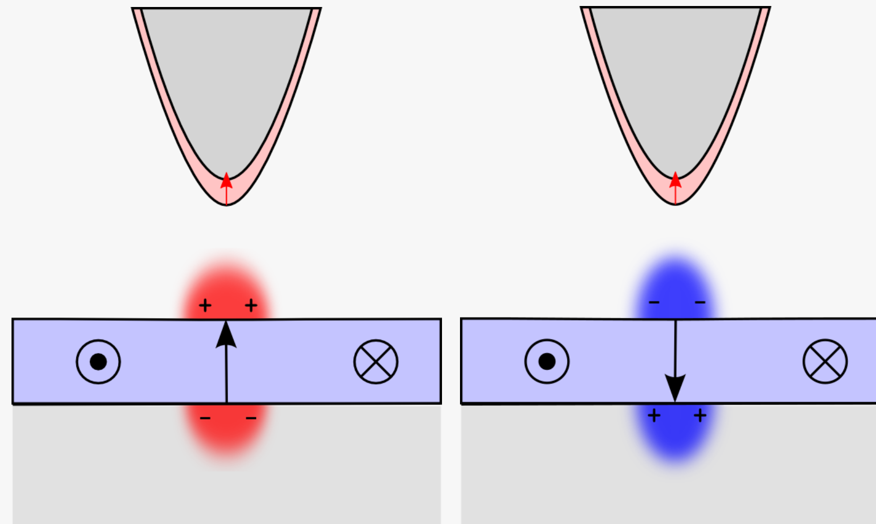


Strip, vortex wall

Vortex is up

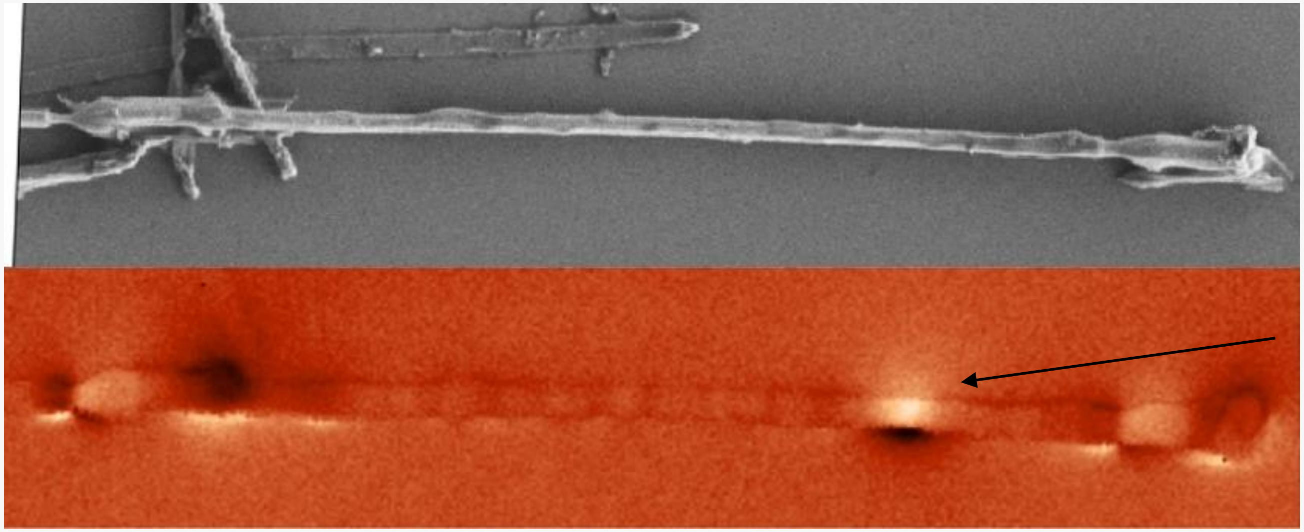
FeNiMo (15nm), strip width 200nm

Contrast

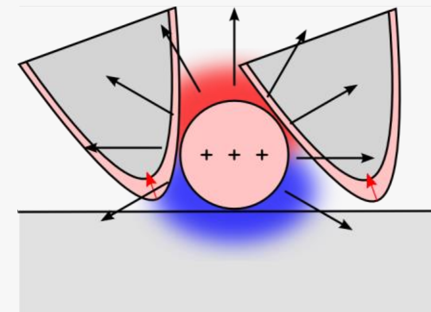


- MONOPOLAR, informs on core polarization
- May be hidden in surrounding wall contrast
- Vortex may be influenced by the tip

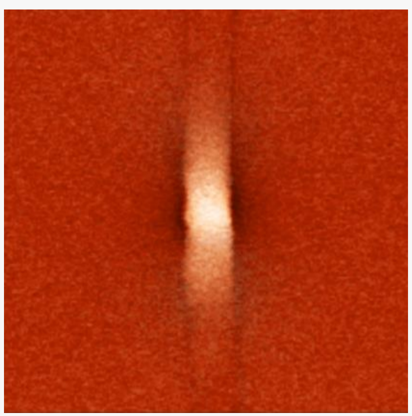
Tilted cantilever, across wire

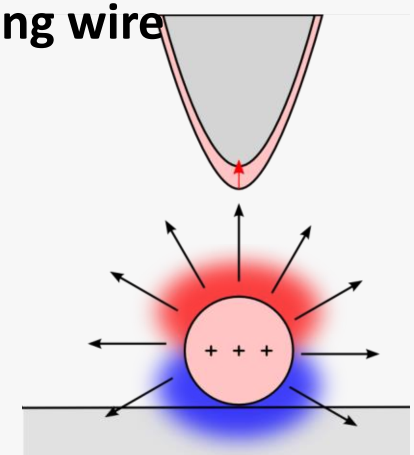


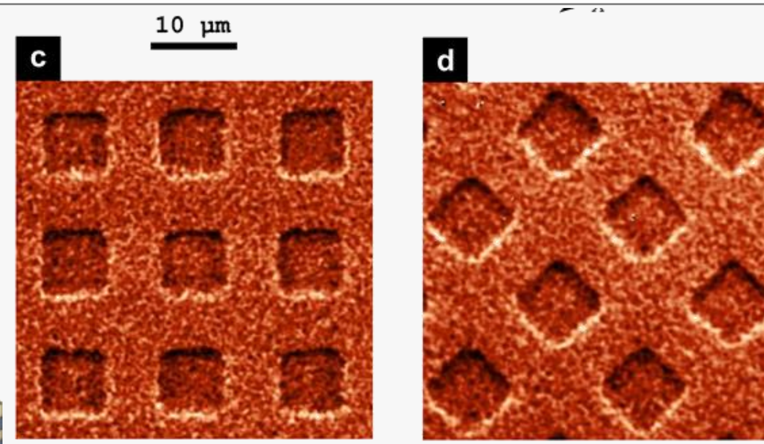
S. Da Col et al., APL109, 062406 (2016)



Tilted cantilever, along wire



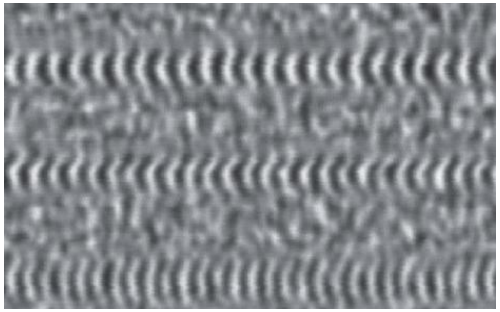




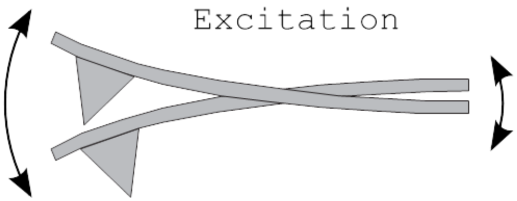
G. Ciuta, IEEEtm 52, 6500408 (2016)

TABLE OF CONTENTS

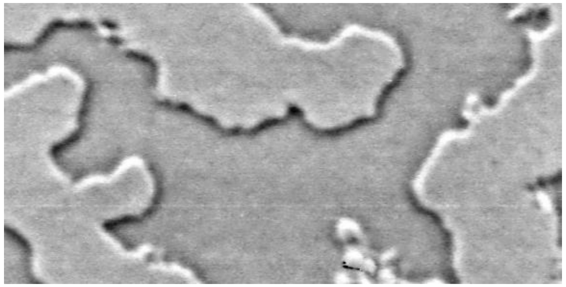
- Motivation and criteria



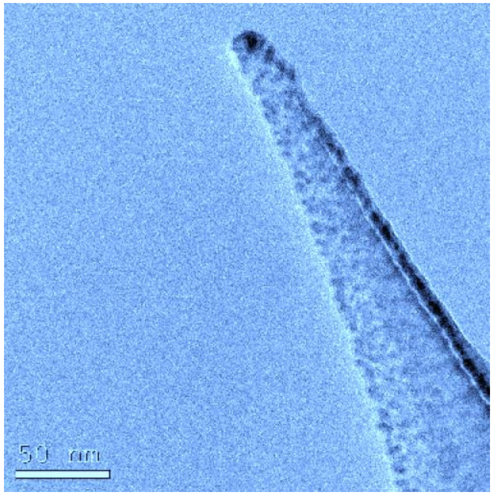
- Working principle



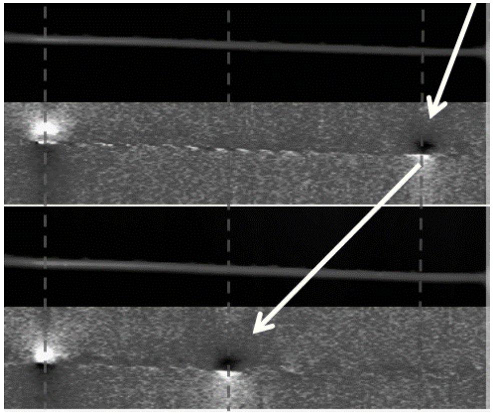
- Image analysis



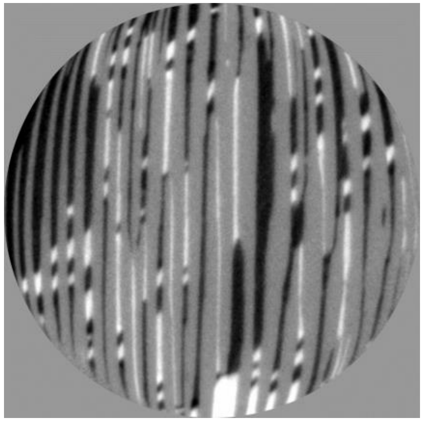
- Choice of tips



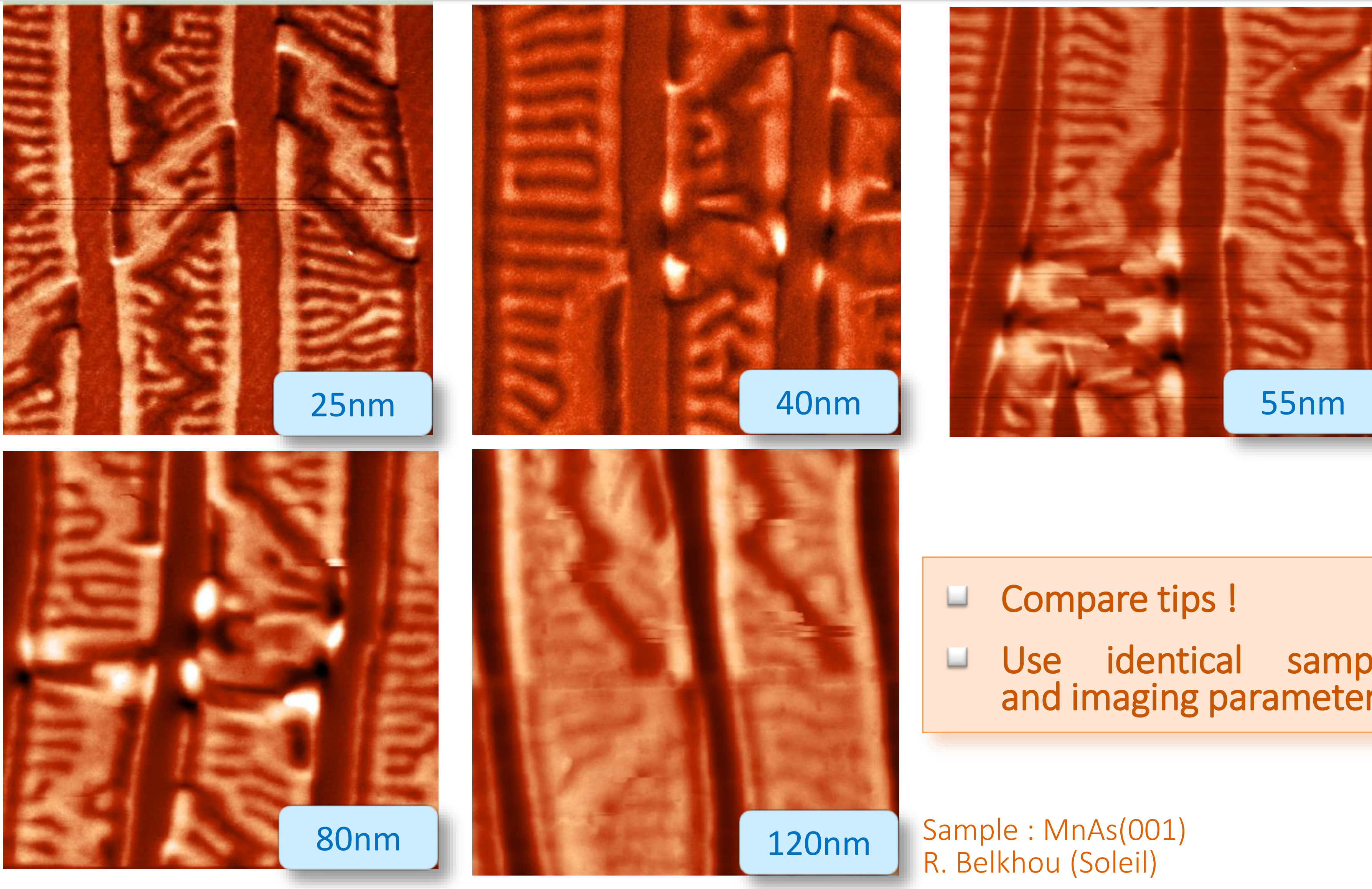
- Operando imaging



- Panorama of other microscopies



TIPS. Calibration | here : commercial



- Compare tips !
- Use identical sample and imaging parameters

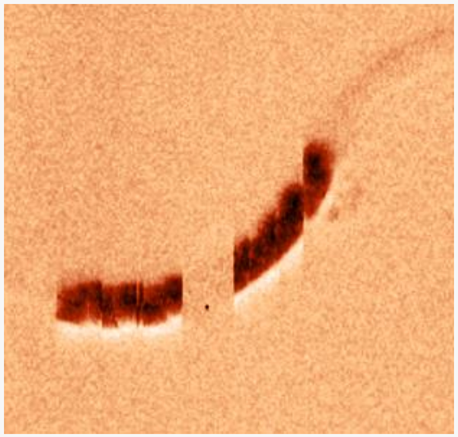
Sample : MnAs(001)
R. Belkhou (Soleil)

TIPS. Influencing samples

High

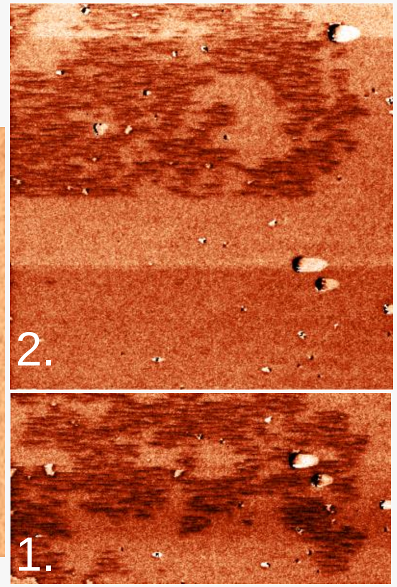
Scanning

Attraction



Permalloy (15nm)
500nm strips

Sample : S. Pizzini
Imaging : Z. Ishaque

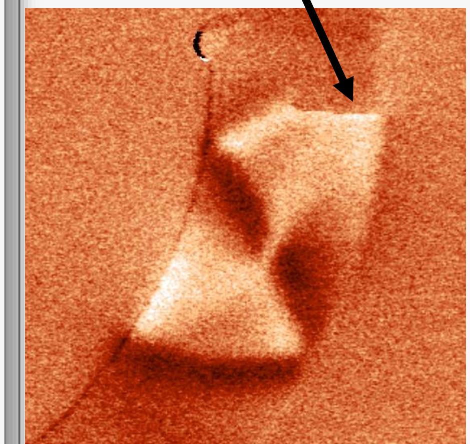


Co (0.6nm)/
graphene (20 mic)

C. Dieudonné

Moderate

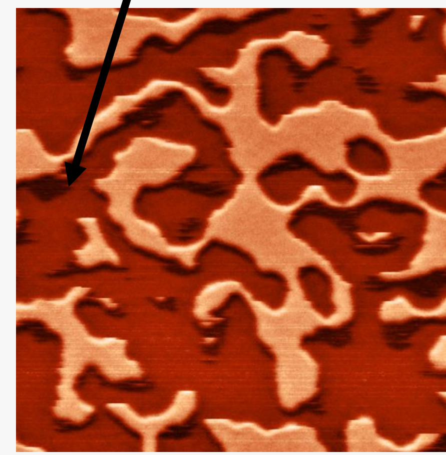
Repulsion



Permalloy (15nm)
500nm wide

Sample : S. Pizzini
Imaging : Z. Ishaque

Attraction



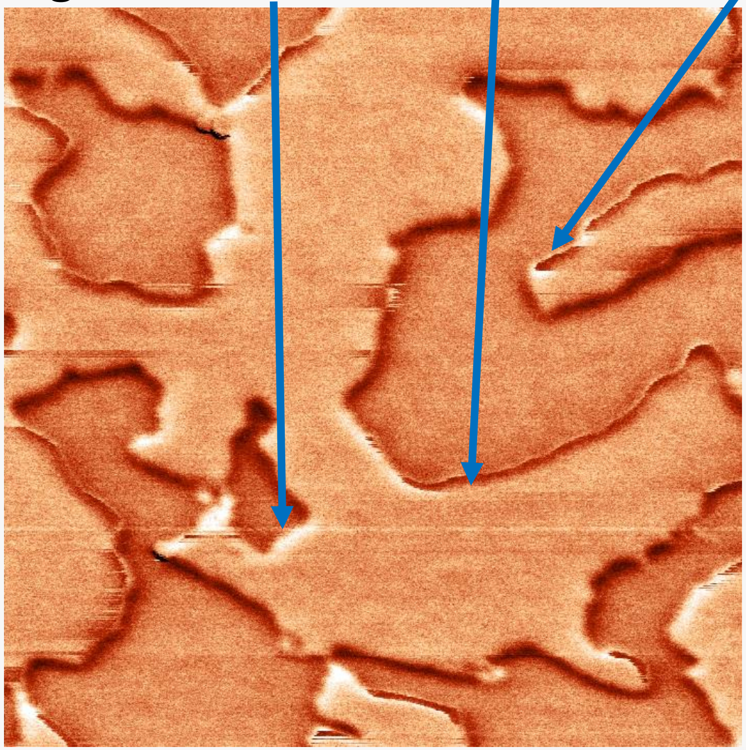
FePt (4nm)
Image 5 microns

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

TIPS. Sample influencing tips

High Normal Attractive Switch

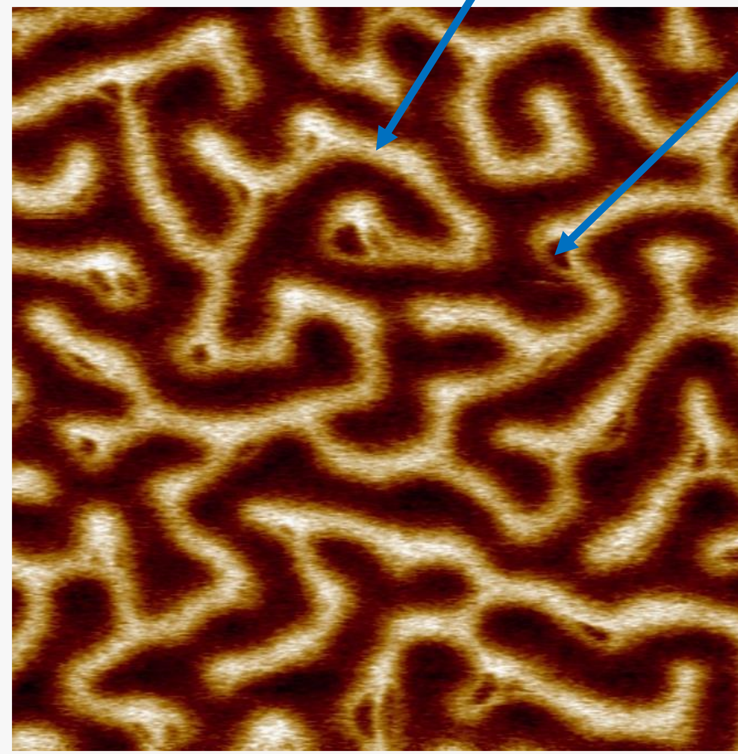


FePt(001) 4nm

Sample: Alain Marty

2x2 µm

Moderate Repulsion Attraction



Pd/Co/Au multilayers

Sample: Chloé Bouard

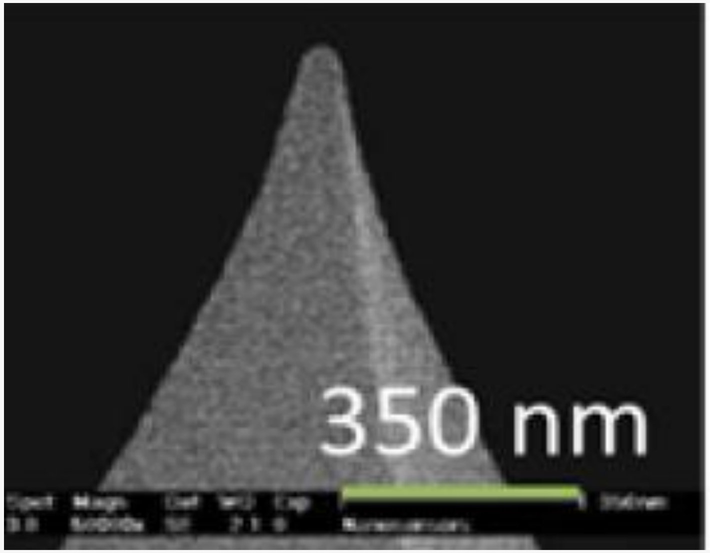
2x2 µm

- Sharp reversal features, and/or streaks parallel to fast direction
- Occurs at the highest repulsive fields

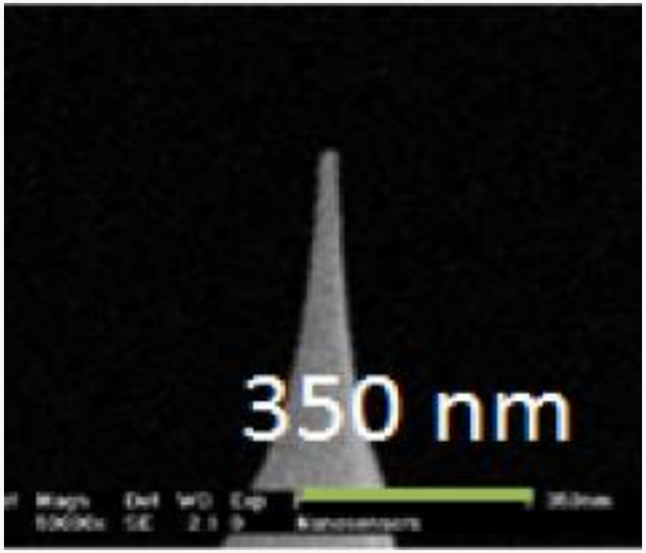
TIPS. Custom tips (basics)

Improve resolution

From sharp to ultrasharp AFM tips



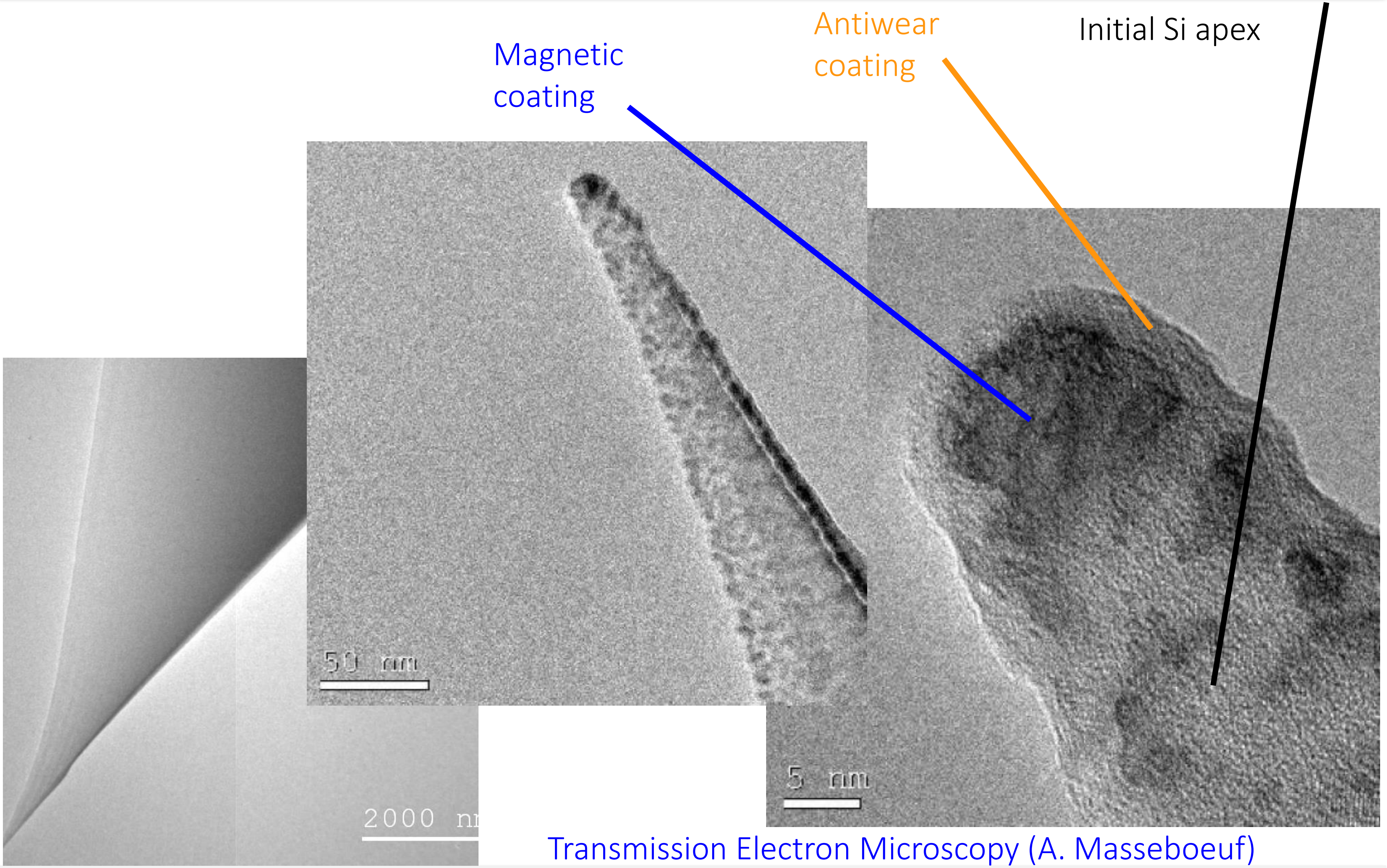
Asylum 240TS
Radius of curvature : 10 nm



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

Engineer magnetic coating

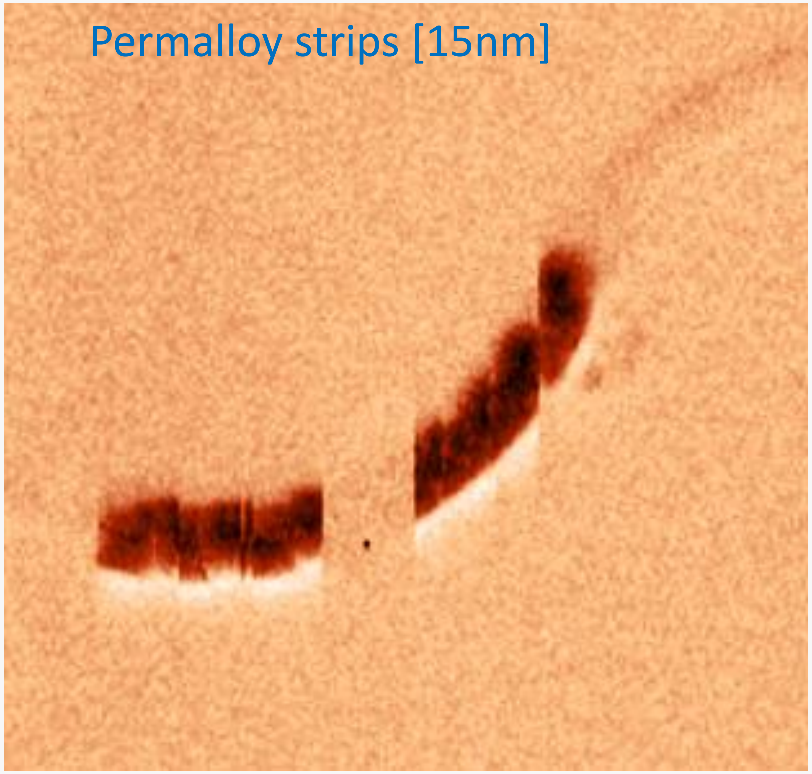
- Basis : Co80Cr20 (similar to hard disk media)
- Means : sputtering.
- Stacking : Based on CoCr [2-50 nm], various buffer and capping layers



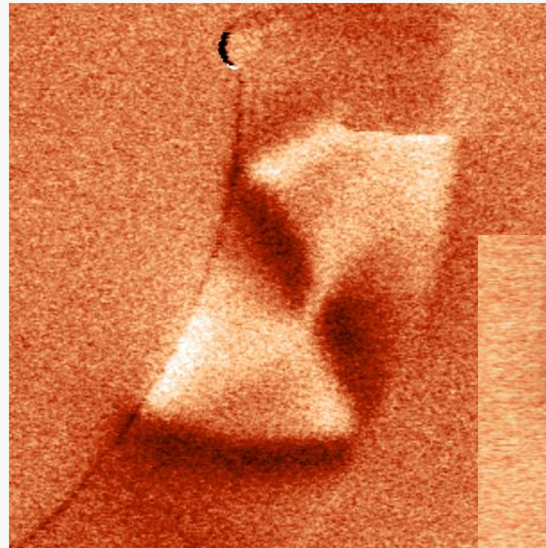
Transmission Electron Microscopy (A. Masseboeuf)

TIPS. Reduce tip-sample interaction

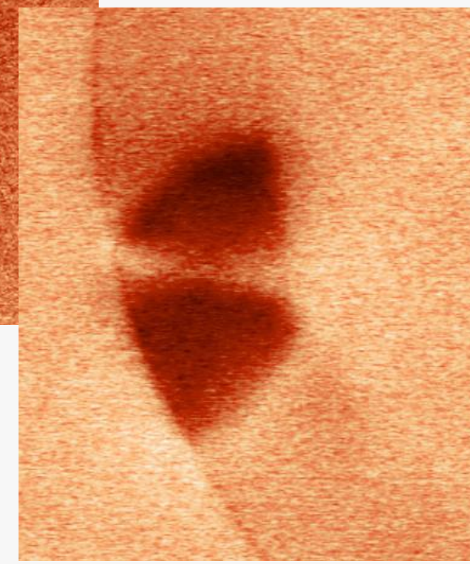
Commercial tips, "low moment"



Home-made tips, truly low moment



Tip : CoCr[10nm]
500nm strips
15nm permalloy



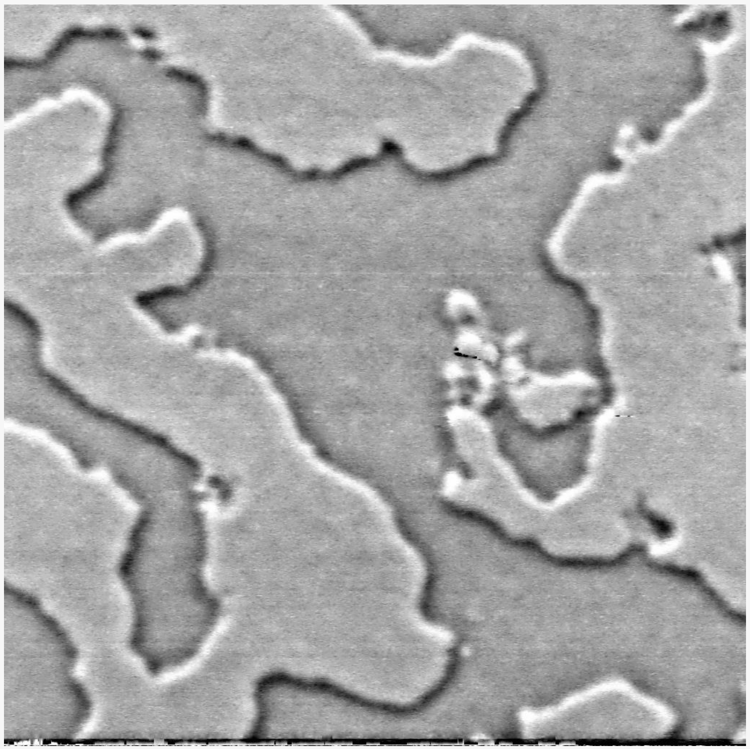
Tip : CoCr[5nm]
300nm strips
15nm Permalloy

Sample: S. Pizzini
Imaging: Z. Ishaque

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

Spatial resolution 15nm

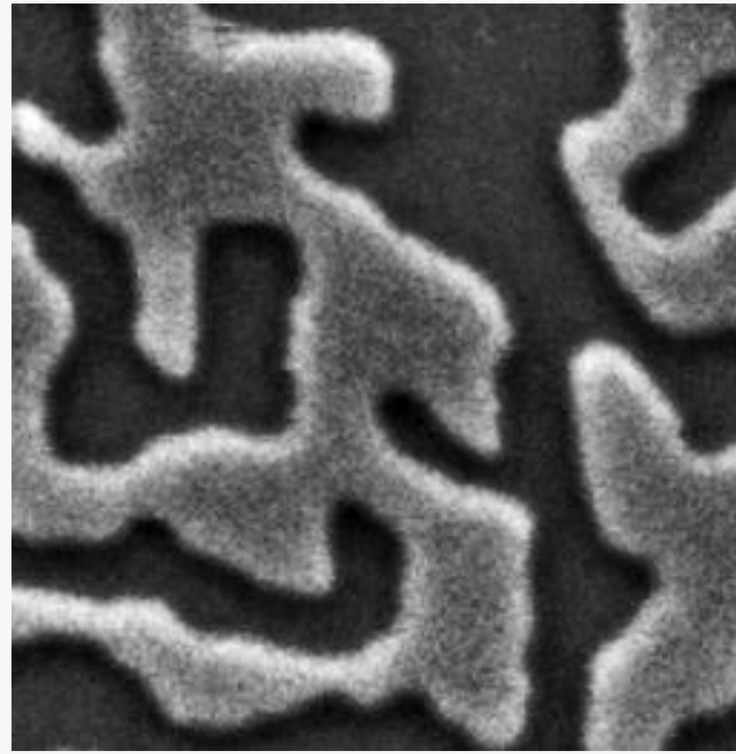
Test sample : FePt[4nm]. Perpendicular magnetization, narrow domain walls



$2x2\ \mu m$

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

Commercial “low-moment” tip

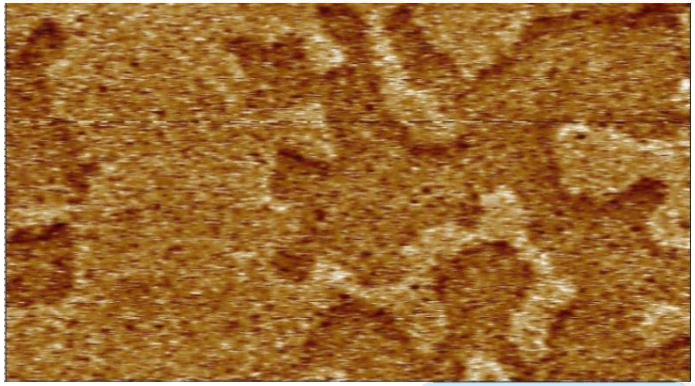


- Spatial resolution: 15-20nm

TIPS. Skyrmions and bubbles in <1nm films

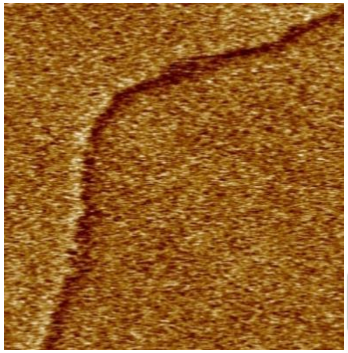
Specific aspects

- Require low stray field tips
- Low stray fields and low film thickness -> Sensitivity?



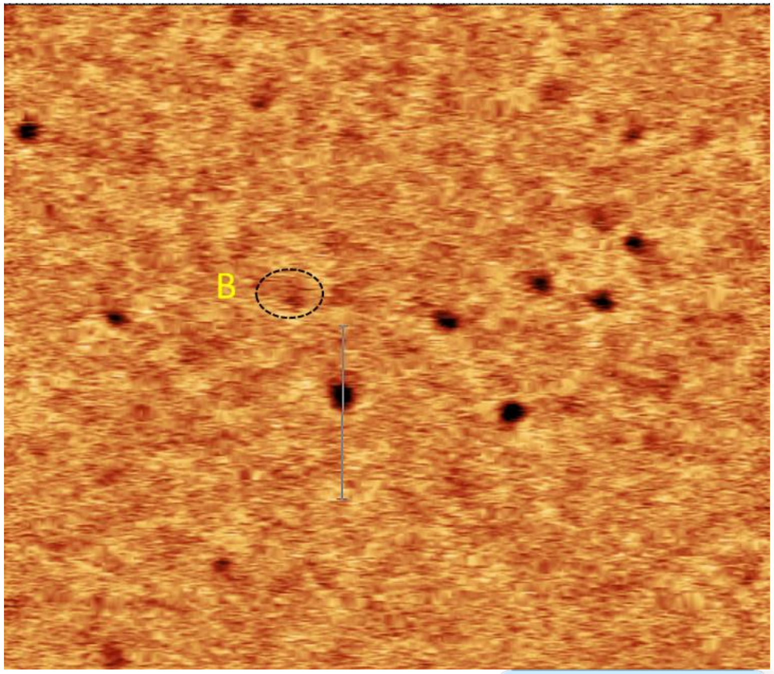
Sample: R. Juge

5x2.8 µm



Imaging: K. Richter

1.2x1.2 µm



Imaging: G. Rana

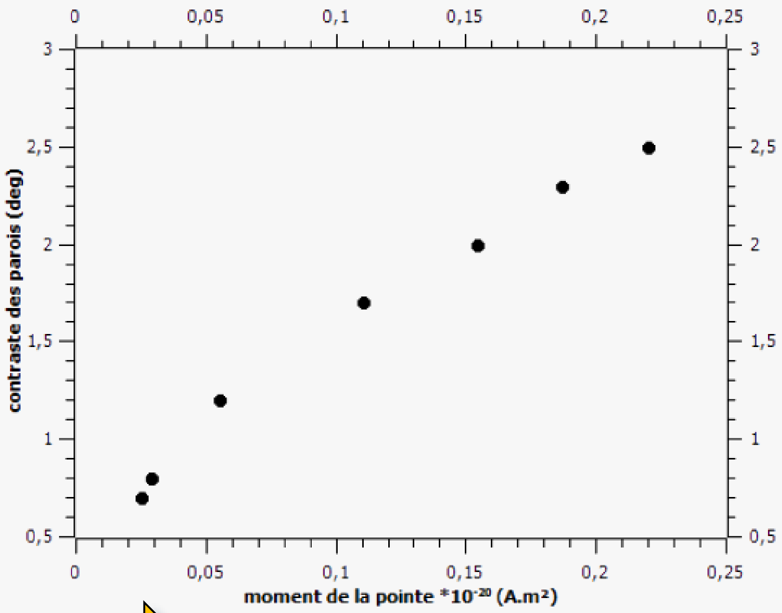
3x2.5 µm

Conclusion

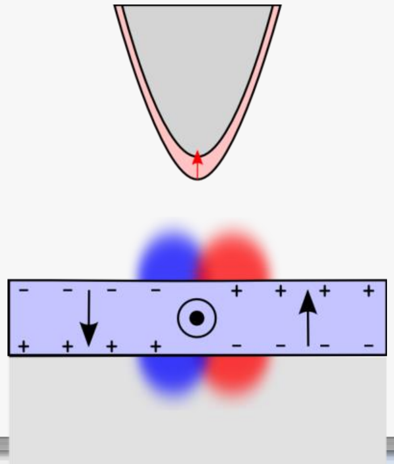
- Remains measurable
- Mutual contrast nearly absent

TIPS. Towards quantitative imaging

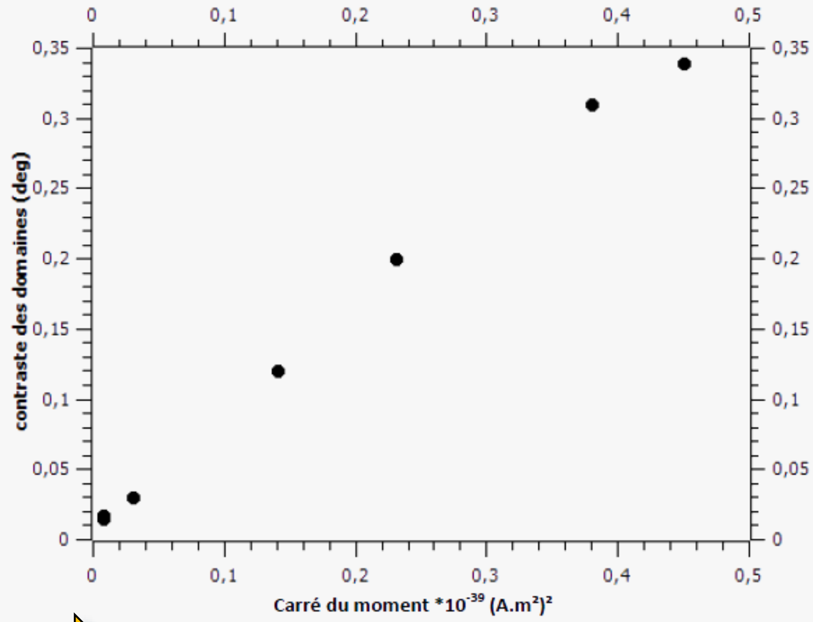
Domain-wall contrast



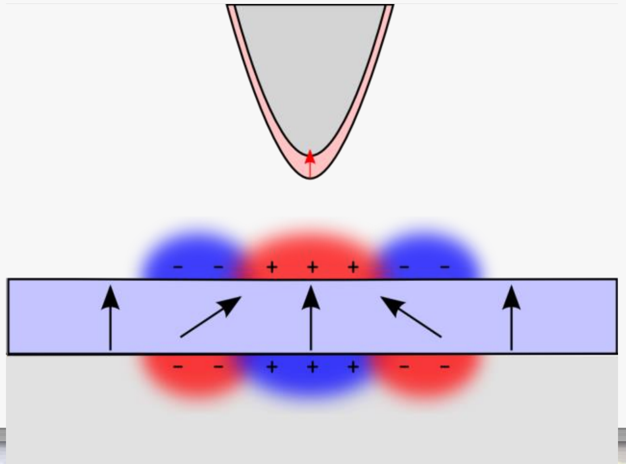
Linear with tip moment



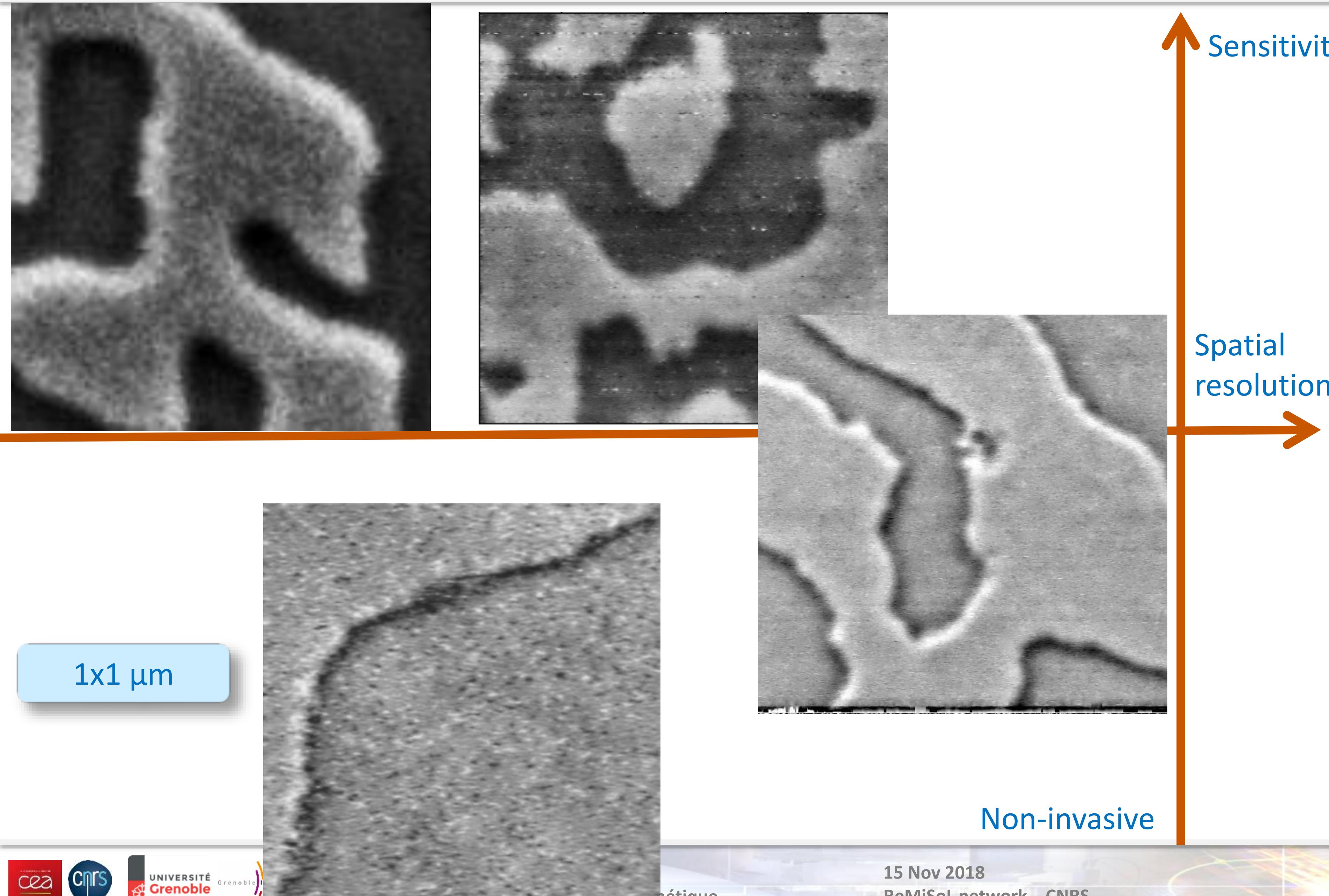
Domain contrast



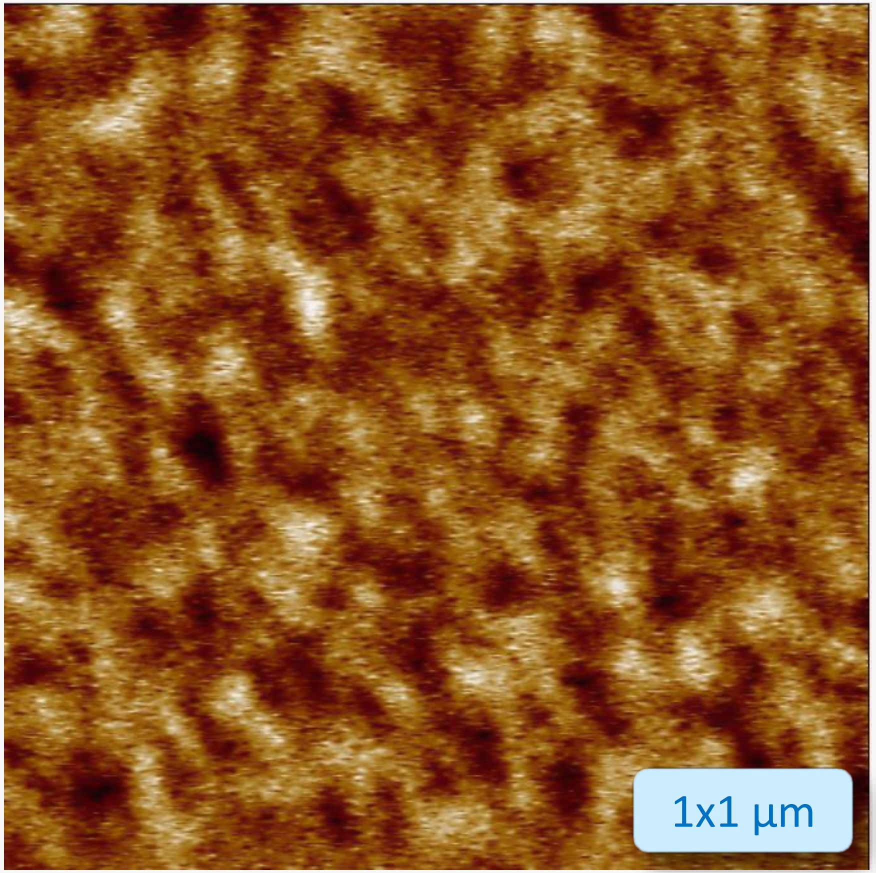
Linear with square of tip moment



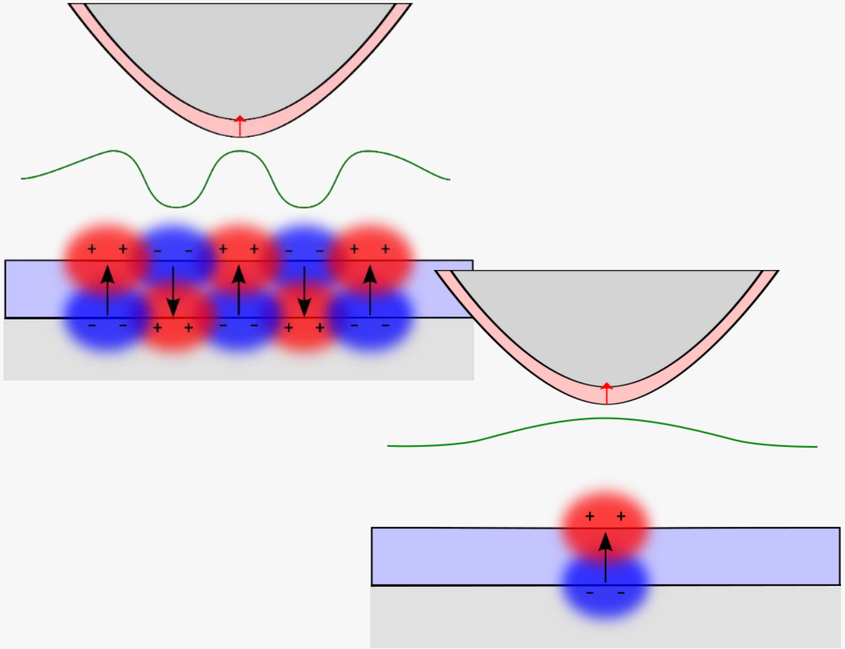
TIPS. Both resolution and sensitivity matter



NOT the smallest feature on an image



FePt-C recording media

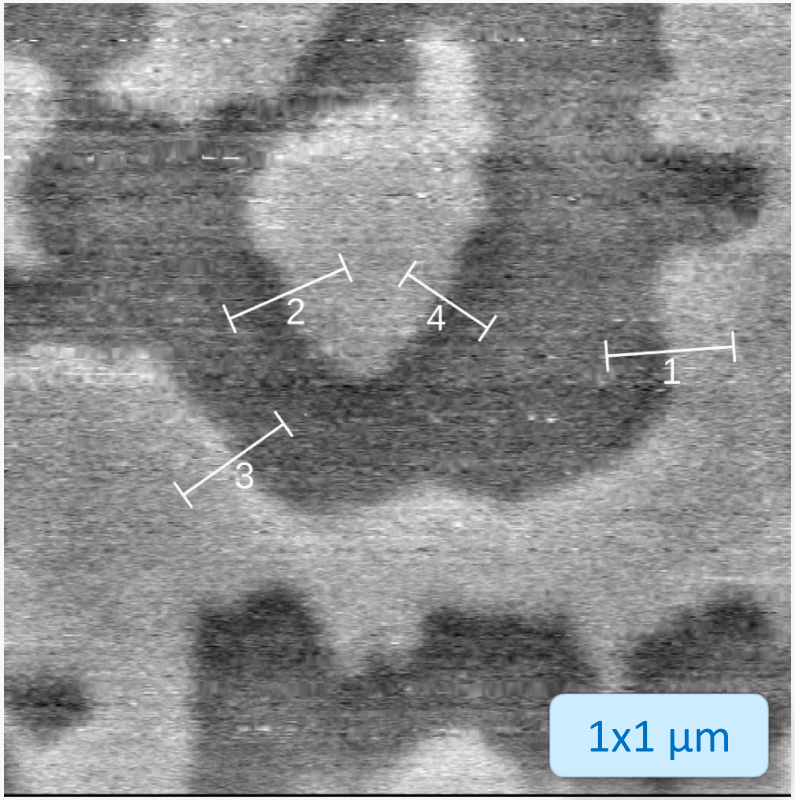


- Small scale modulation
- Reduced magnitude
- A single object would appear larger

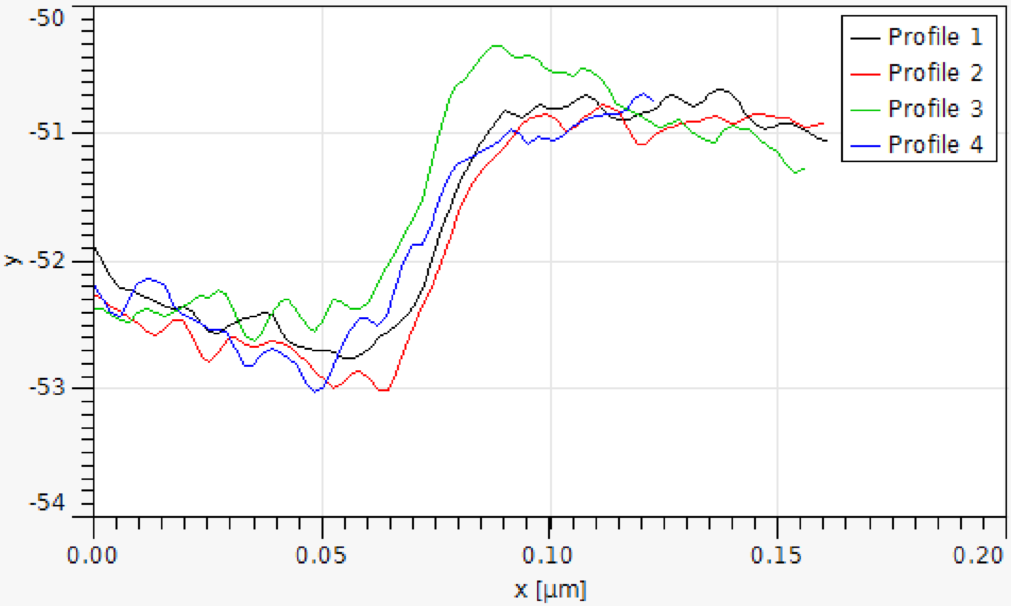
D. Diény et al., IEEE Trans. Mag., in print (2018)

TIPS. Define spatial resolution

Use isolated well-defined magnetic pattern



FePt, epitaxial (4nm)

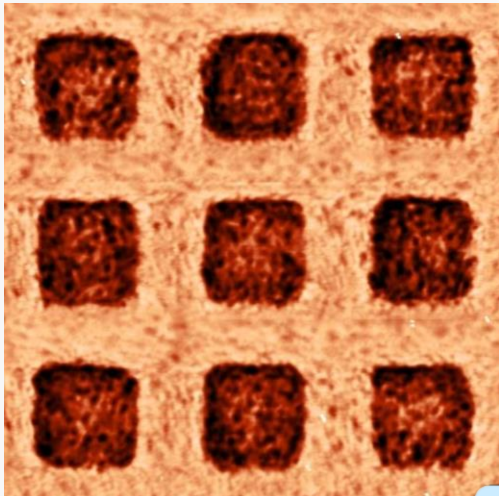


- Definition-dependent: FWHM, variance, 85% etc.
- Make statistics: object, orientation etc.
- Here: around 20nm
- Advanced: modeling, deconvolution

Quantitative analysis, see e.g.: H. Hug, J. Appl. Phys. 83, 5609 (1998) and followers

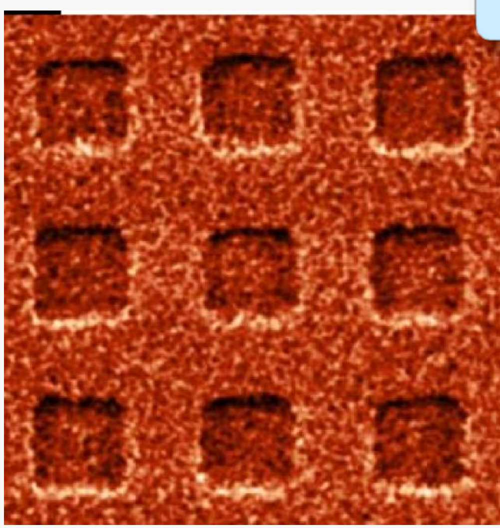
TIPS. Hard magnetic materials

May require hard tip coating



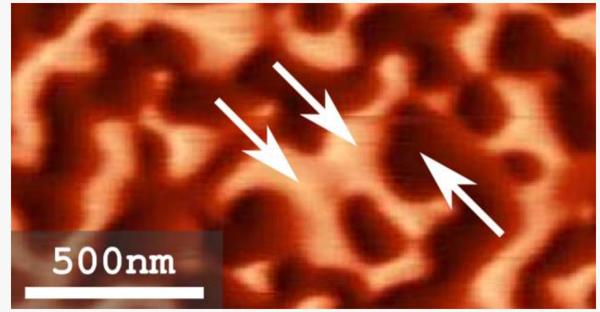
Soft coating

50x50 µm

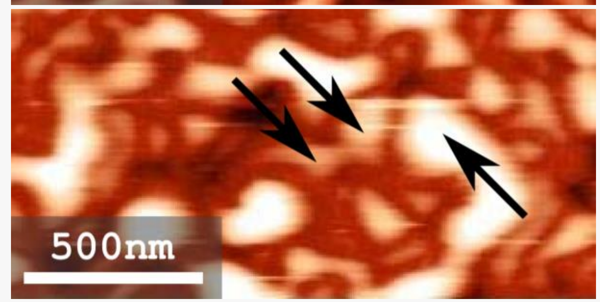


Hard coating

May require stiff cantilevers



MFM



Topography (artefacts)

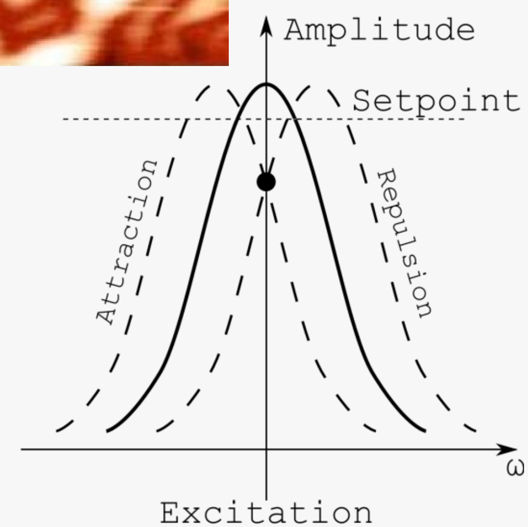
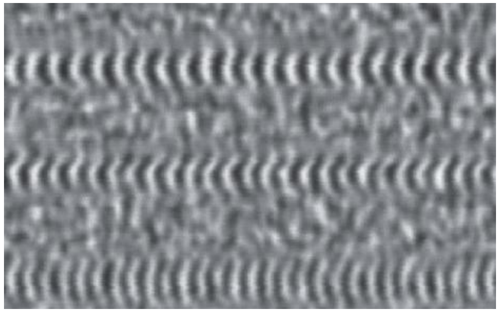
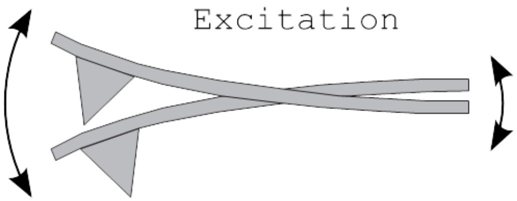


TABLE OF CONTENTS

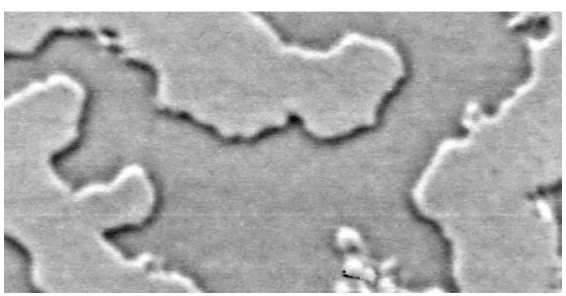
- Motivation and criteria



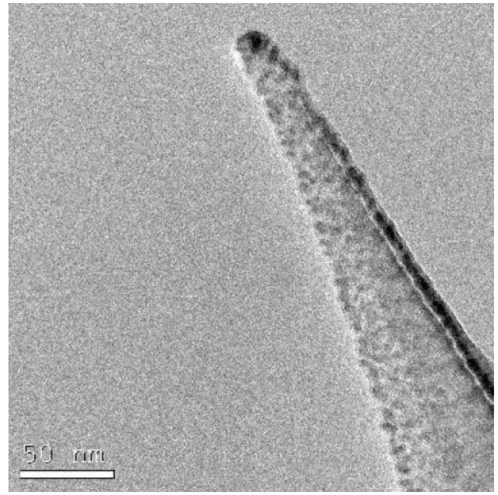
- Working principle



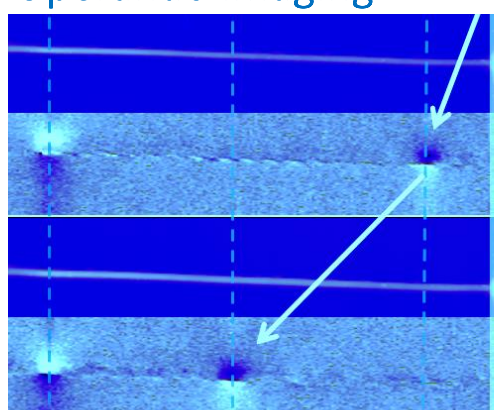
- Image analysis



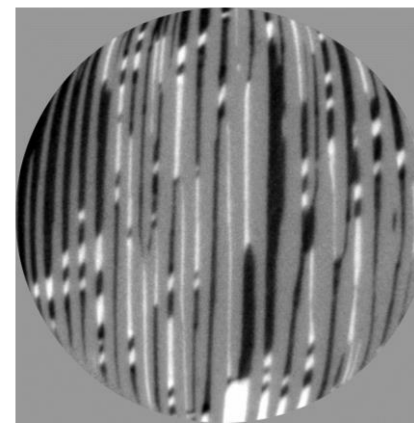
- Choice of tips



- Operando imaging

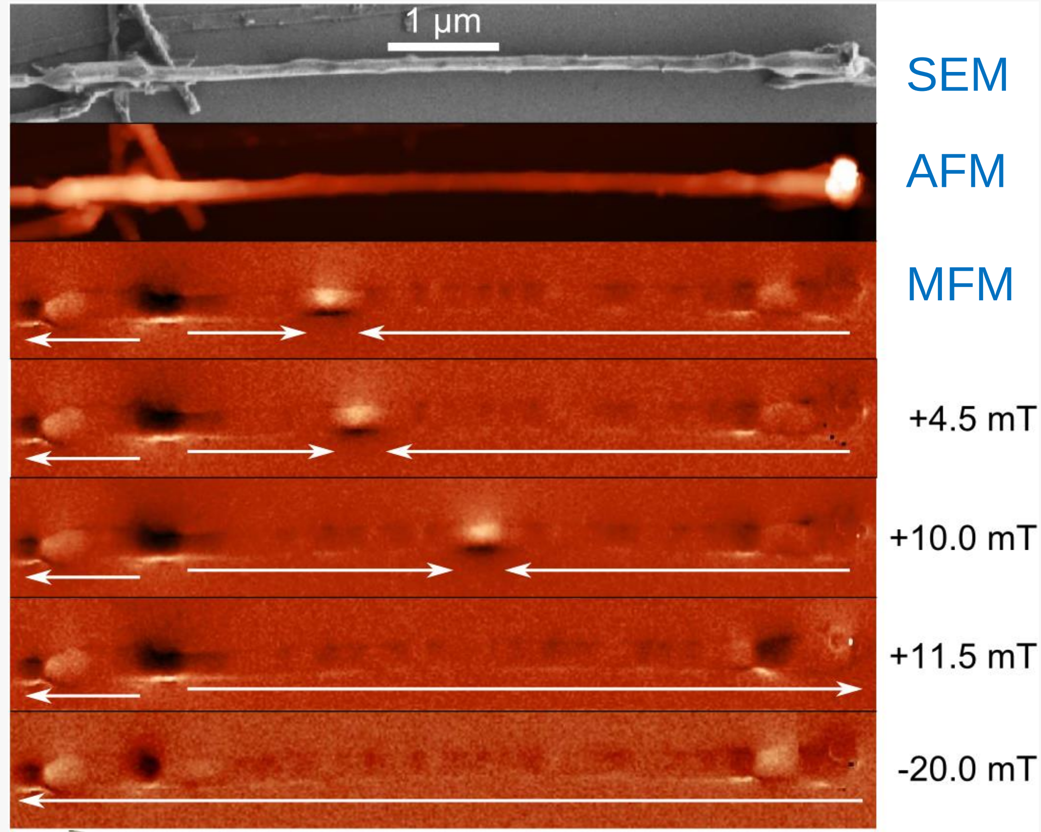


- Panorama of other microscopies



OPERANDO. In-plane field

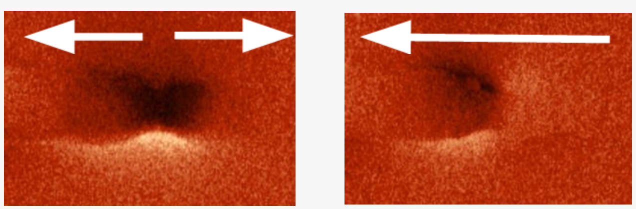
Domain wall motion



S. Da-Col et al., APL109, 062406 (2016)

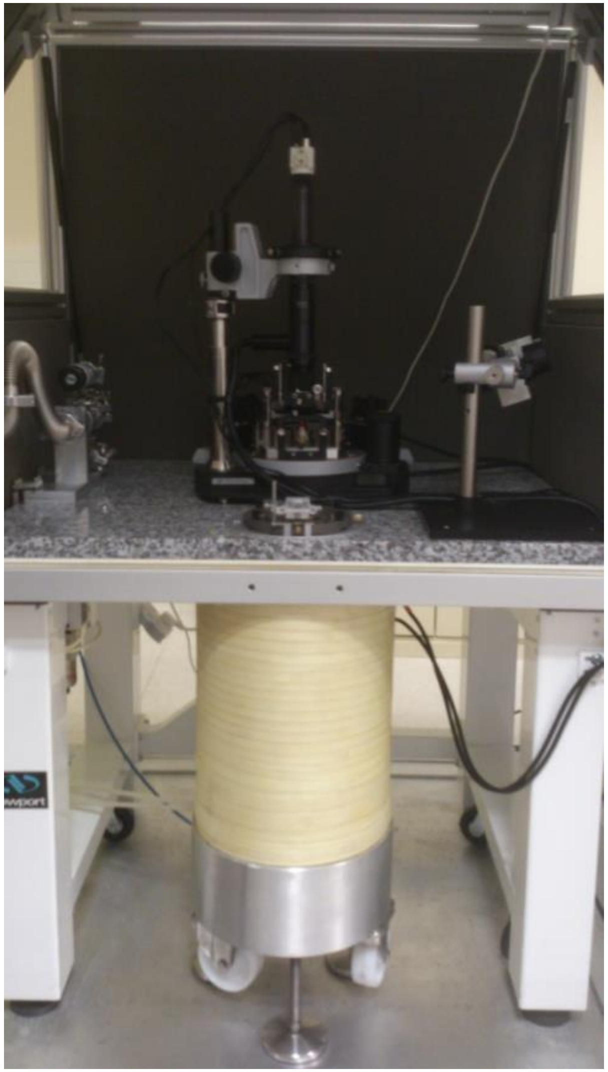
- Imaging under field
- Magnetization processes

Protrusions and constrictions

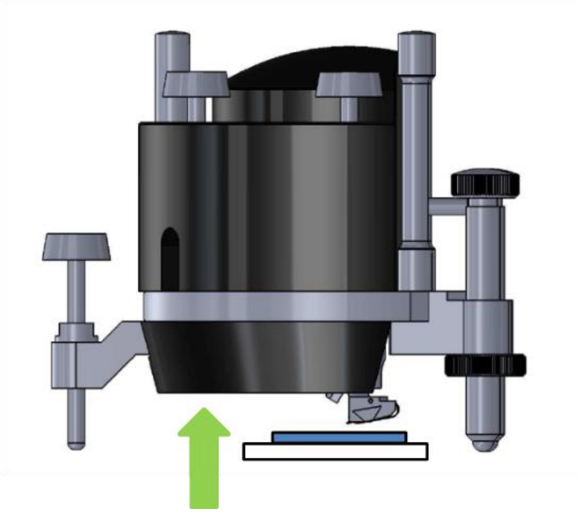


➡ Pinning field ~30mT

OPERANDO. Out-of-plane field

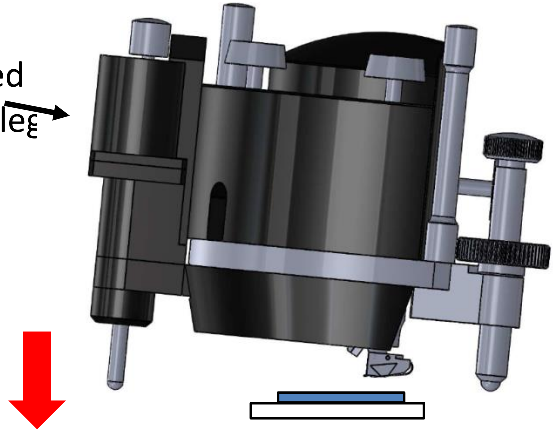


Field >1T (custom-made)
Optimized cooling



Microscope approach
by moving the sample up
(standard configuration)

Motorized
approach leg

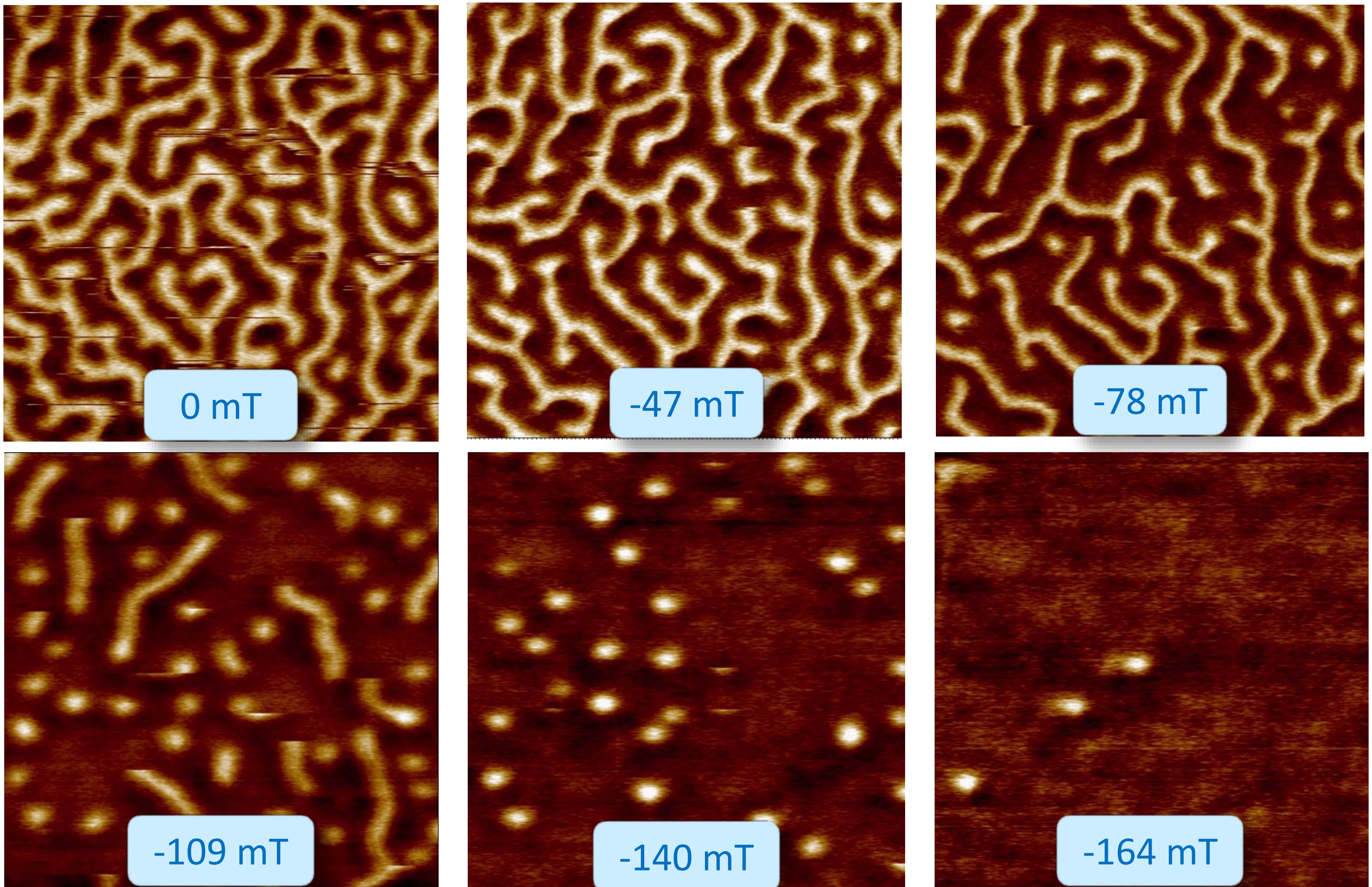


Microscope approach
by tilting the head
thanks to the motorized leg
(coil coupled configuration)

- Approach by head (motorized leg)

OPERANDO. Out-of-plane field

Pd/Co/Au multilayers, 2x2µm

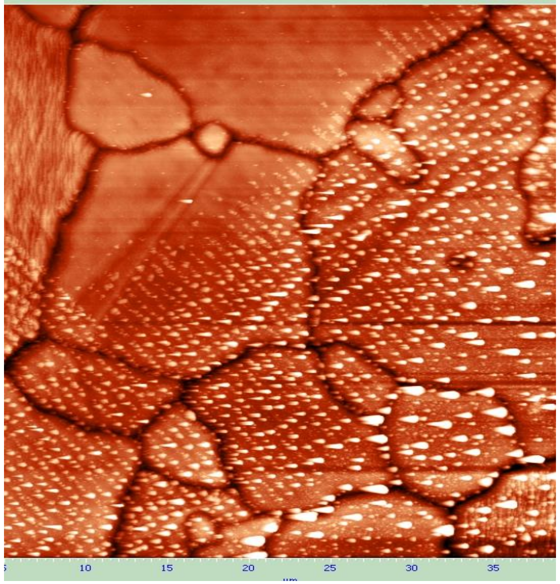


Sample: Chloé Bouard

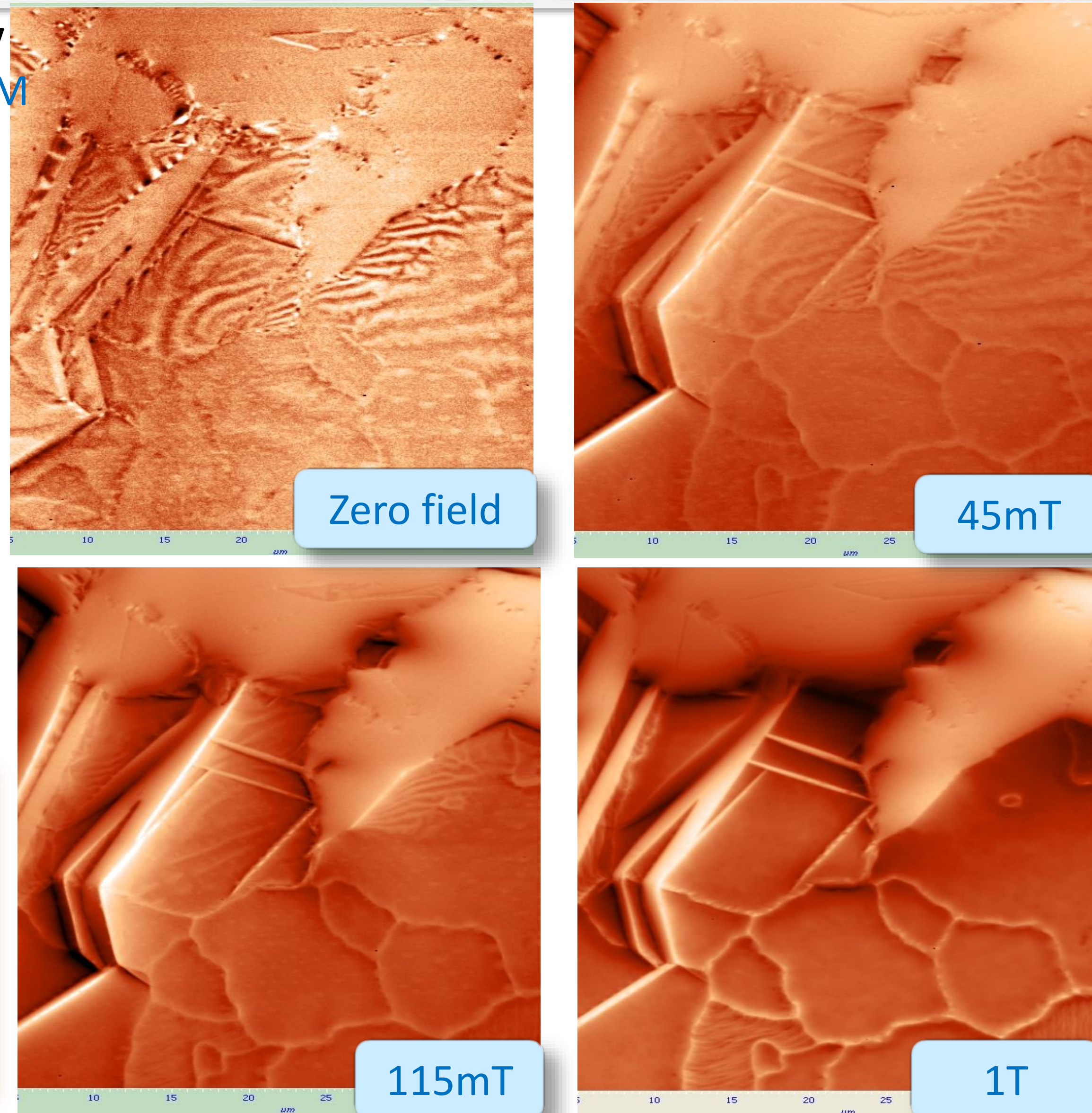
OPERANDO. Out-of-plane field

Magnetic shape-memory alloy

Topography (grains)



MFM

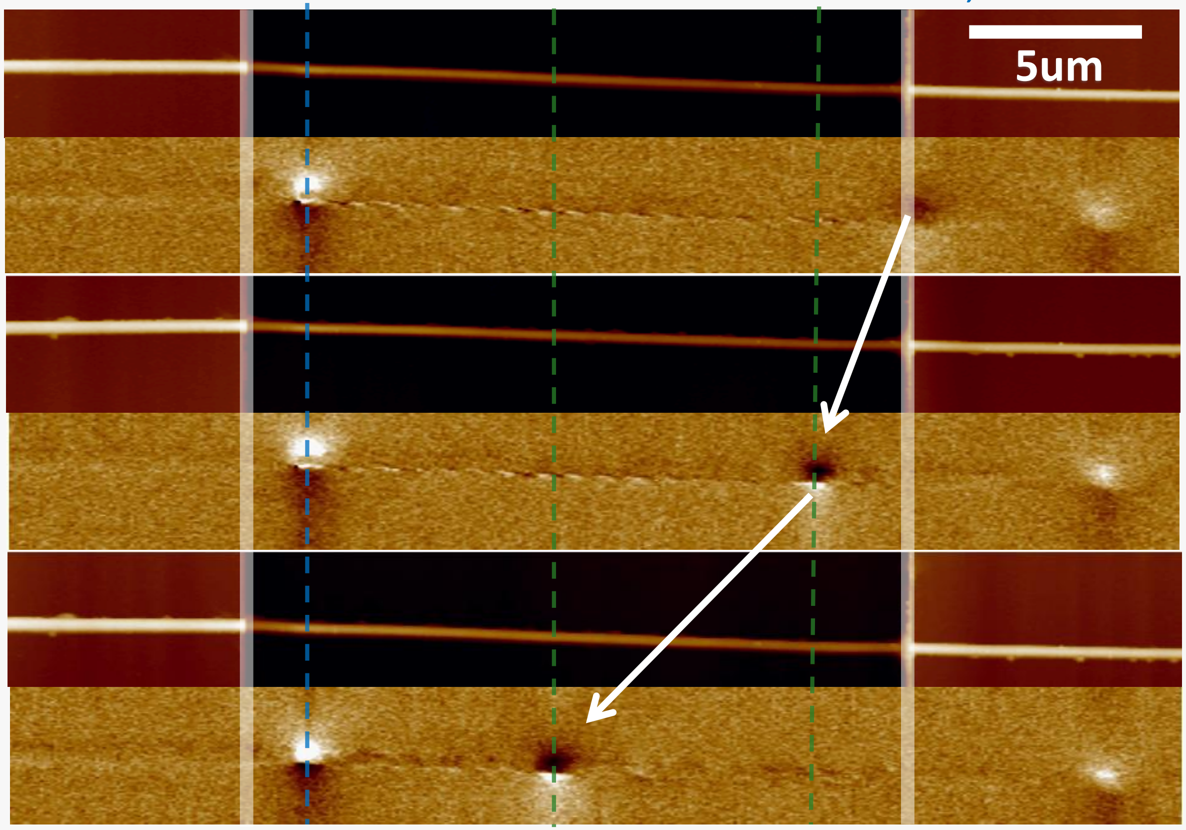


Sample: G. Crouigneau

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

Domain-wall motion

Initial state → Ni, 200nm diameter



$j \simeq 1.5 \cdot 10^{12} \mathrm{A/m^2}$

during 30 ns

$j \simeq 1.5 \cdot 10^{12} \mathrm{A/m^2}$

during 30 ns

-200 100

Phase1, 10^{-3} °

Sample, imaging: Sylvain Martin

M. Schöbitz et al, in preparation

Contributors

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, Gaurav Rana, Kornel Richter, Jérémy Tillier

Tip development

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

Simulations

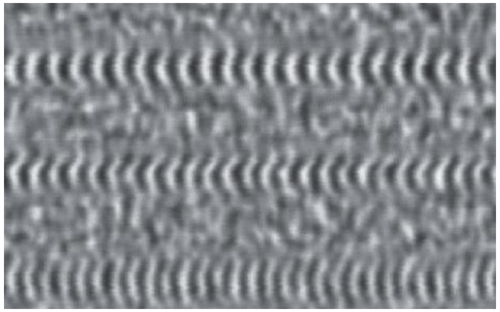
S. Jamet, JC Toussaint

Instrumental development and maintenance

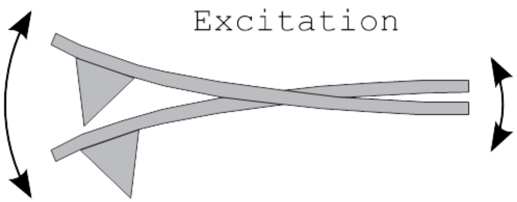
S. Le Denmat, C. Thirion, E. Wagner

TABLE OF CONTENTS

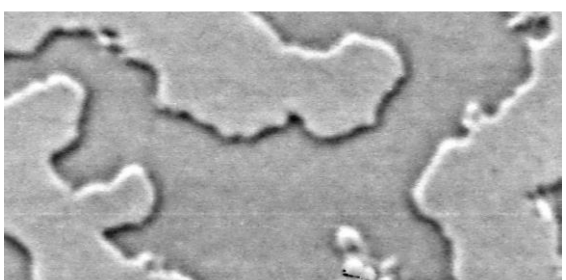
- Motivation and criteria



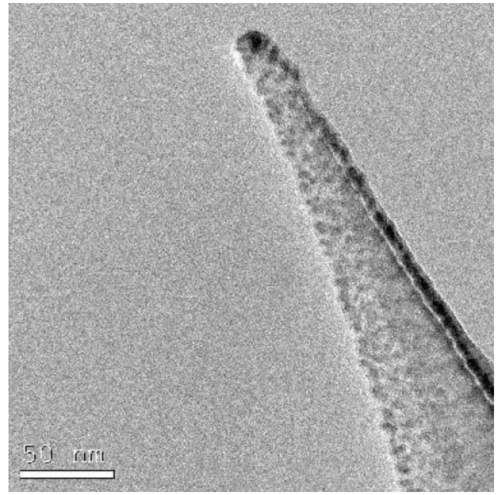
- Working principle



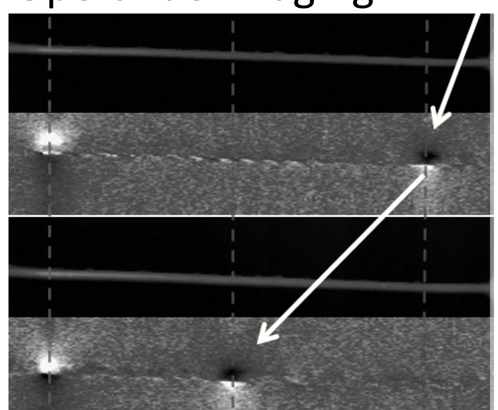
- Image analysis



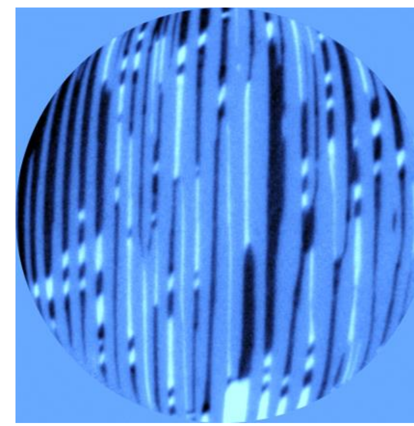
- Choice of tips



- Operando imaging



- Panorama of other microscopies



MOTIVATION / Practical considerations

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 ?

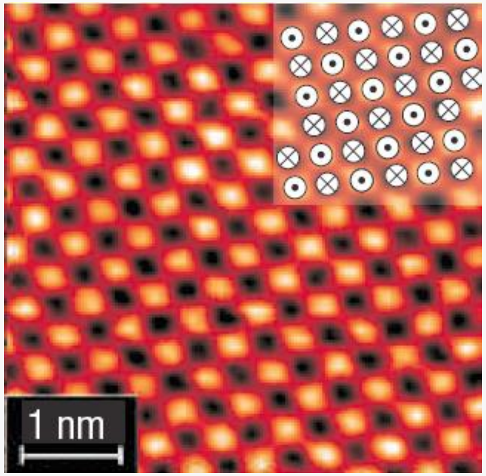
Access
- Large-scale instrument or in-lab ?
- Expensive or cheap ?

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

- No universal technique
- Many criteria to be balanced

Spin-polarized STM

Fe(1ML)/W(001)

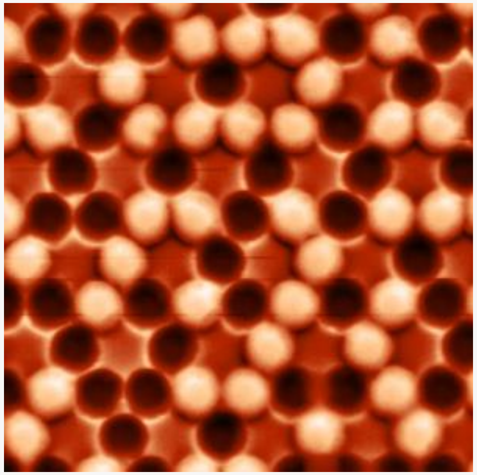


Antiferromagnetic domain

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

Magn. Force Microscopy

Array of dots

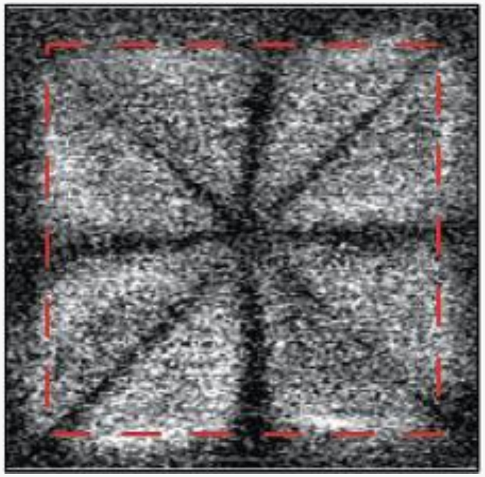


Up-and-down 'single-domains'

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

NV center microscopy

Square Fe20Ni80 dot



Signature of flux-closure

L. Rondin et al., Nat. Comm. 4, 2279 (2013)

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

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

Overview

- Large variety
- Rather slow

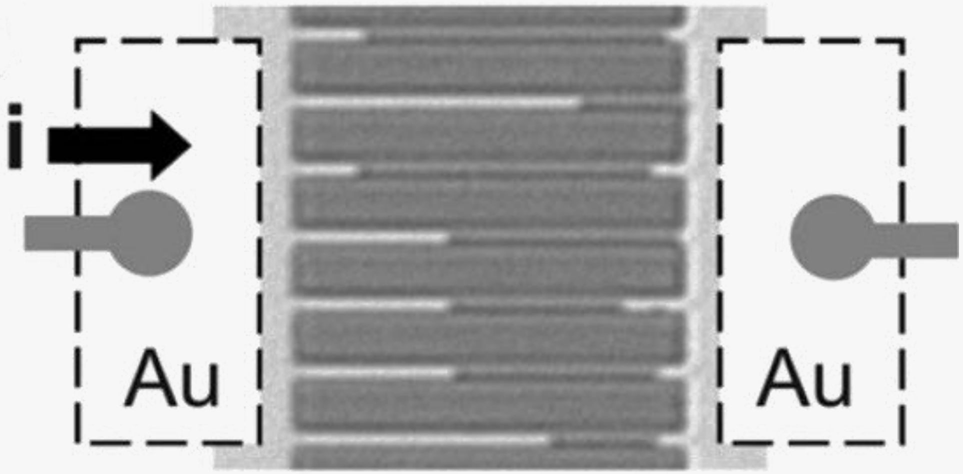
Others : scanning Hall probe, near-field optical etc.

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

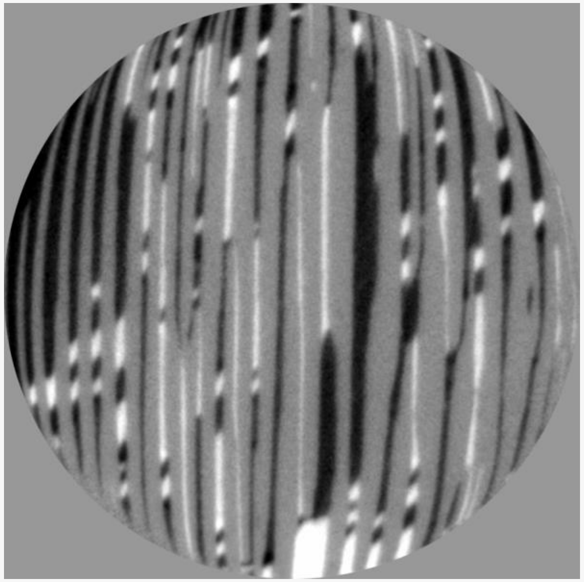


T. A. Moore et al., Appl. Phys. Lett 93, 262504 (2008)

Overview

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

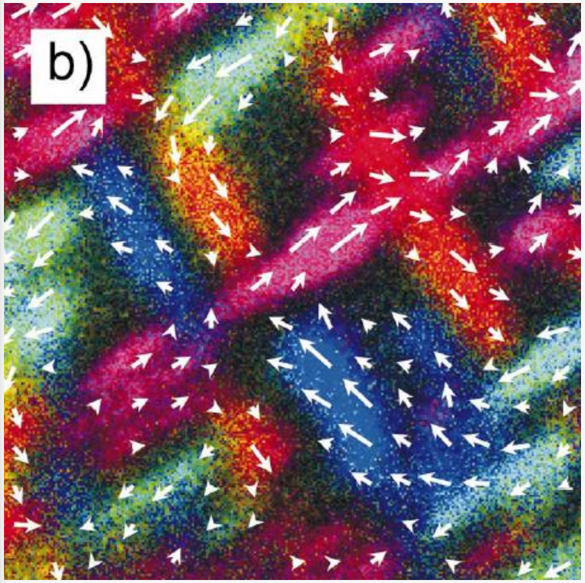
SPLEEM
Spin-Polarized Low Energy Electron Microscopy



Stripes of Fe/W(110)

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

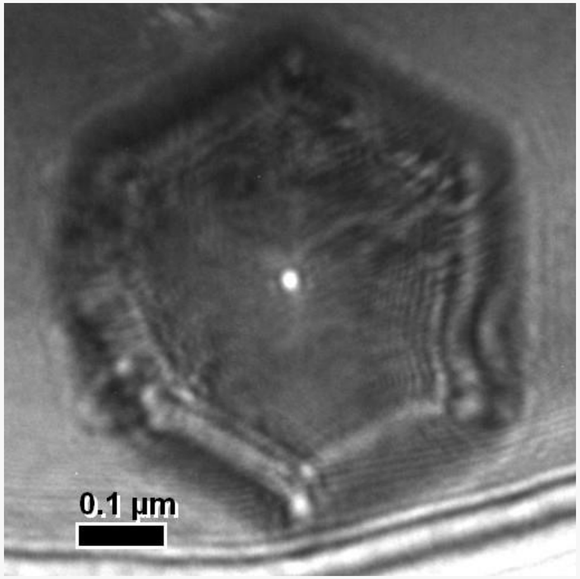
SEMPA
Scanning Electron Microsc. with Polarization Analysis



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



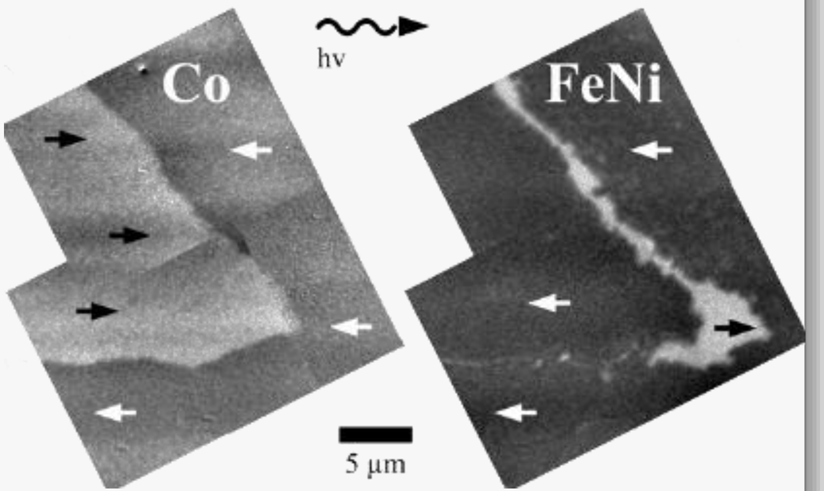
Self-assembled Co/W(110)

O. Fruchart et al., J. Phys. Condens. Matter 25, 496002 (2013)

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

XMCD-PEEM

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

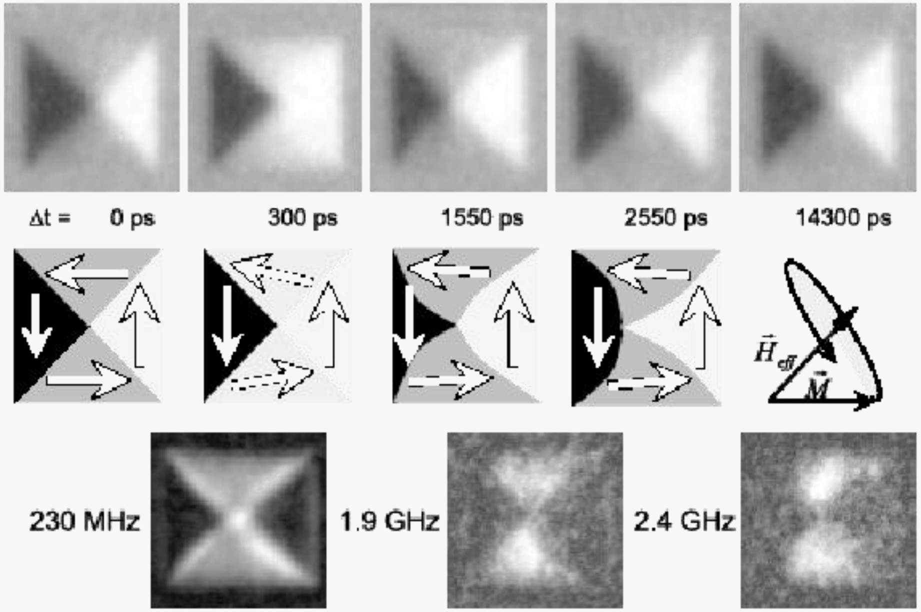


Co\Cu\FeNi trilayer
→ elemental resolution

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

TXM

Transmission X-ray Microscopy



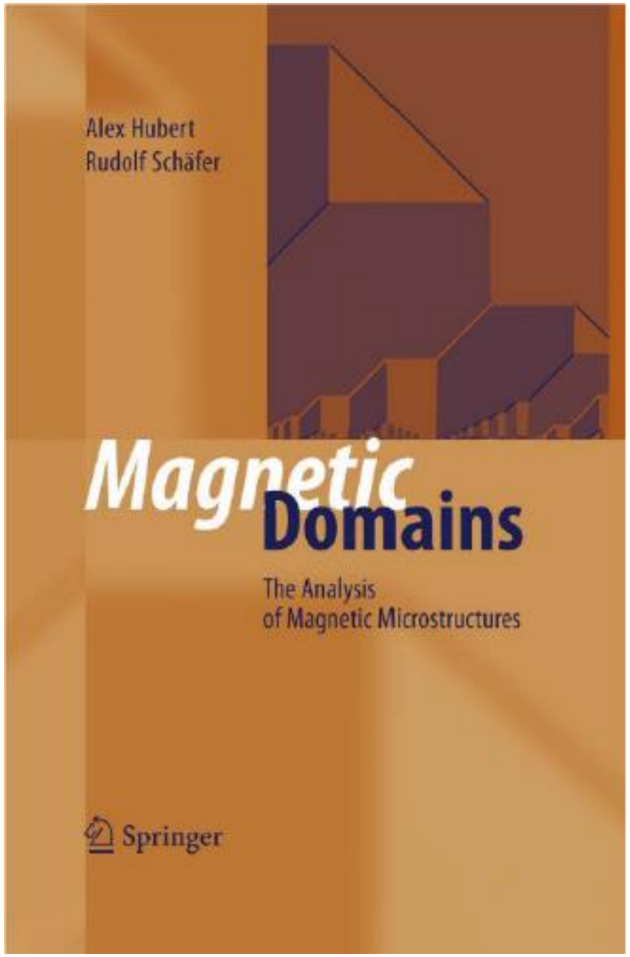
FeNi 6µm square dot → time resolution

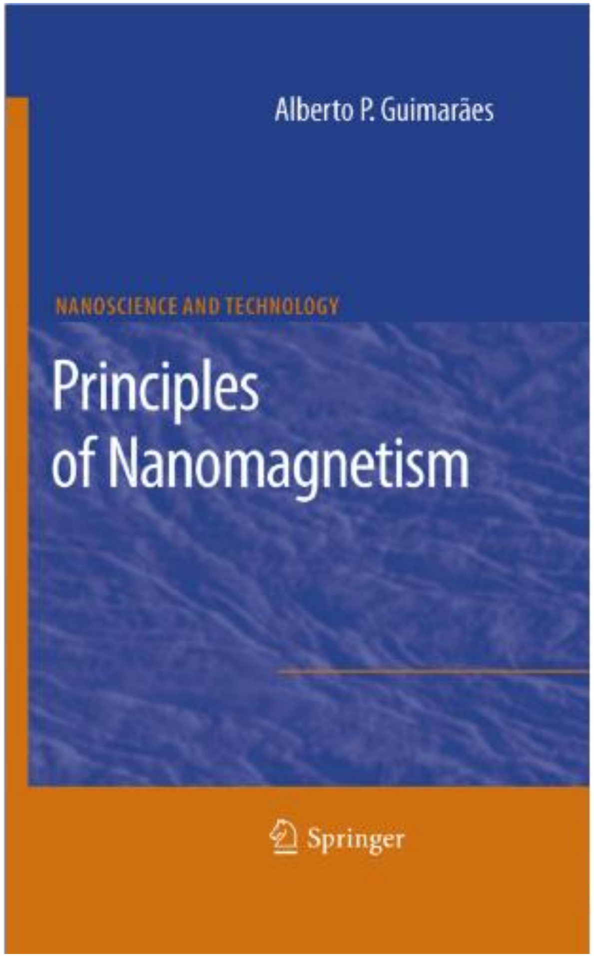
J. Raabe et al., Phys. Rev. Lett. 94, 217204 (2005)

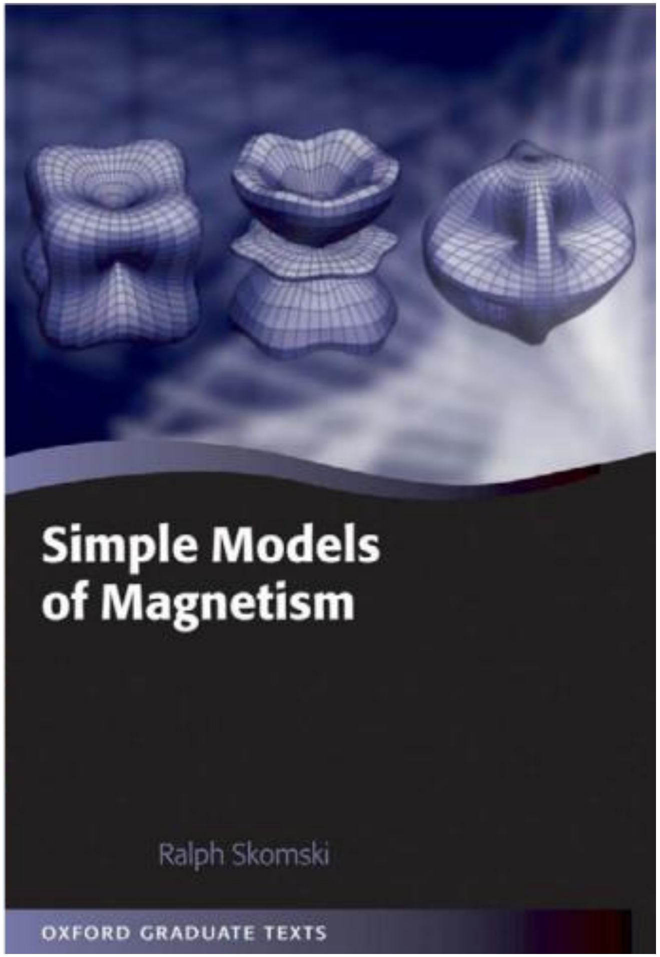
Others : holography, scattering

- Elemental sensitivity
- Compatible with time resolution
- Rather versatile

Books | Nanomagnetism







Thank you for your attention !

www.spintec.fr

e-mail: olivier.fruchart@cea.fr

http://fruchart.eu/slides