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Measurements using magnetic force microscopy

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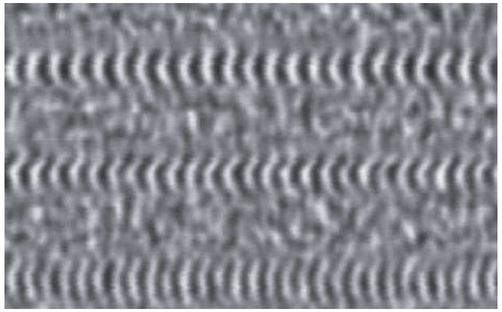
NEEL
DOWNTOWN
LYON

- Motivation and criteria



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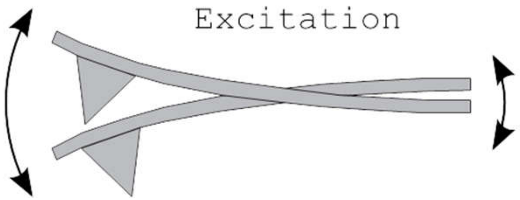
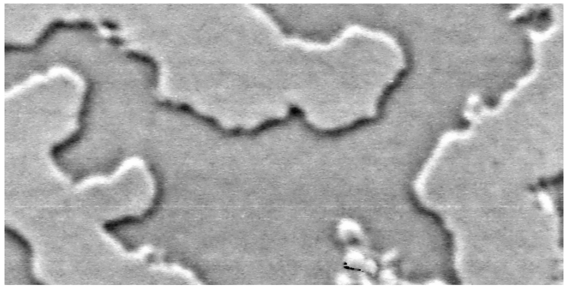


- Image analysis



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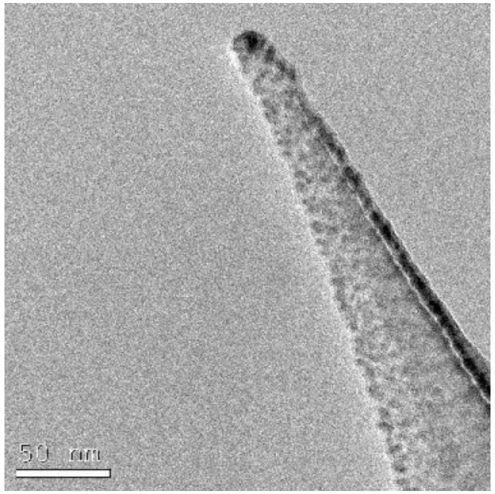

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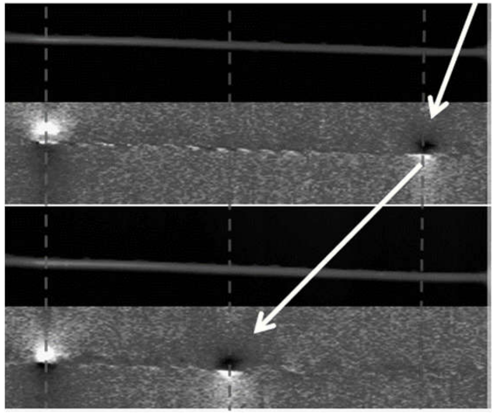

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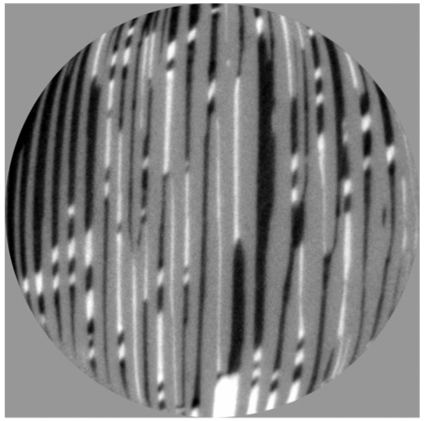

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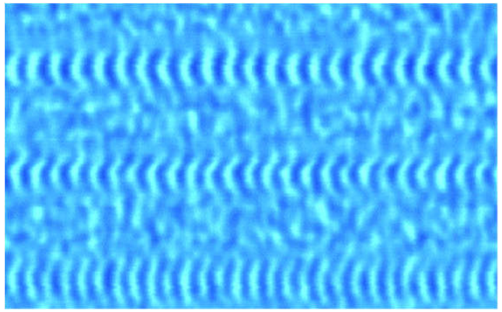

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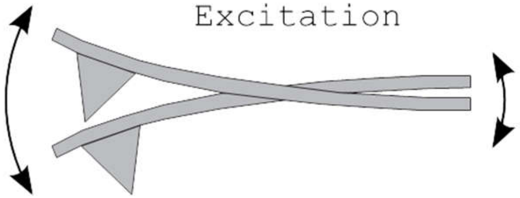

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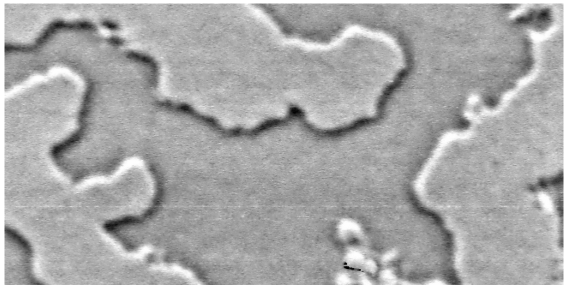

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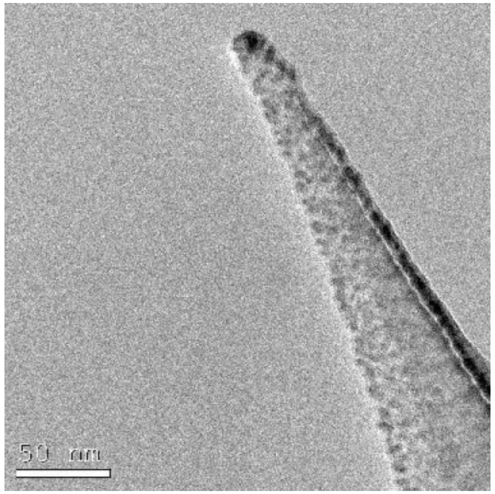

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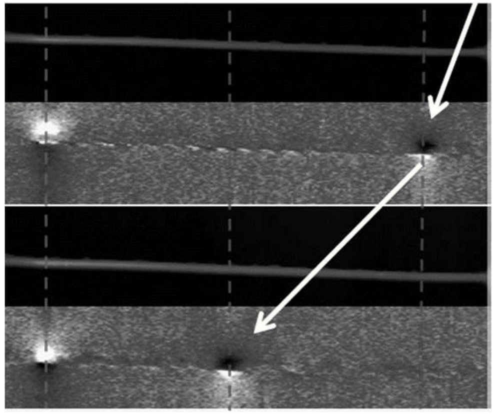

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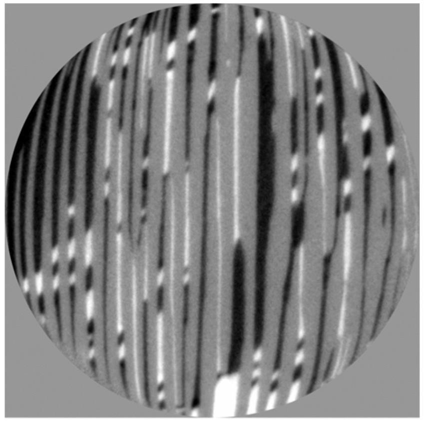
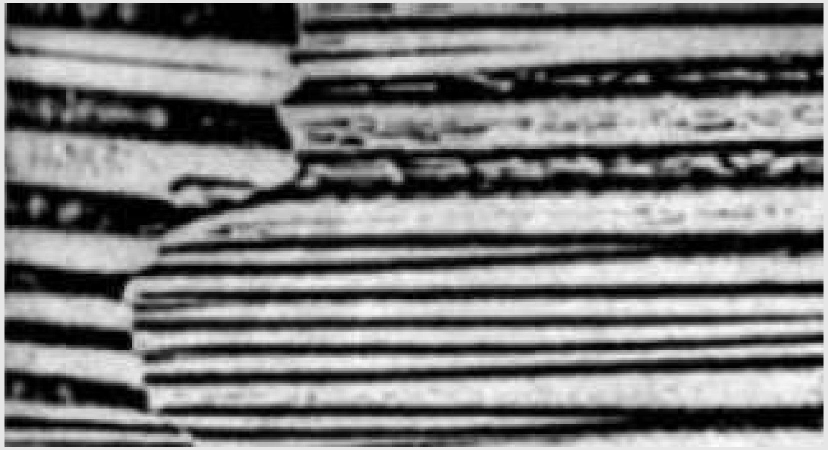


Magnetic domains

Numerous and complex magnetic domains



(History : Weiss domains)

Anisotropy exchange length (domain wall width)

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

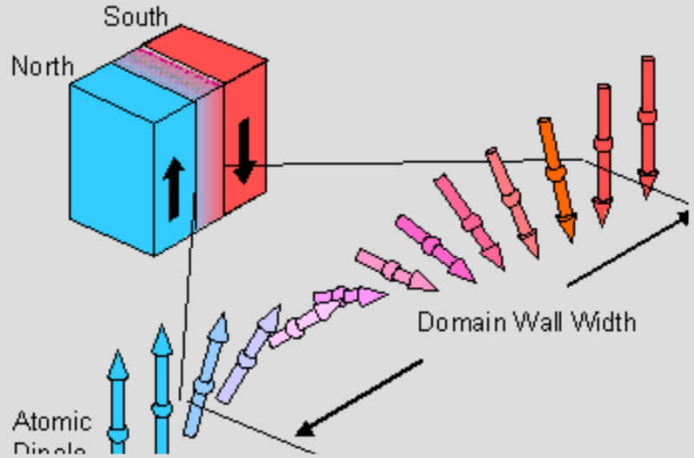
Exchange → J/m

Anisotropy → J/m^3

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

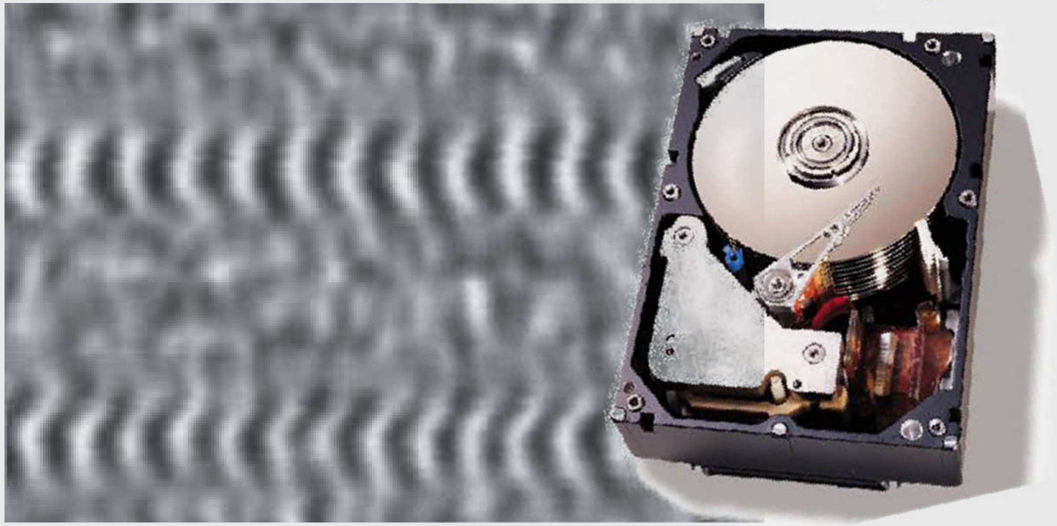
$\Delta_u \approx 1\ nm$ → $\Delta_u \geq 100\ nm$

Hard — Soft



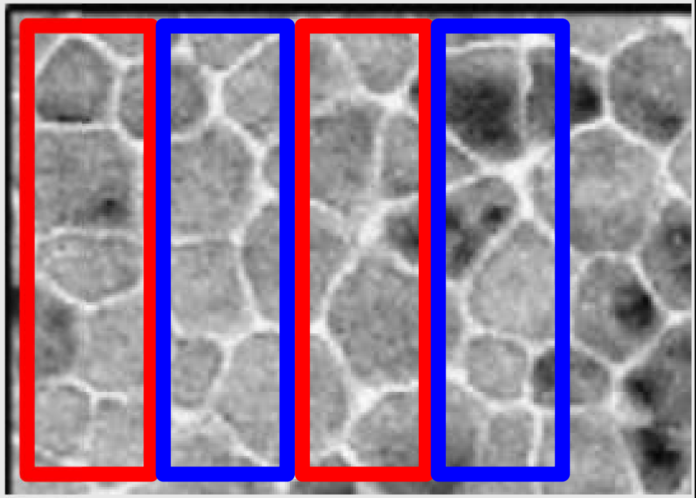
Magnetic bits on Hard Disk Drive

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



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

Underlying microstructure



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

Relevant spatial resolution

➯ 10-100nm

MOTIVATION / Time scale

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:

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

Gyromagnetic factor

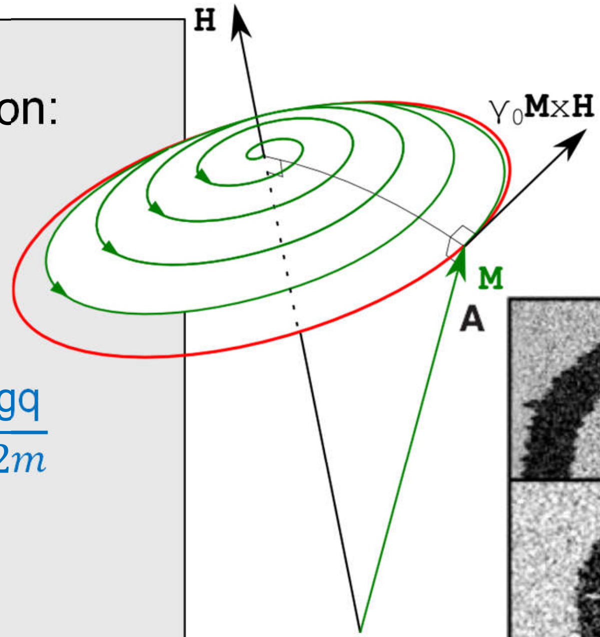
$$\gamma_0 = \mu_0 \gamma \qquad \gamma = \frac{\mathrm{gq}}{2m}$$

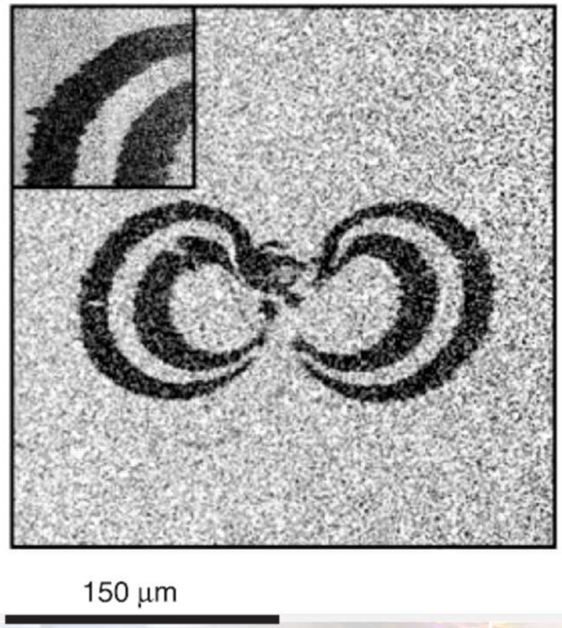
$$\gamma / 2\pi = 28\ \mathrm{GHz/T}$$

H_{eff} Effective field (including applied)

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

Demonstration: 1999

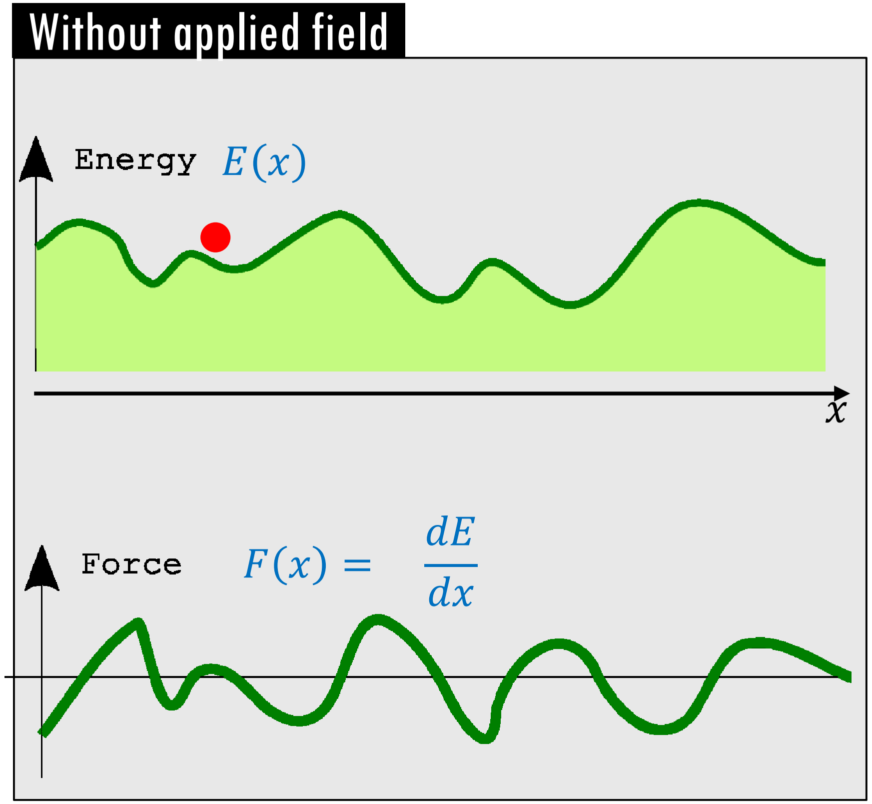


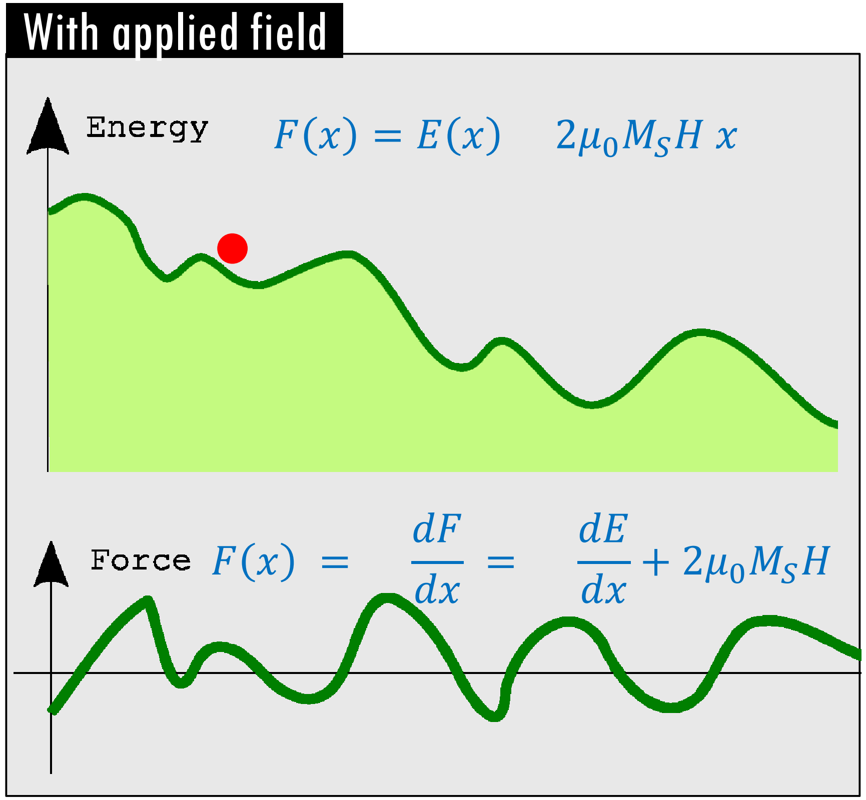


C. Back et al., Science 285, 864 (1999)

MOTIVATION / Link with structure

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





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

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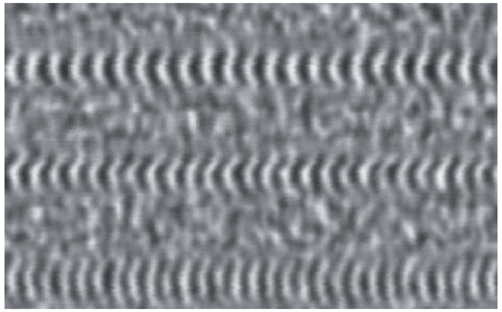

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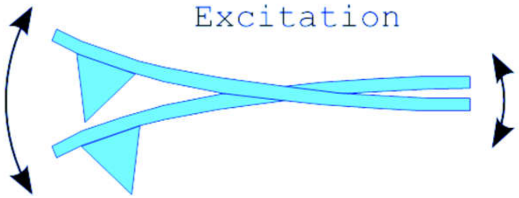

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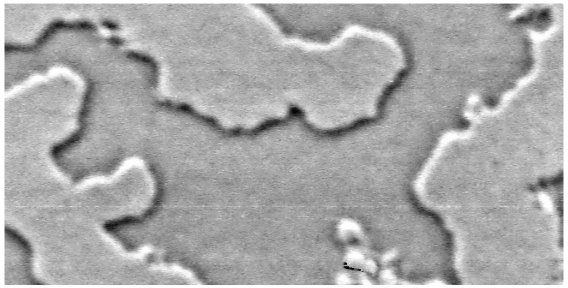

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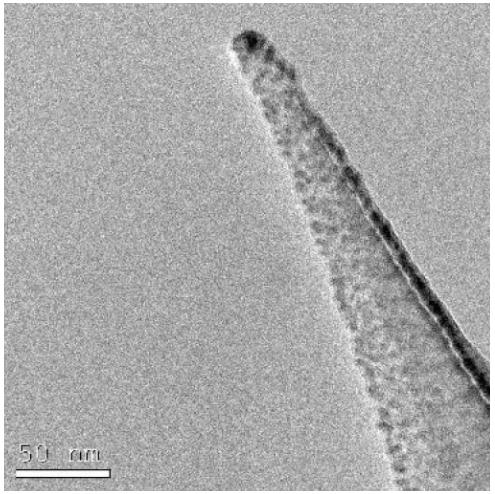

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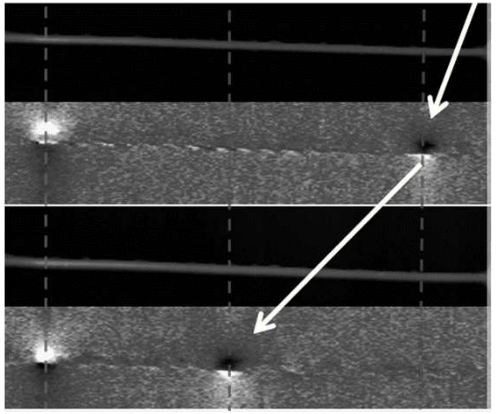

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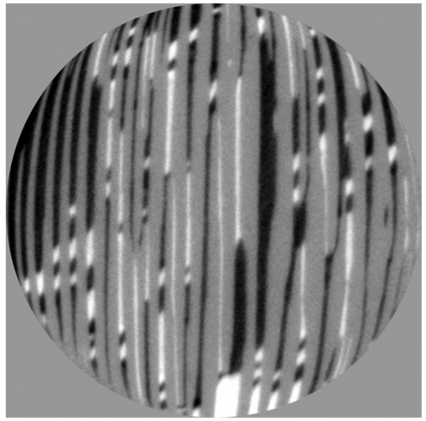
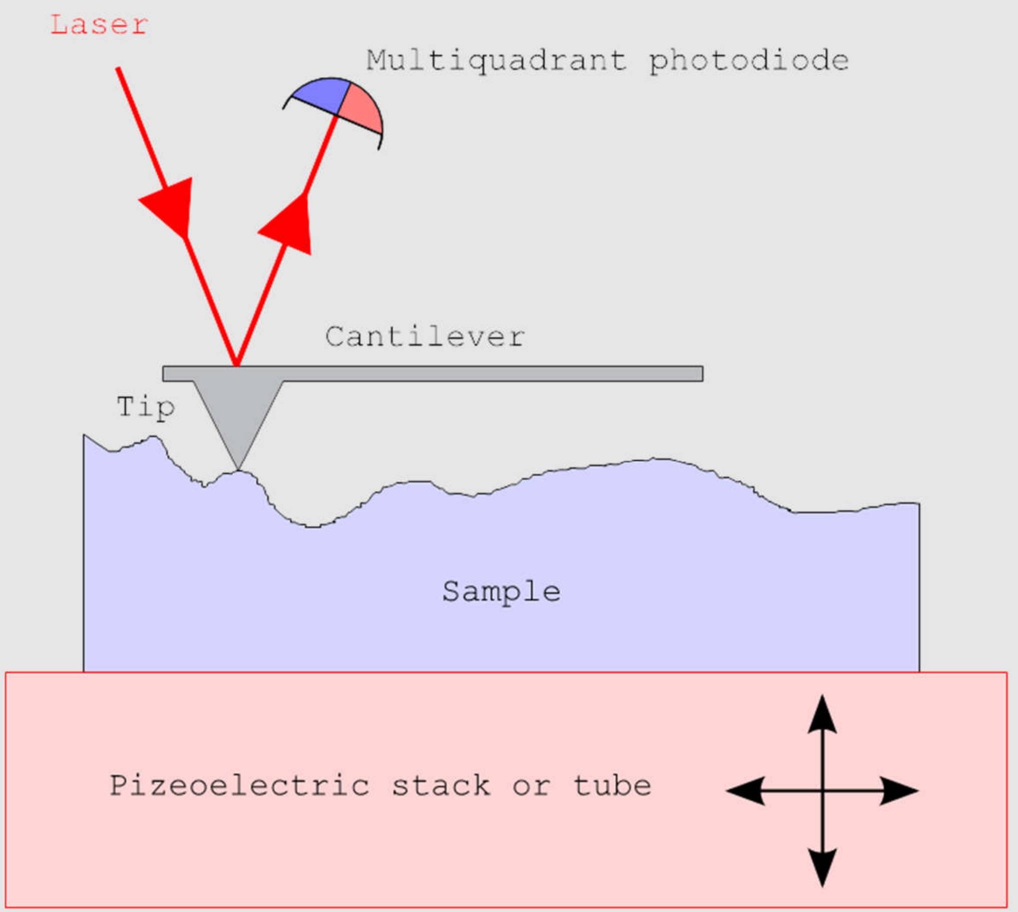


Key elements of an Atomic Force Microscope (AFM)

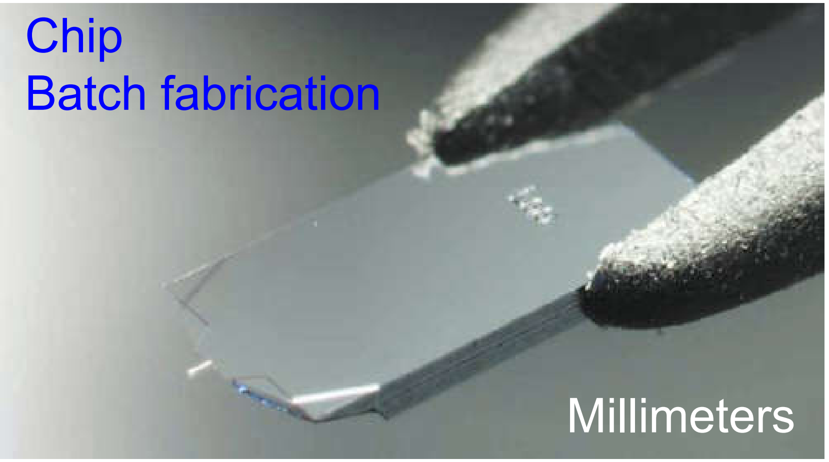


G. Binnig et al., Phys. Rev. Lett. 56, 930-933 (1986)

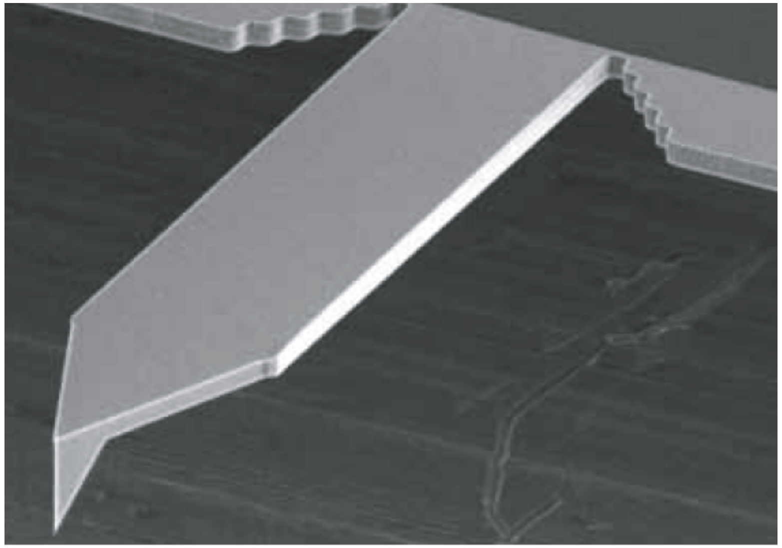
Overview

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

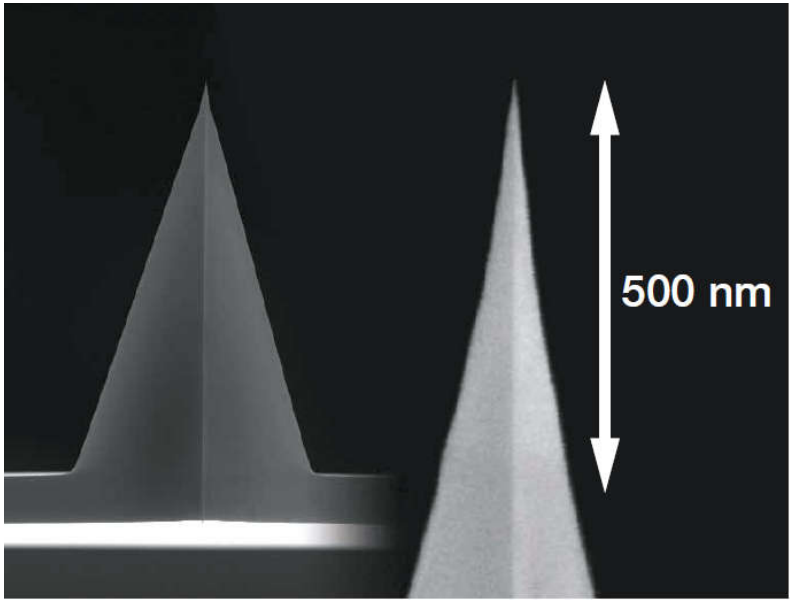
MFM / Conventional cantilevers and tips



Cantilever



Full tip + apex

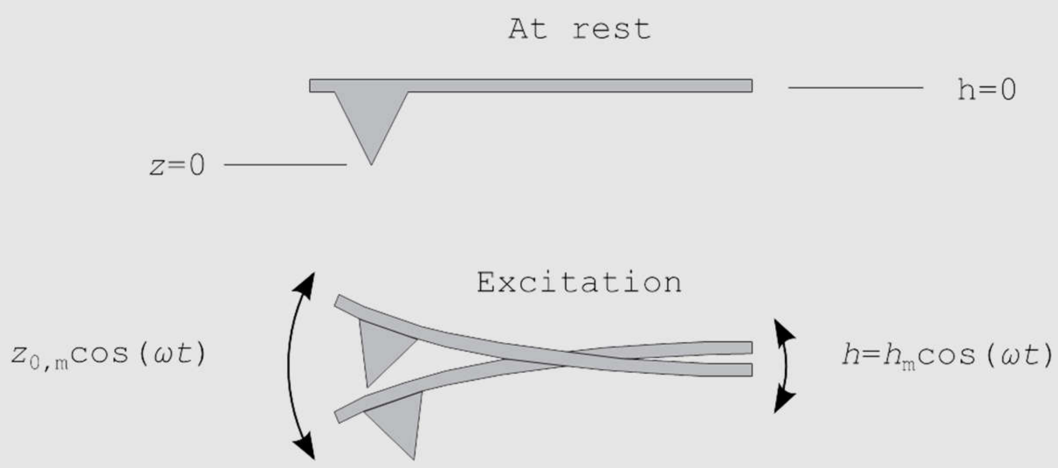


Overview

- 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 $\quad \omega_0=\sqrt{\dfrac{k}{m}}$

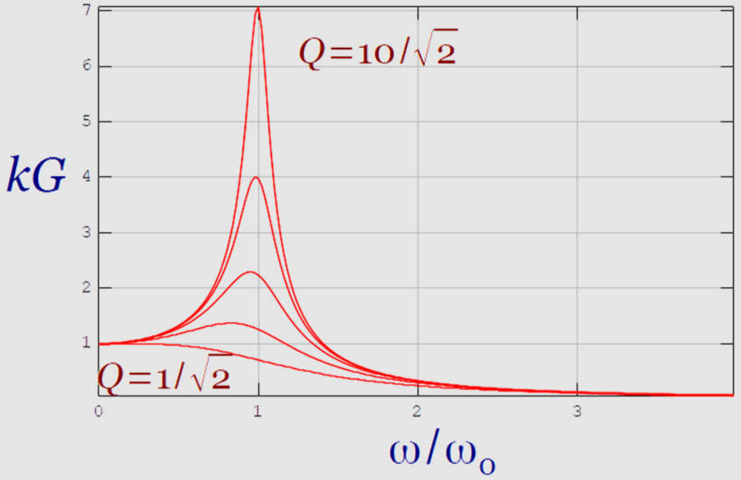
Quality factor $\quad Q=\dfrac{\sqrt{k\,m}}{\Gamma}$

⇨ Transfert function

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

MFM / Solutions for a harmonic oscillator

Gain



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

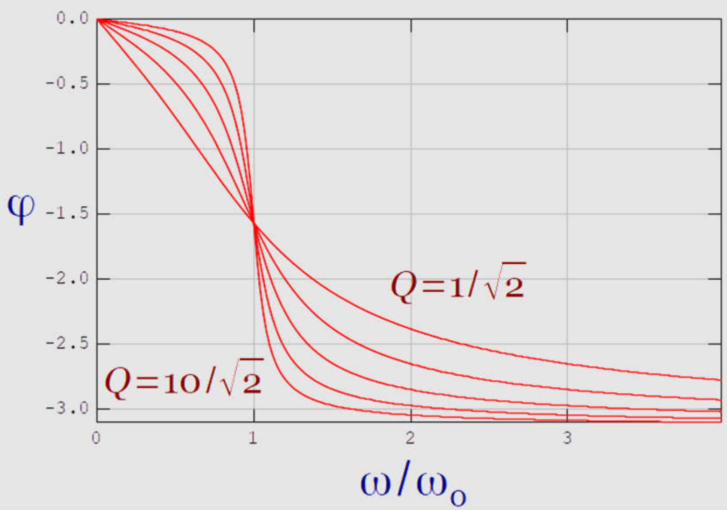
Peak at : $\omega_r=\omega_0\sqrt{1-\frac{1}{2Q^2}}$

$kG(0)=1$

$kG(\omega_r)=Q$

$kG(\infty)=0$

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

$\omega_r\approx\omega_0$

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

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

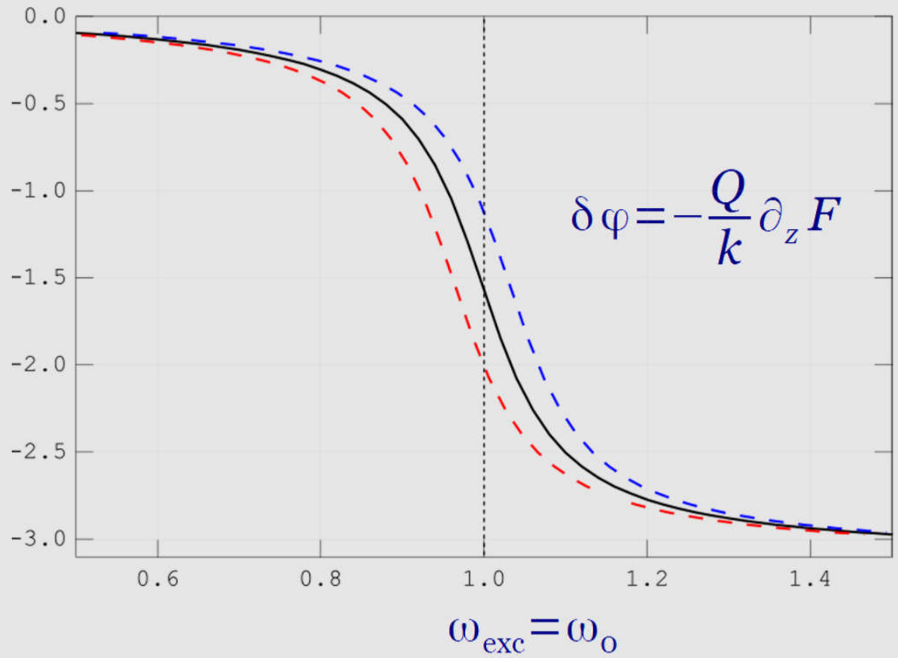
MFM / Detecting forces on the phase shift

Tip-sample interaction treated as perturbation

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

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

Phase shift



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

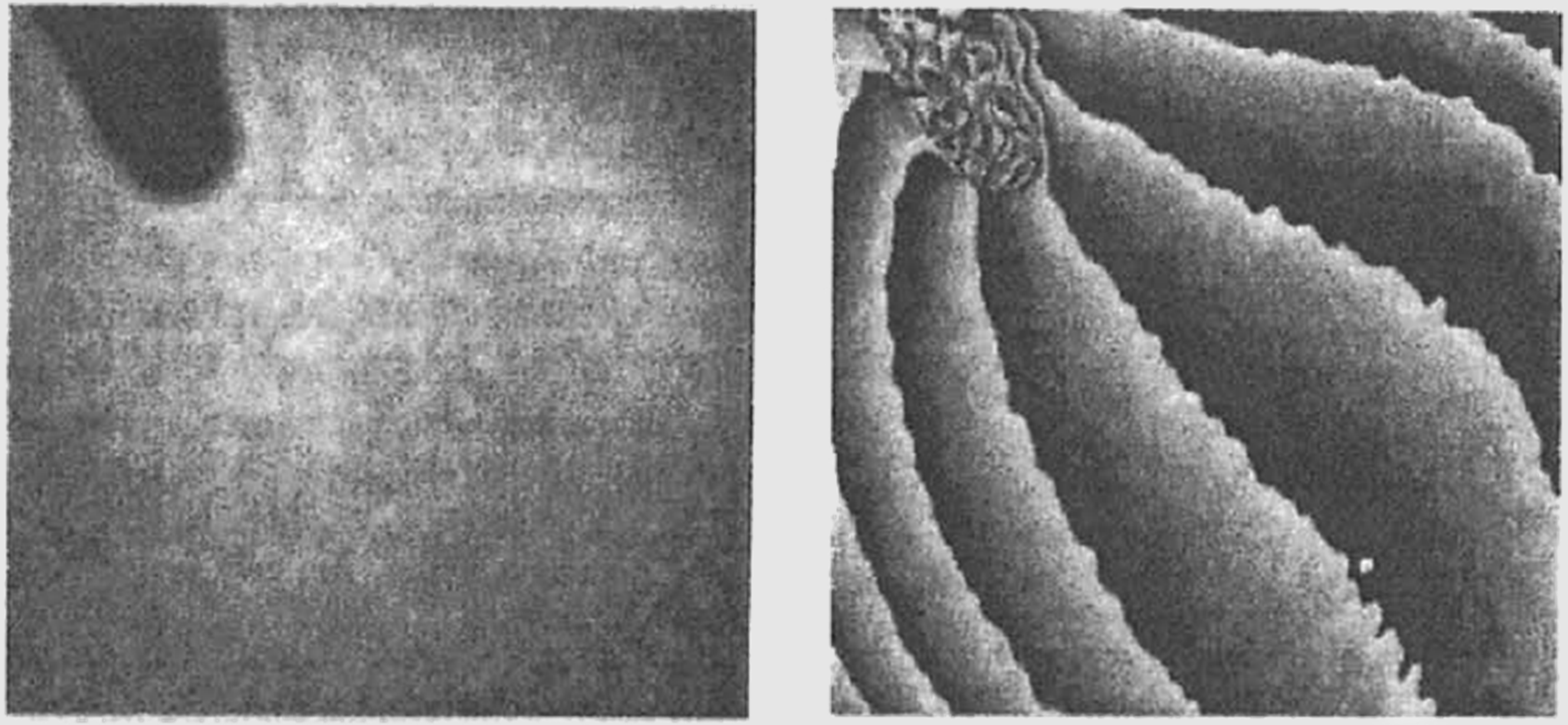
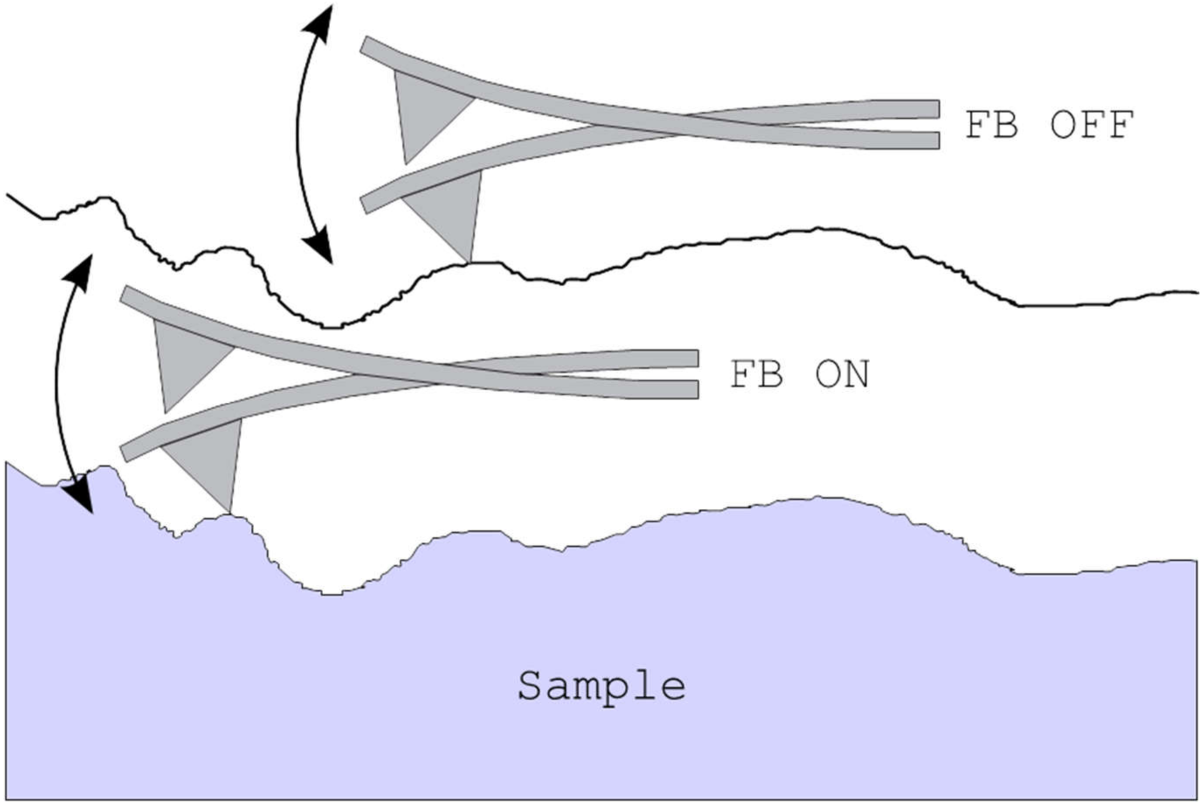
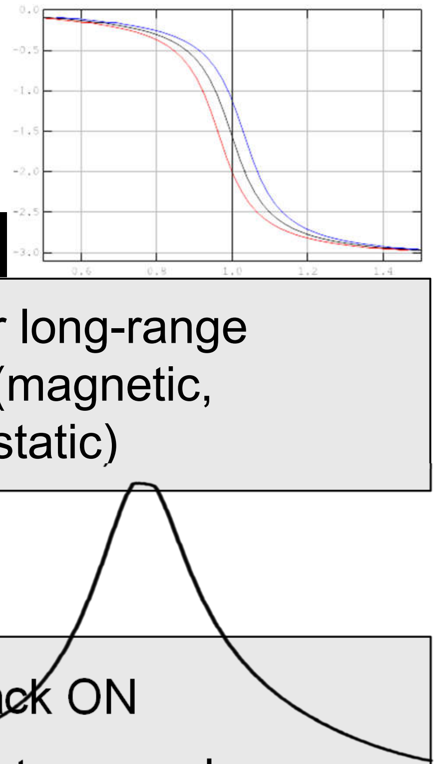


Figure 11-20: The electron amplitude (left) and phase (right) near an MFM tip visible as a dark shadow on the upper left corner of the left image.

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





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)**

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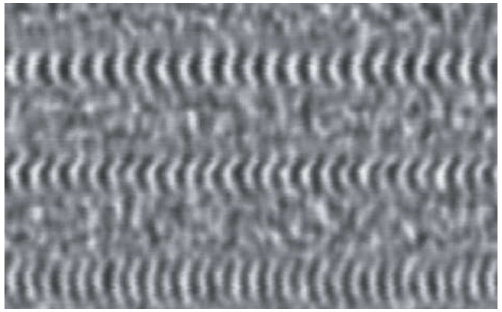

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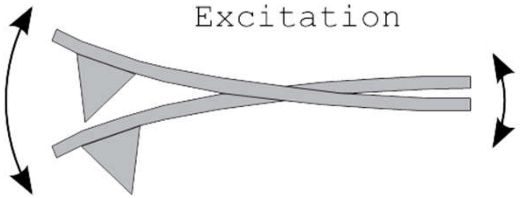

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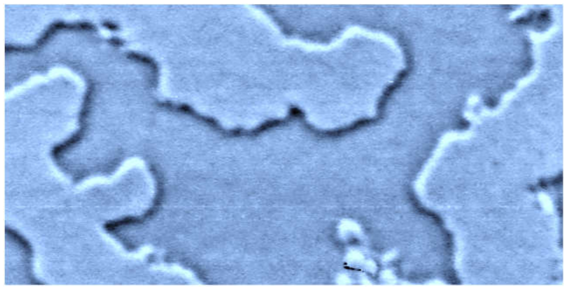

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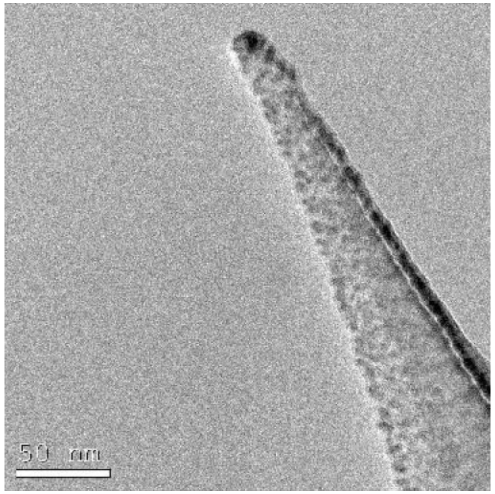

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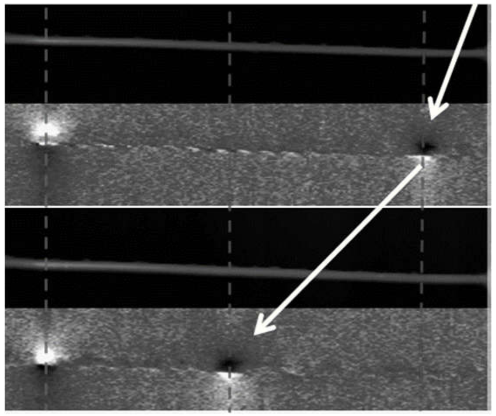

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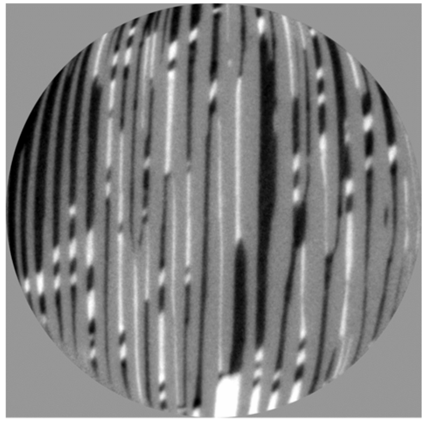
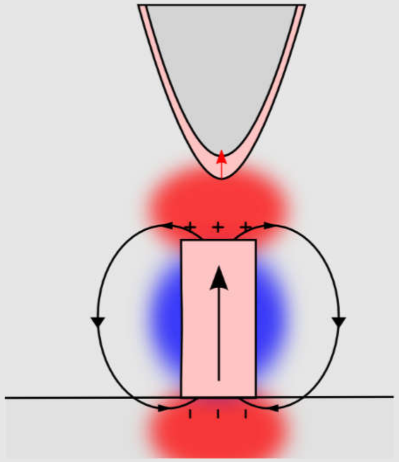


PRACTICE / MFM – tip/sample interaction

Tip is a dipole



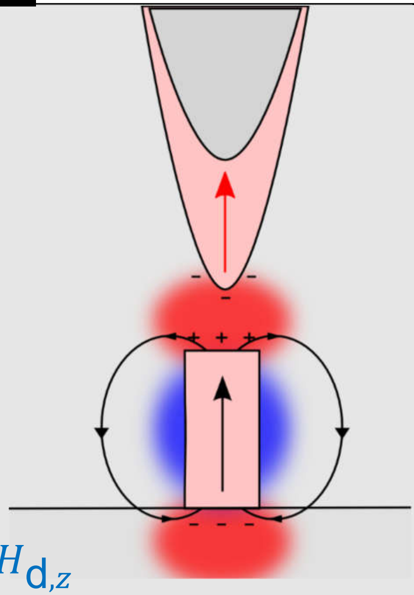
$$E_{1,2} = \mu_0 \mu_2 . H_{\mathrm{d}}$$

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

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

Tip is a monopole

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



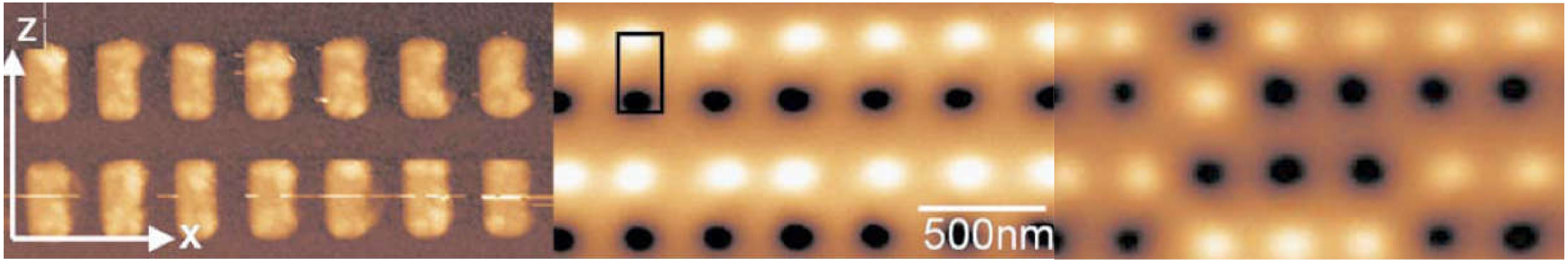
$$F_z = \mu_0 \sigma H_{\mathrm{d},z}$$

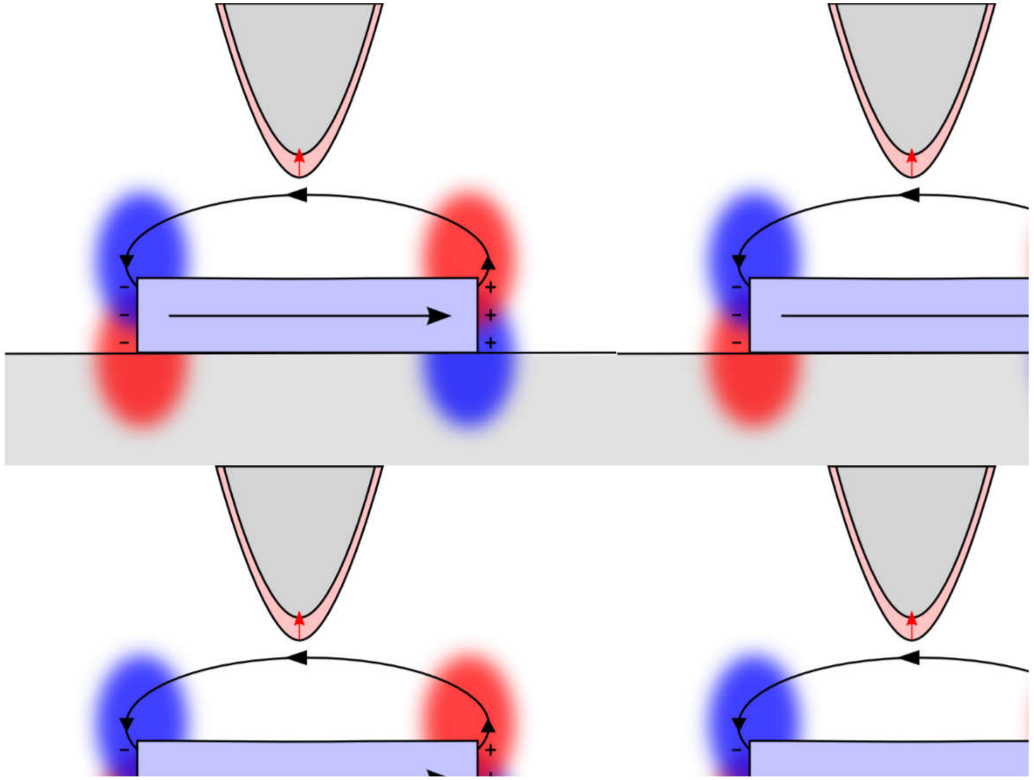
$$\Rightarrow \quad \delta\varphi = \frac{Q}{k} \mu_0 \sigma \partial_z H_{\mathrm{d},z}$$

- 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

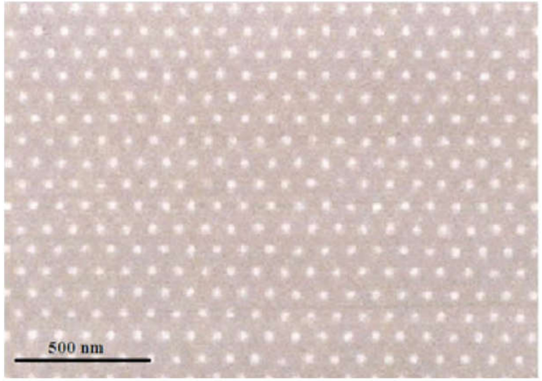




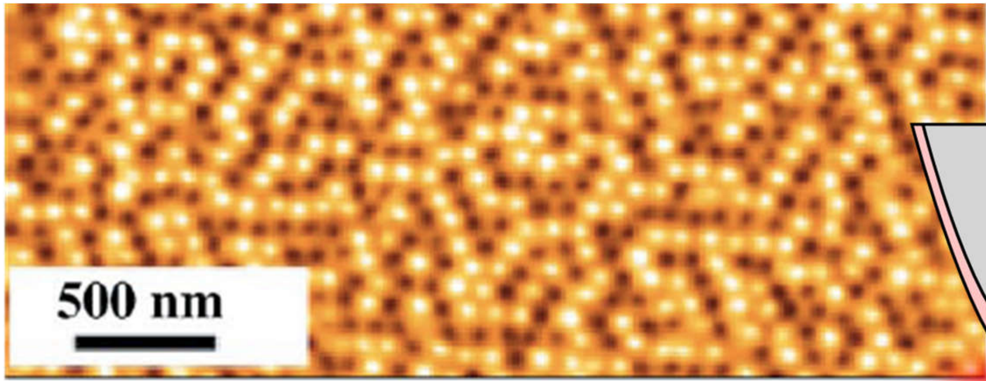
S. Y. Suck et al., APL95, 162503 (2009)

Single-domain in-plane magnetized dots appear as dipoles

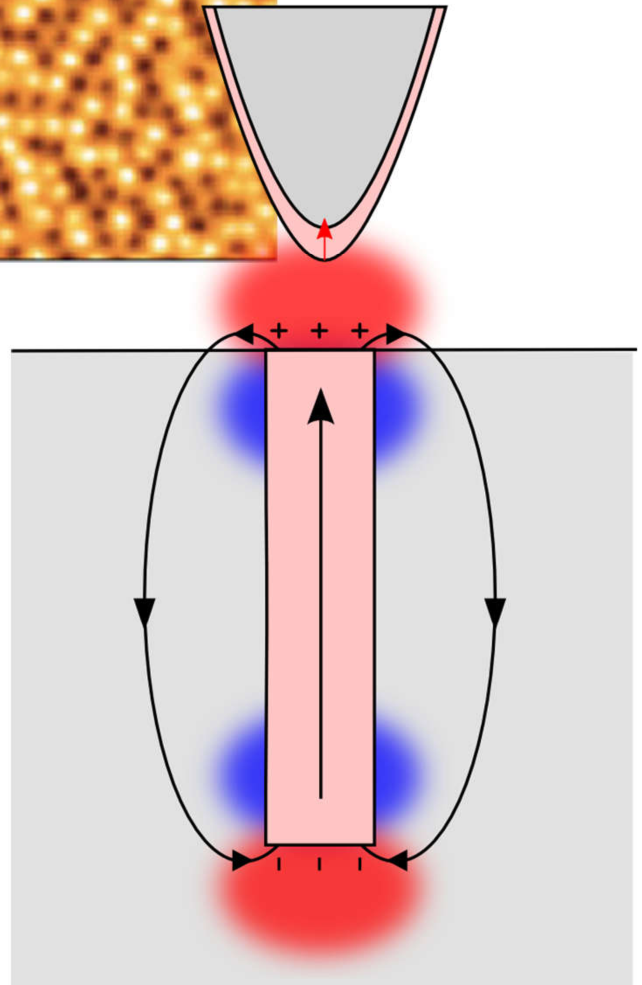
Structure (SEM)



MFM, partly reversed

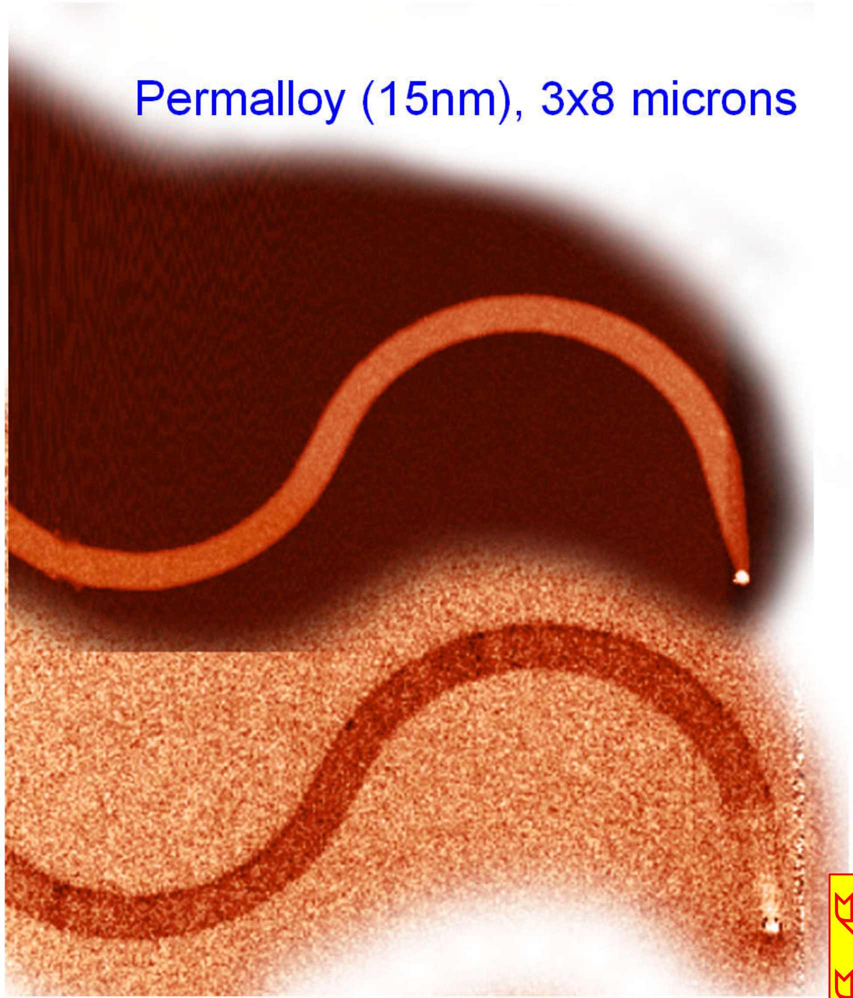


T. Wang et al., APL 92, 192504 (2008)



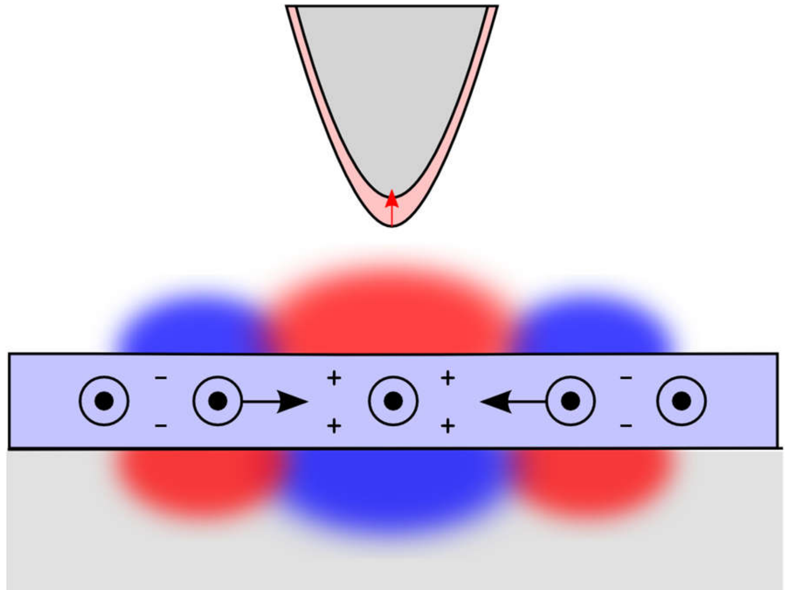
➪ Single-domain out-of-plane magnetized dots appear as monopoles

PRACTICE / Single-domain (mutual interaction)



Contrast : -0.1°, LM tip

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

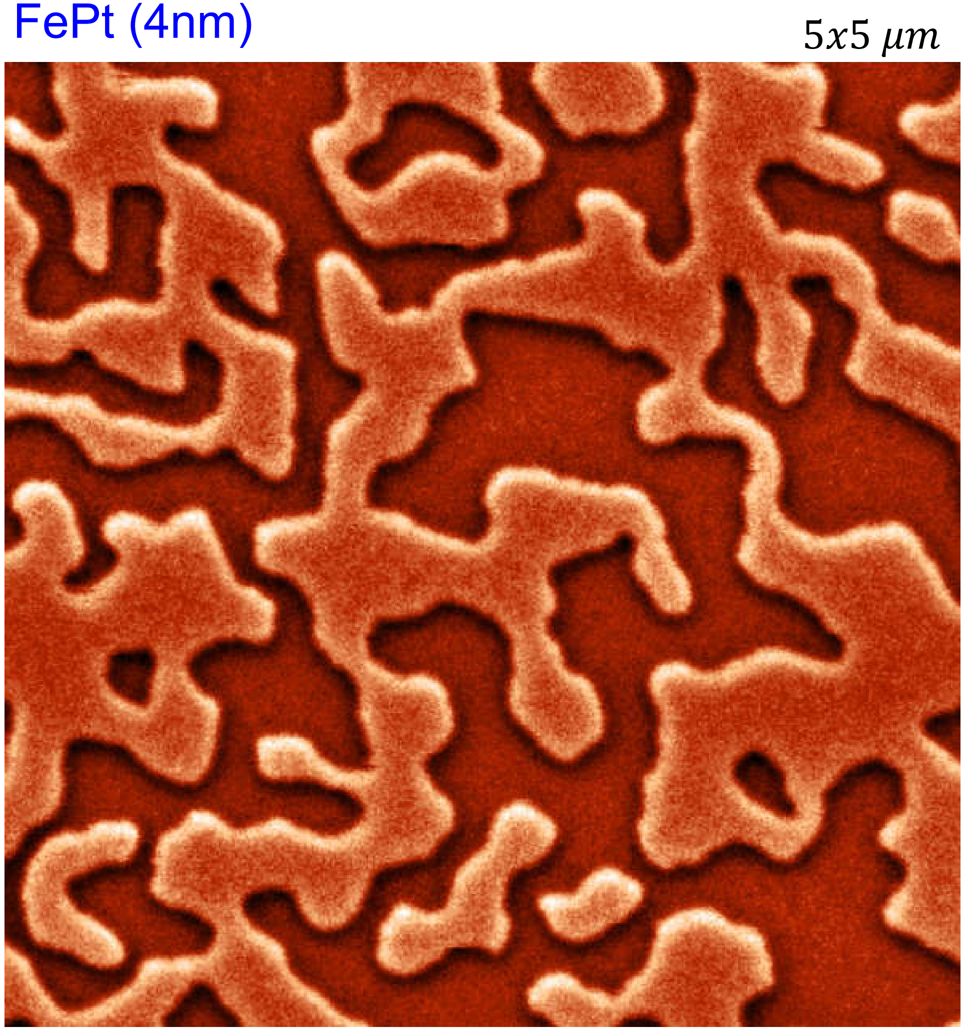


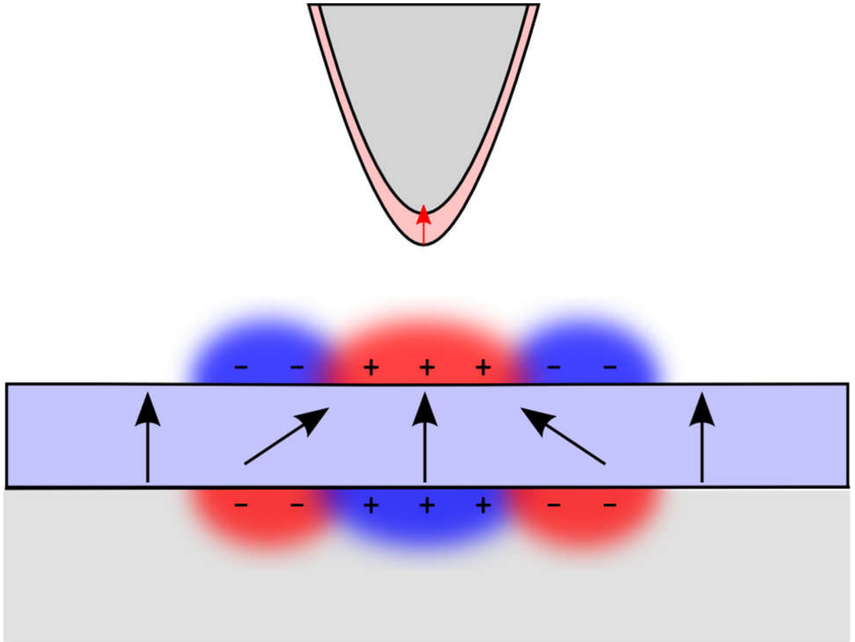
Principle :

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)





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

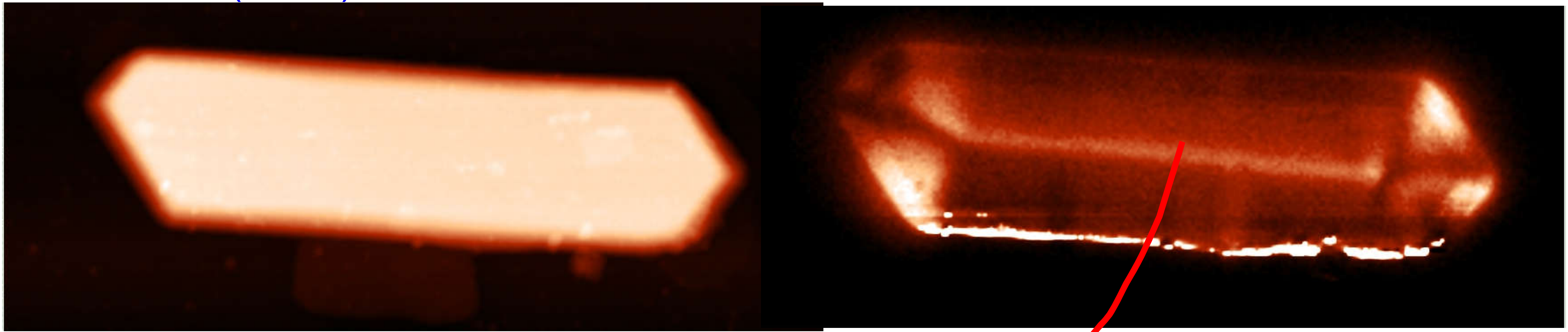
Sample : A. Marty (CEA-Grenoble)
Imaging : M. Darques (Institut Néel)

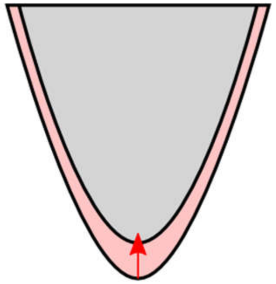
Contrast : ±0.4°, LM tip

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

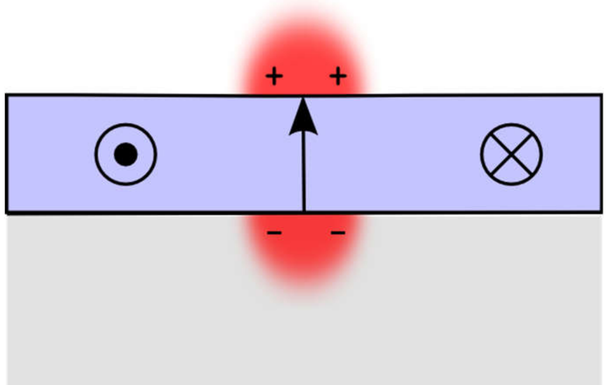
PRACTICE / Imaging domain walls (Bloch)

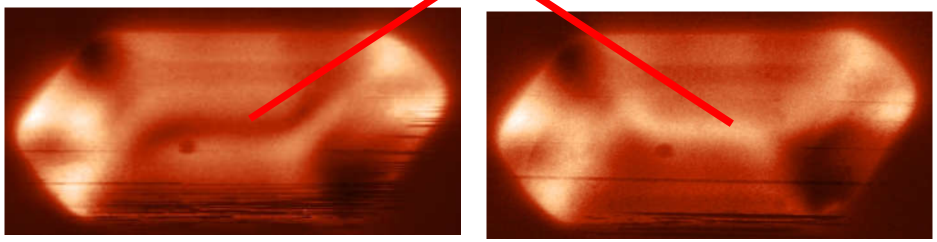
Fe dot (25nm), 2.5x1 microns





- Contrast is MONOPOLAR
- Informs about the <u>polarity</u> of the wall core

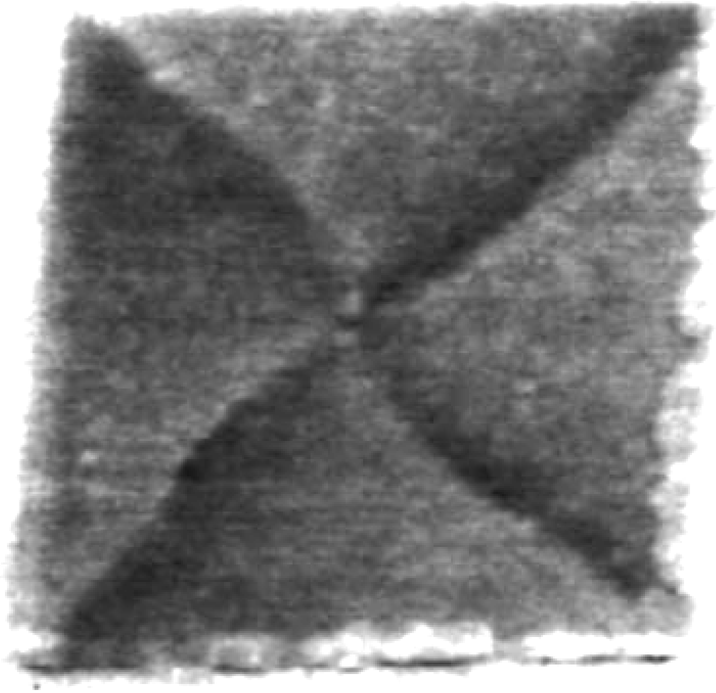




Down core

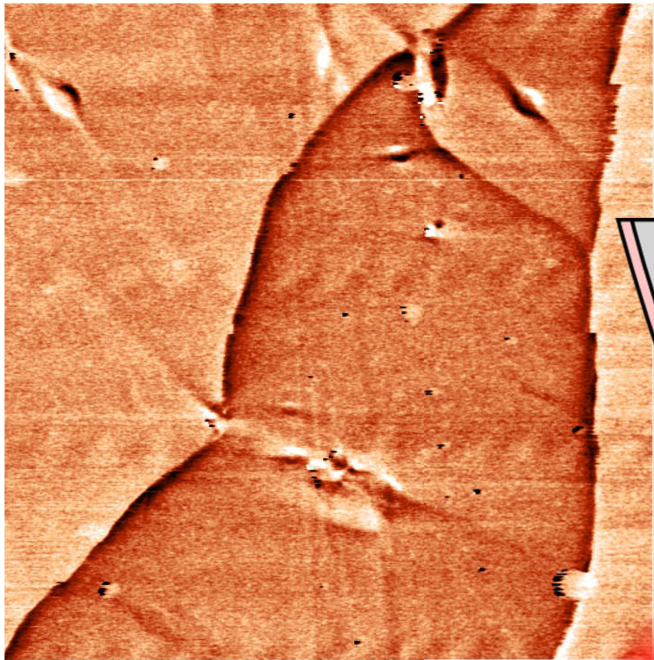
Up core

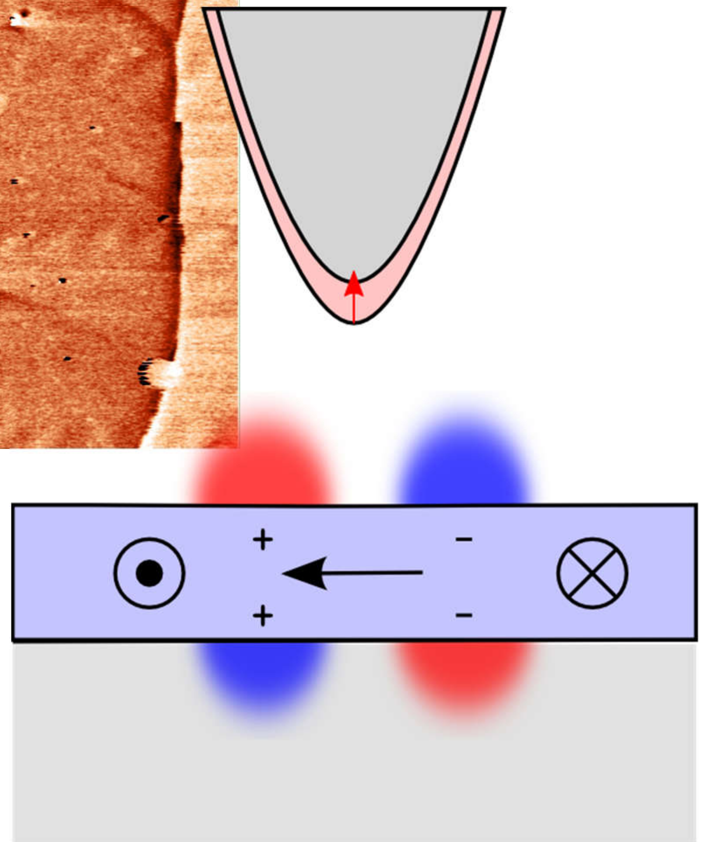
Permalloy dot (16nm)
2x2 microns



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

Permalloy film (20nm)
10x10 microns

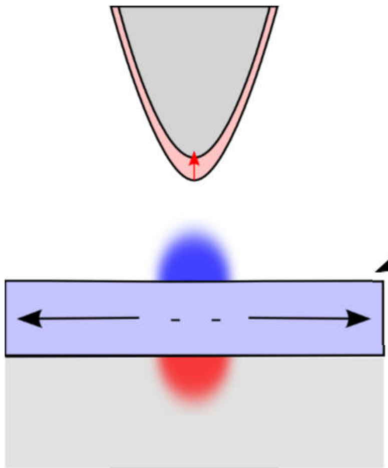


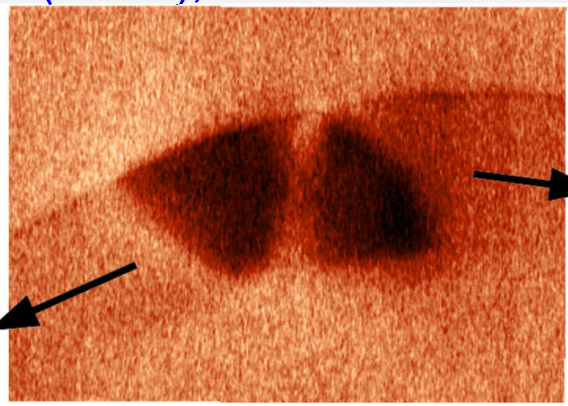


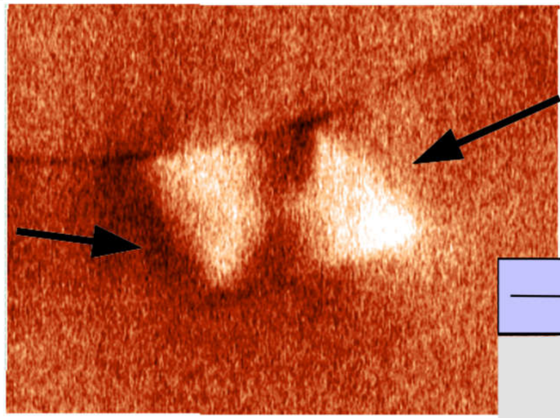
- Néel wall give rise to DIPOLAR contrast
- Informs about the chirality of the wall core

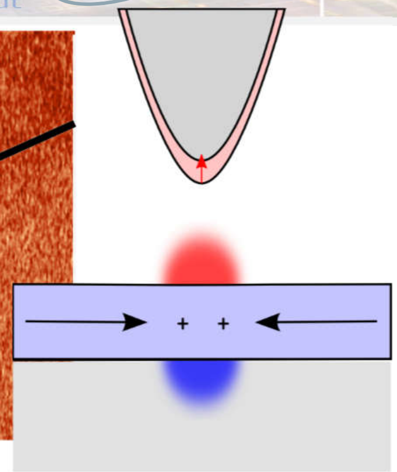
PRACTICE / Head-to-head domain walls

Permalloy strips (15nm), 250nm wide



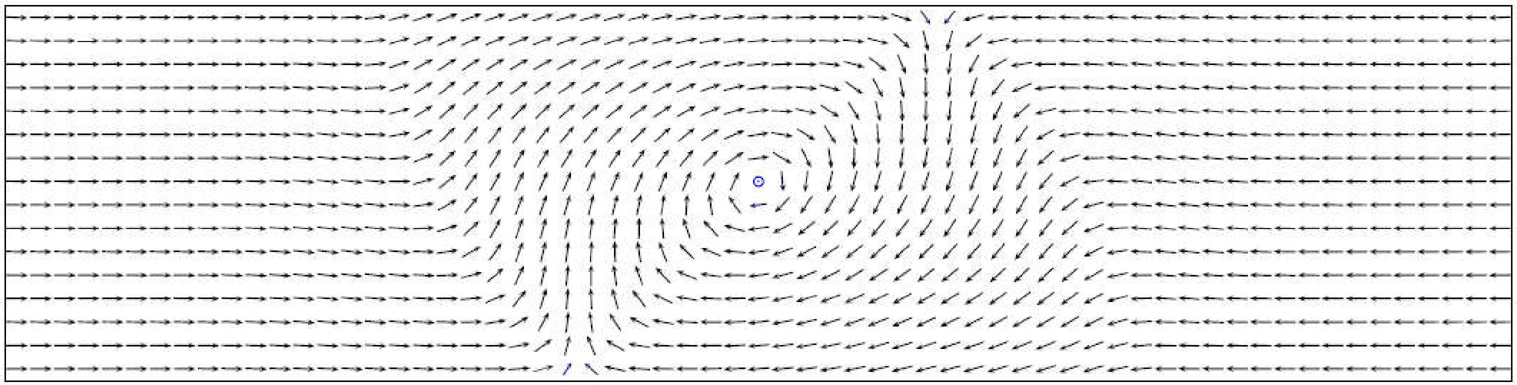






Contrast : ±0.3°, tip 5nm CoCr

Known as vortex domain-wall

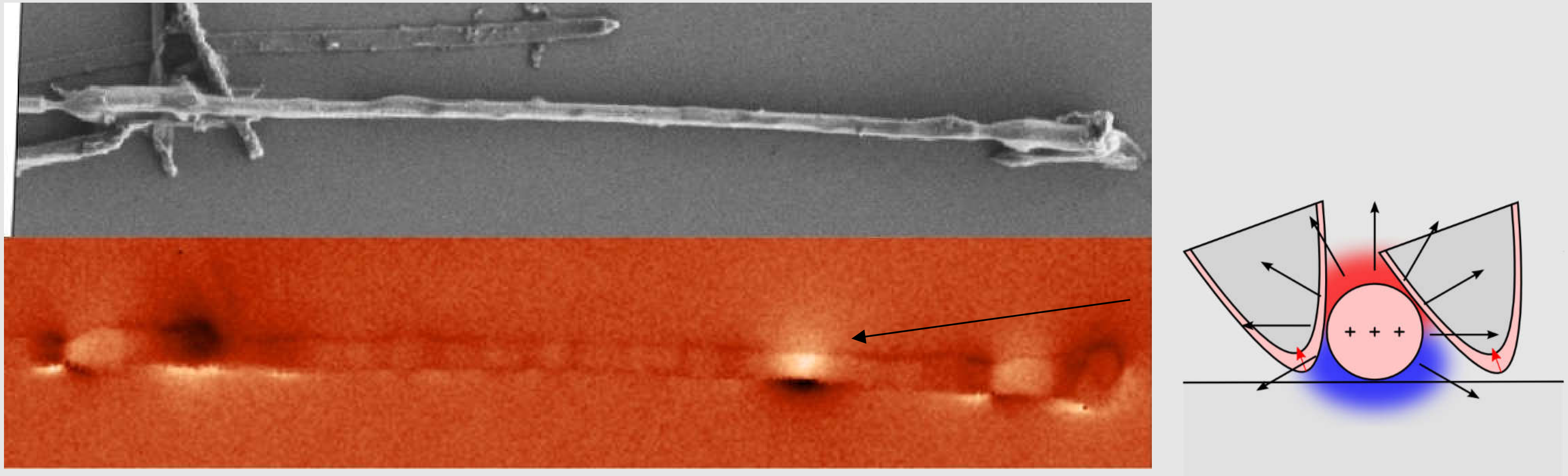


R. McMichael and M. Donahue, IEEE Trans. Magn. 33, 4167 (1997)

↳ Walls in in-plane magnetized stripes ⟶ MONOPOLAR

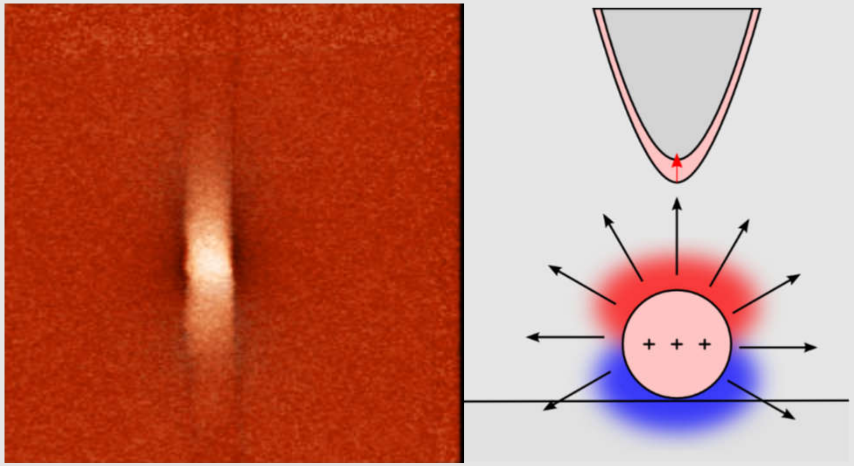
↳ Contrast informs about head-to-head ot tail-to-tail

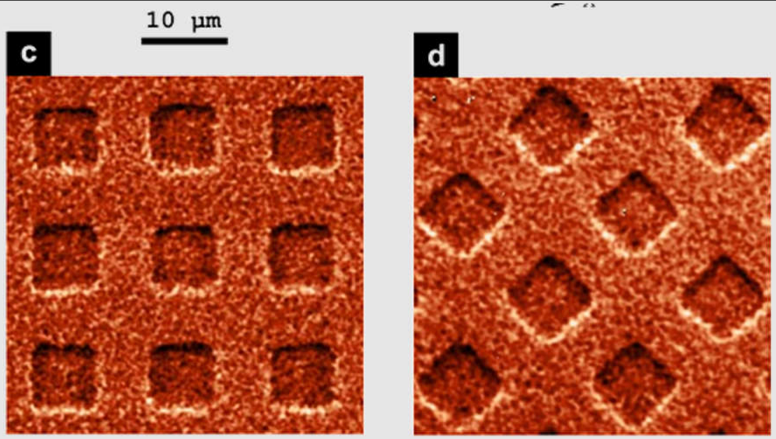
Tilted cantilever, across wire



Tilted cantilever, along wire

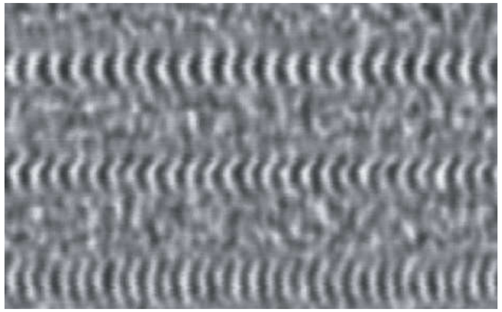
@NEEL/SPINTEC : S. Da Col et al., APL109, 062406 (2016)



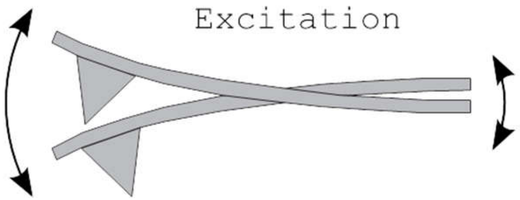


@NEEL : G. Ciuta, IEEEtm 52, 6500408 (2016)

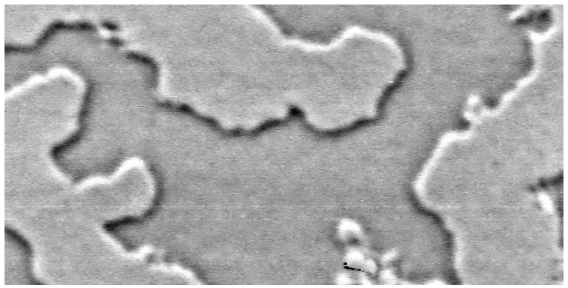
- Motivation and criteria



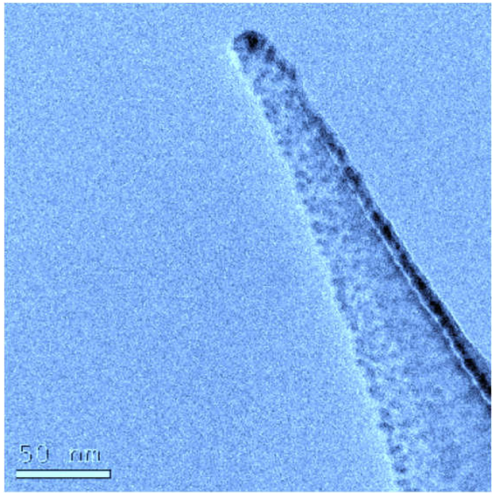
- Working principle



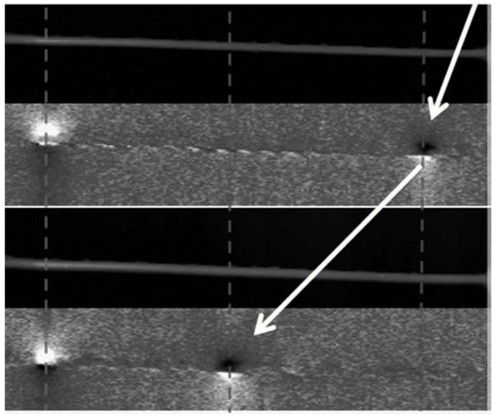
- Image analysis



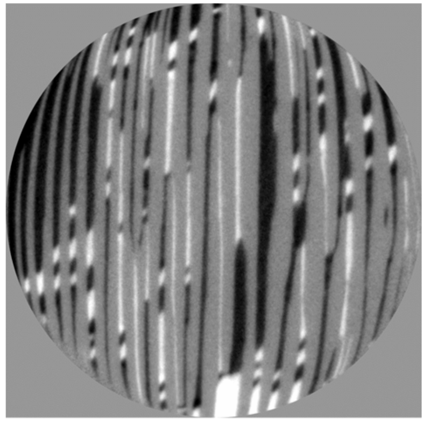
- Choice of tips



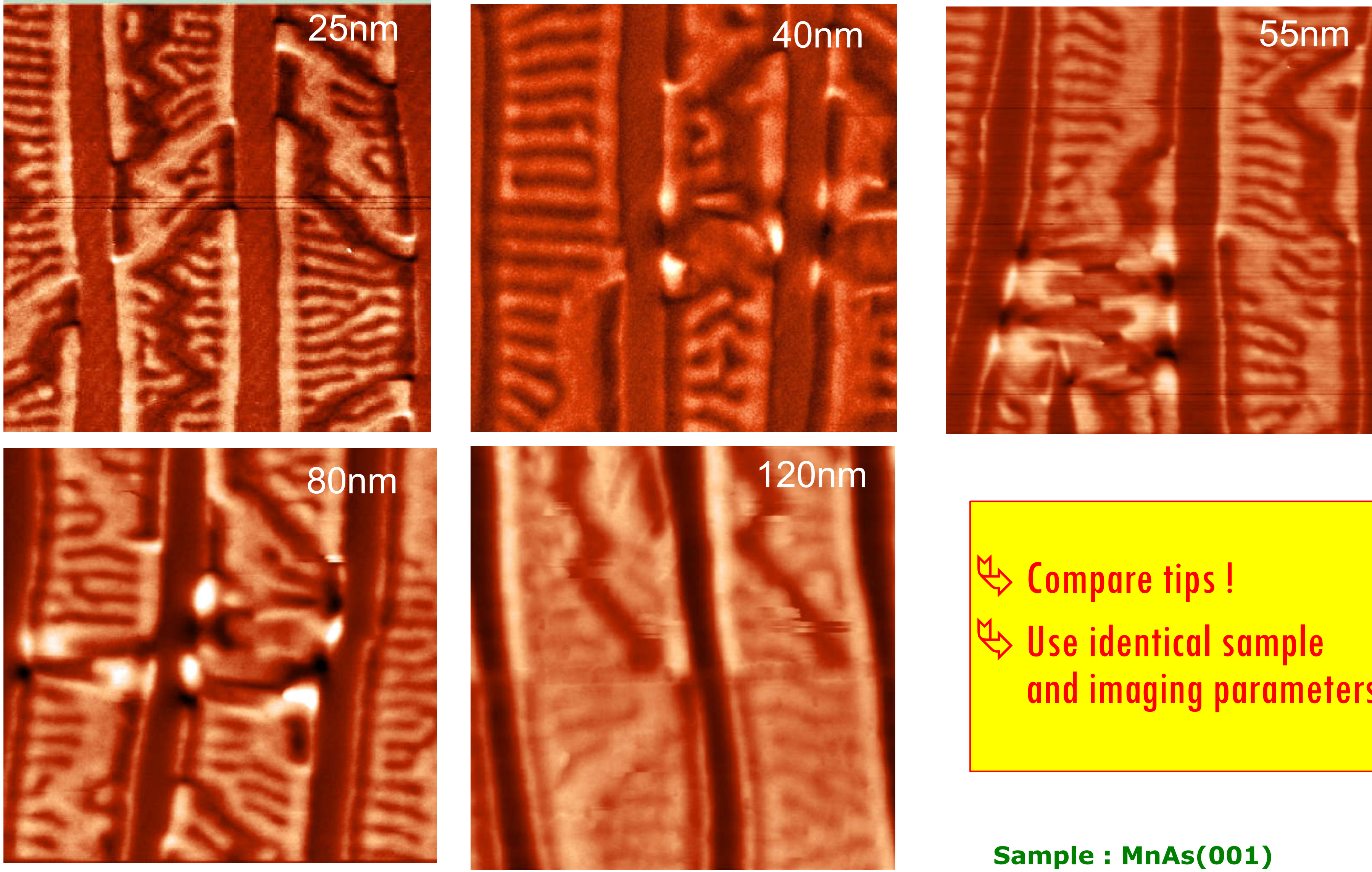
- Operando imaging



- Panorama of other microscopies



TIPS. Calibration | here : commercial



- Compare tips !
- Use identical sample and imaging parameters

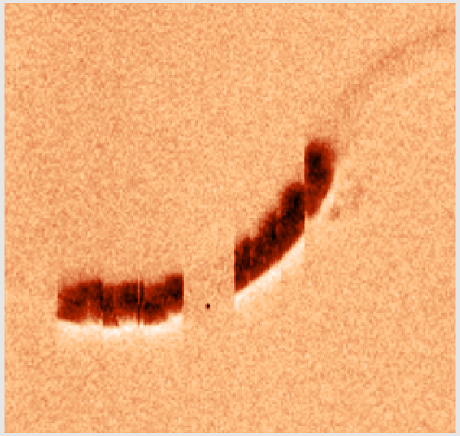
Sample : MnAs(001)
R. Belkhou (Soleil)

TIPS. Influencing samples

High

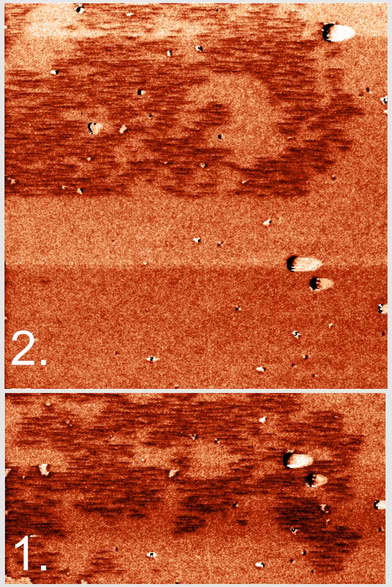
Scanning

Attraction



Permalloy (15nm)
500nm strips

Sample : S. Pizzini
Imaging : Z. Ishaque

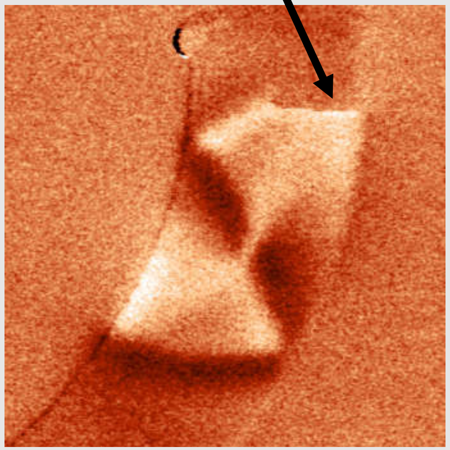


Co (0.6nm)/
graphene (20 mic)

C. Dieudonné

Moderate

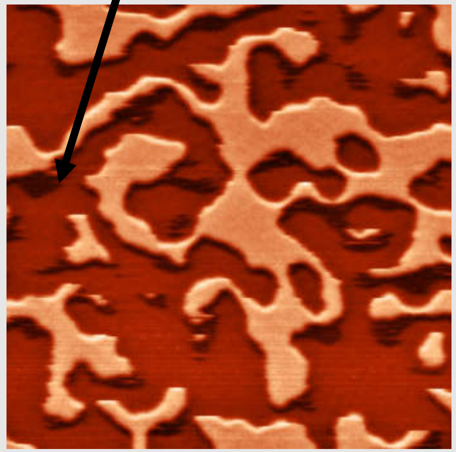
Repulsion



Permalloy (15nm)
500nm wide

Sample : S. Pizzini
Imaging : Z. Ishaque

Attraction



FePt (4nm)
Image 5 microns

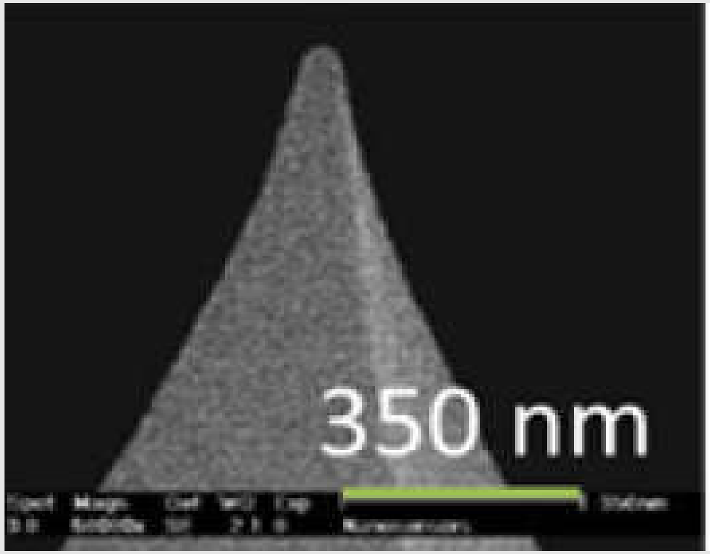
Sample : A. Marty
Imaging : M. Darques

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

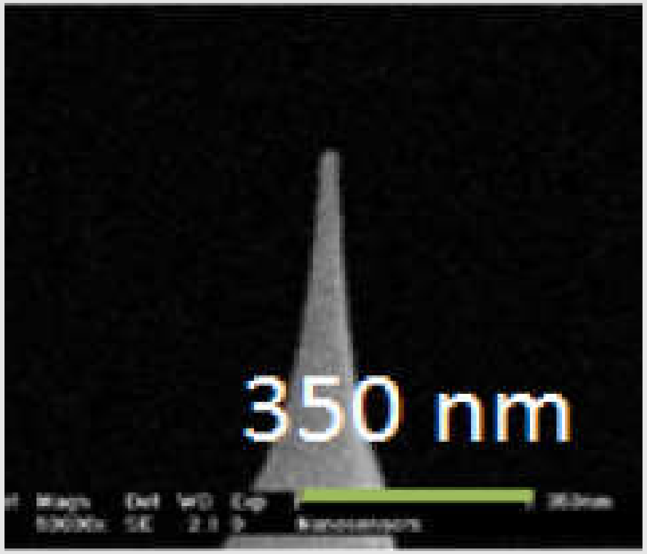
TIPS. Custom tips (basics)

Improve resolution

From sharp to ultrasharp AFM tips



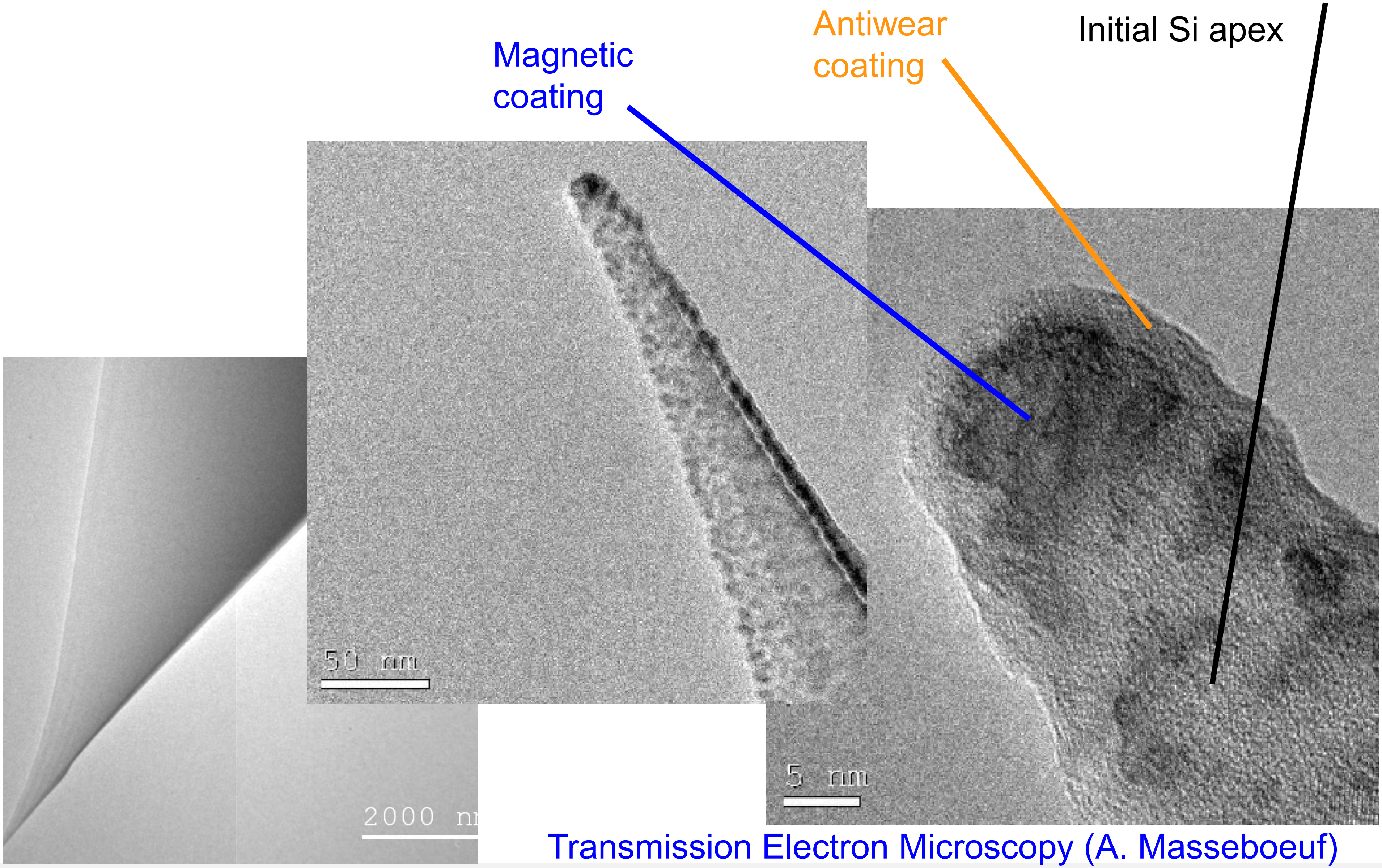
Asylum 240TS
Radius of curvature : 10 nm



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

Engineer magnetic coating

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



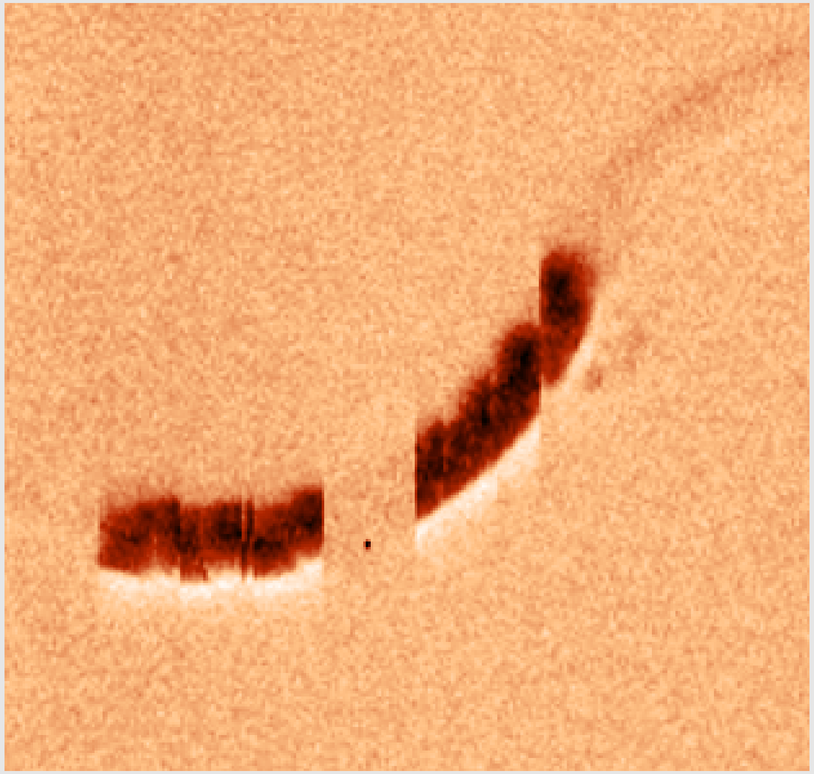
Transmission Electron Microscopy (A. Masseboeuf)

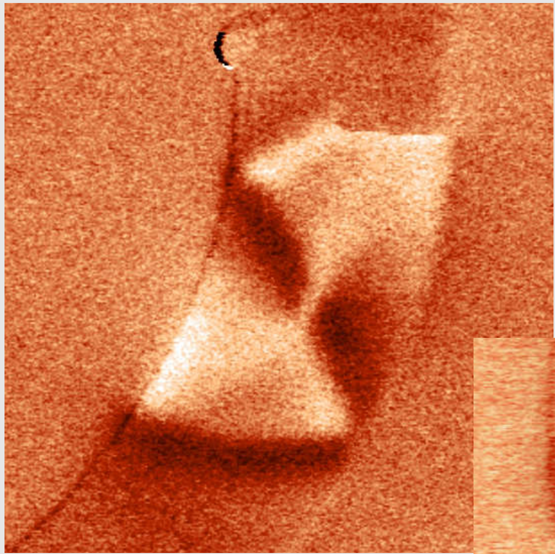
TIPS. Reduce tip-sample interaction

Commercial tips, 'low moment'

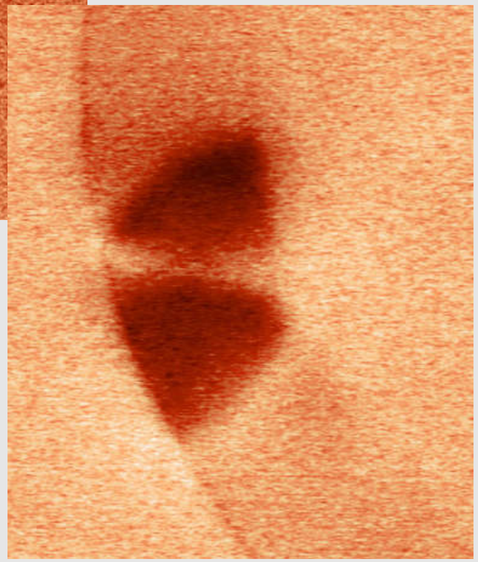
Permalloy strips [15nm]

Home-made tips, really low moment





Tip : CoCr[10nm]
500nm strips



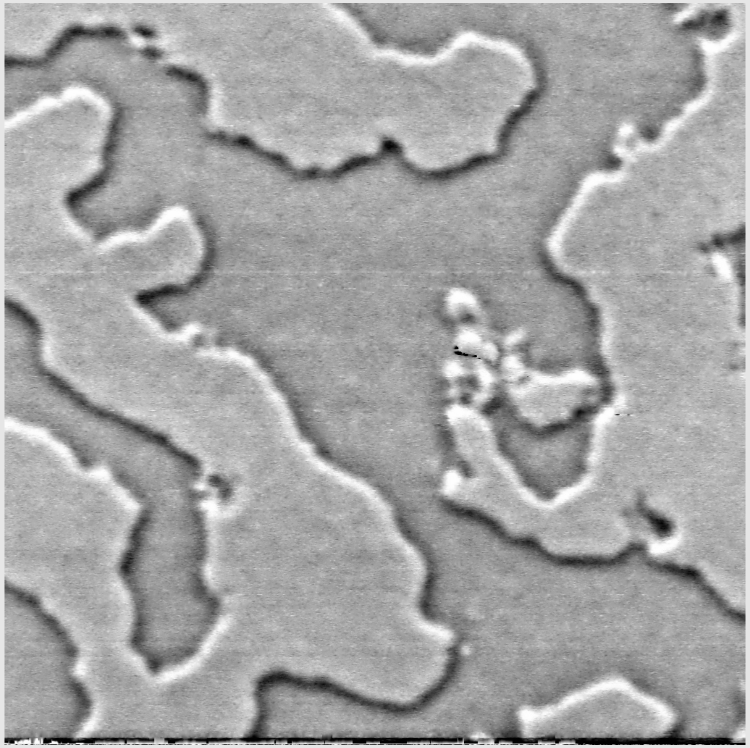
Tip : CoCr[5nm]
300nm strips

Sample : S. Pizzini
Imaging : Z. Ishaque

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

Spatial resolution 15nm

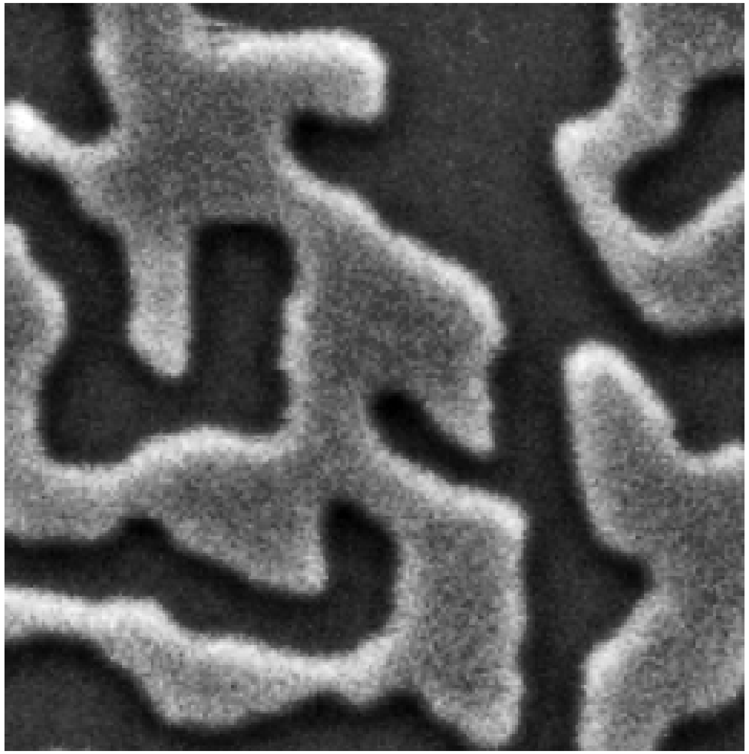
Test sample : FePt[4nm]. Perpendicular magnetization, narrow domain walls



$2x2\ \mu m$

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

Commercial 'low moment' tip

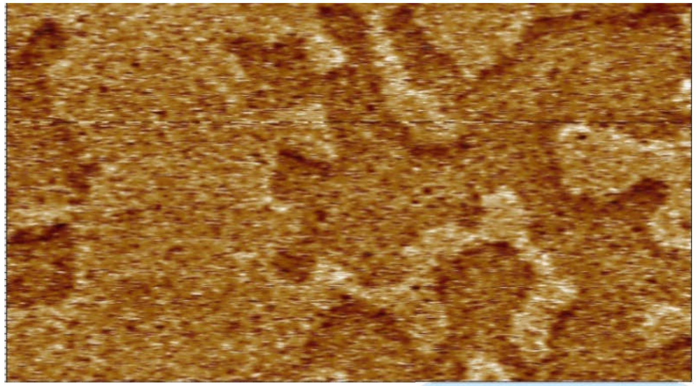


Spatial resolution : 20nm

TIPS. Skyrmions and bubbles in <1nm films

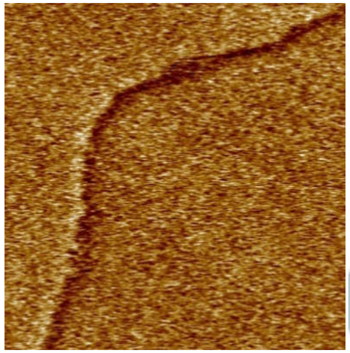
Specific aspects

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



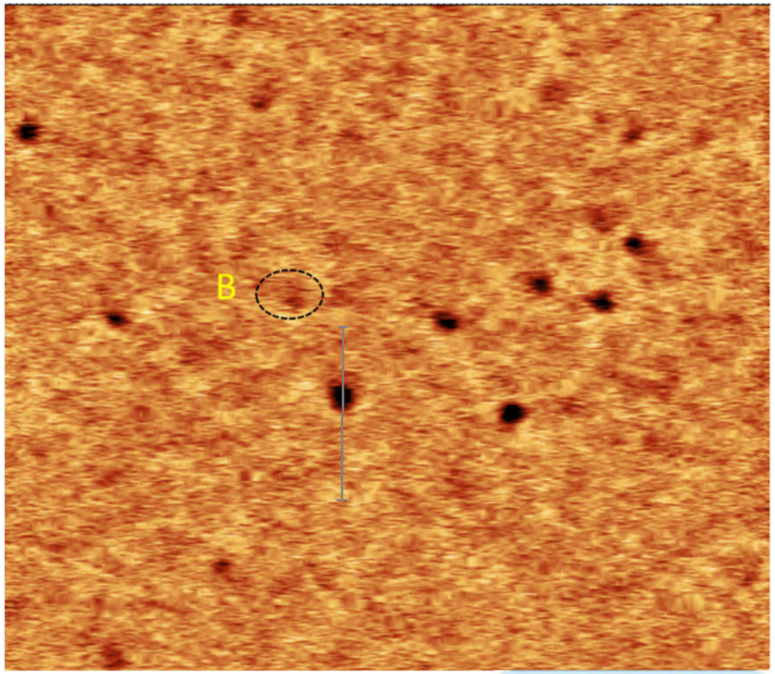
Sample: R. Juge

5x2.8 µm



Imaging: K. Richter

1.2x1.2 µm



Imaging: G. Rana

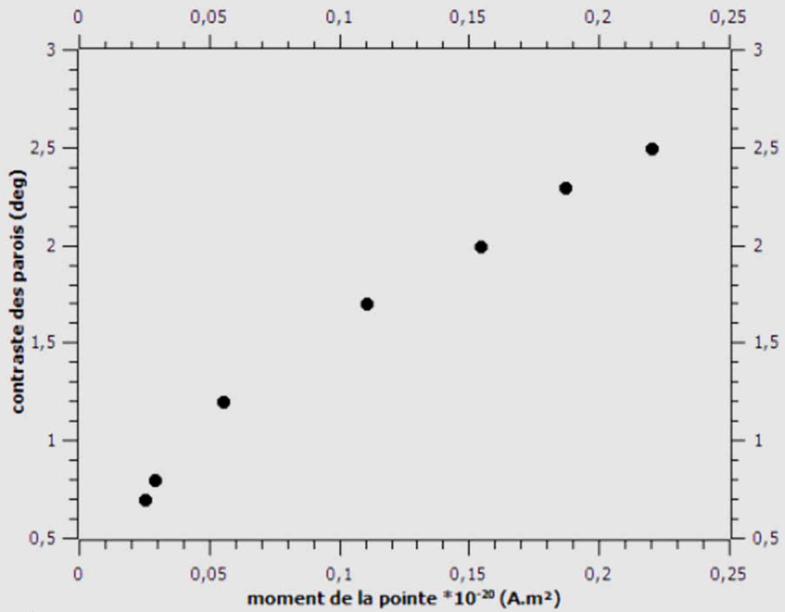
3x2.5 µm

Conclusion

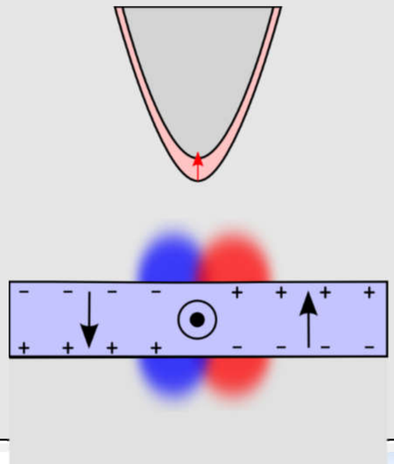
- Remains measurable
- Mutual contrast nearly absent

TIPS. Towards quantitative imaging

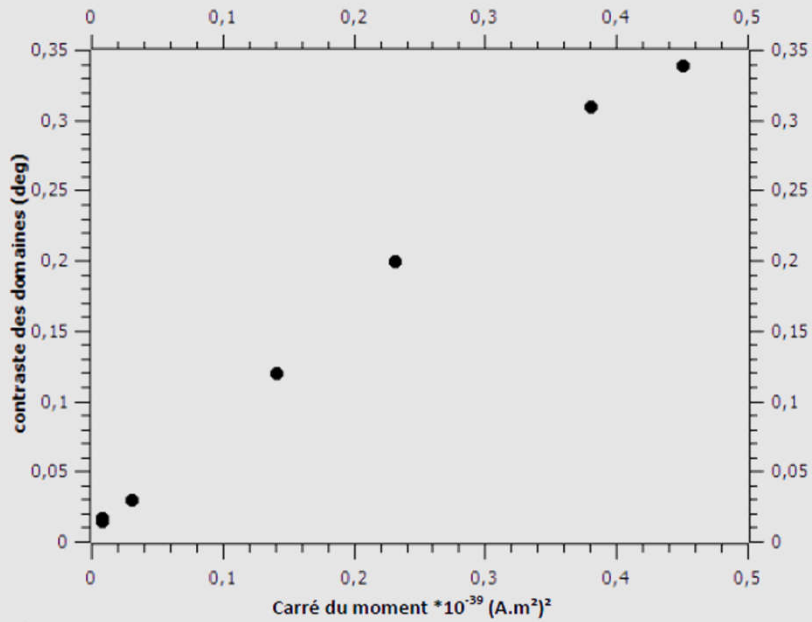
Domain wall contrast



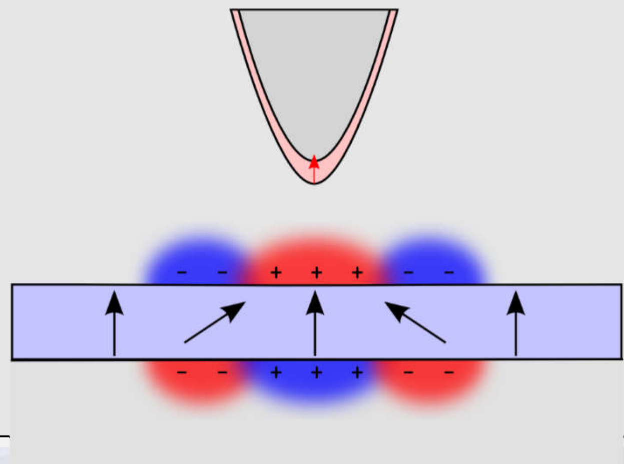
⇨ Linear with <u>tip moment</u>



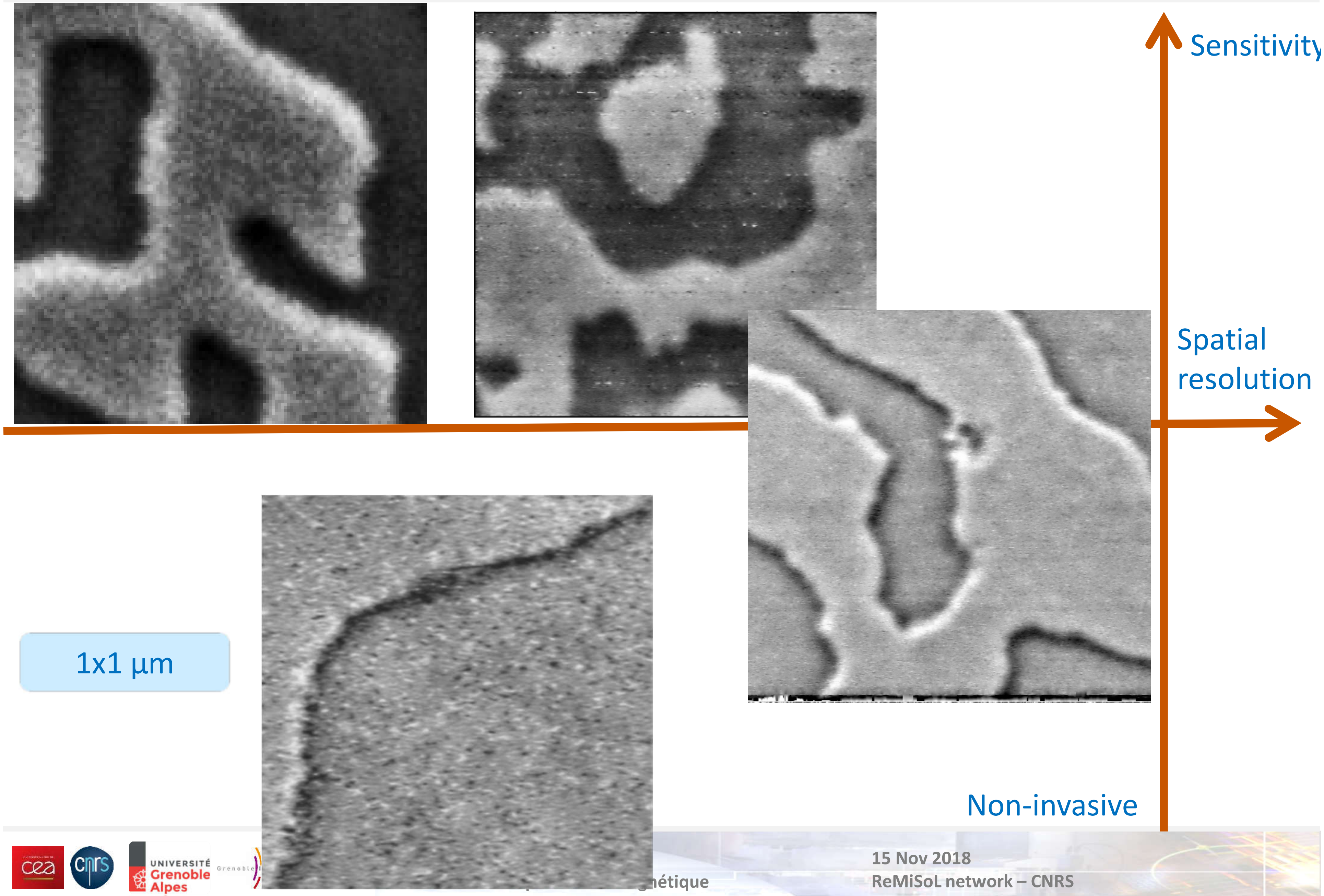
Domain contrast



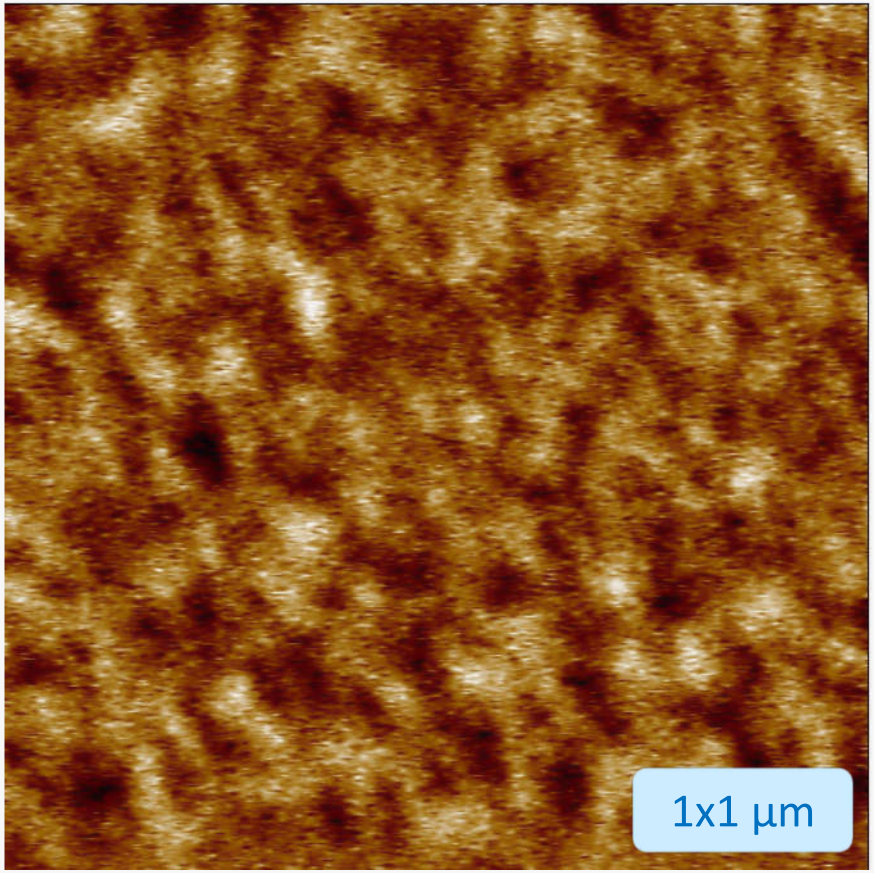
⇨ Linear with <u>square of tip moment</u>



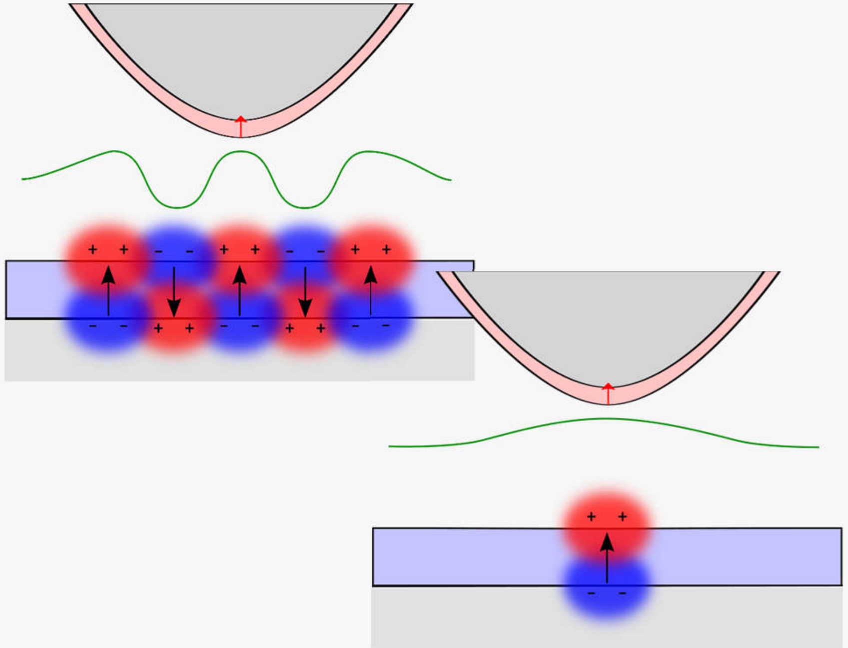
TIPS. Both resolution and sensitivity matter



NOT the smallest feature on an image



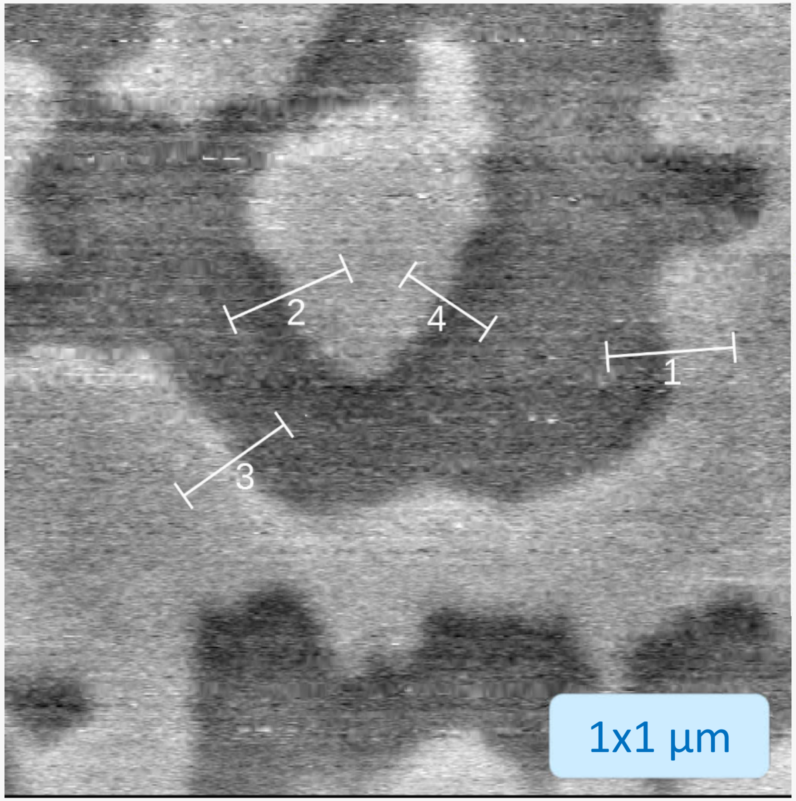
FePt-C recording media



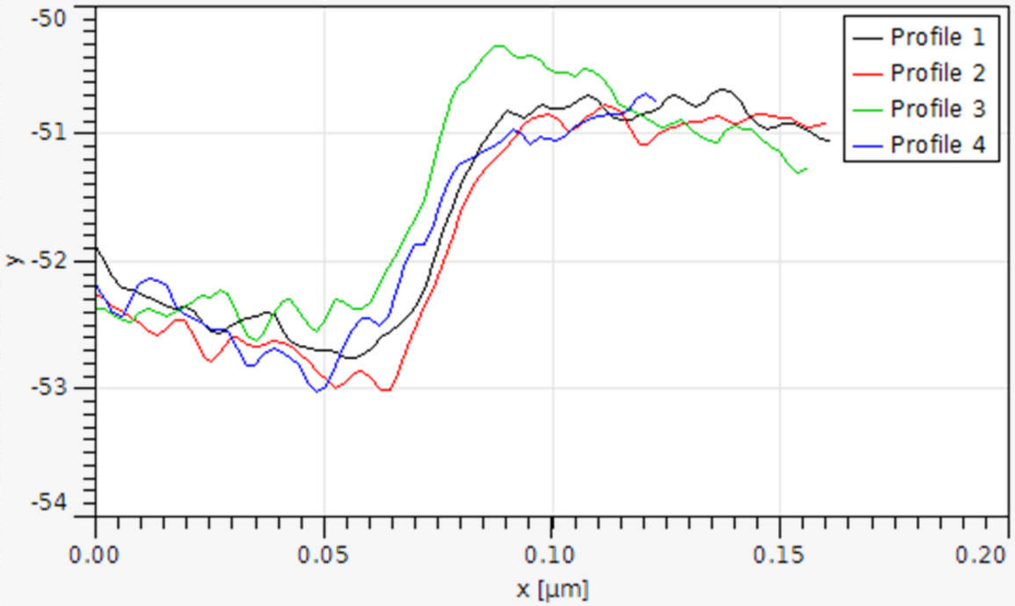
- Small scale modulation
- Reduced magnitude
- A single object would appear larger

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

Use isolated well-defined magnetic pattern



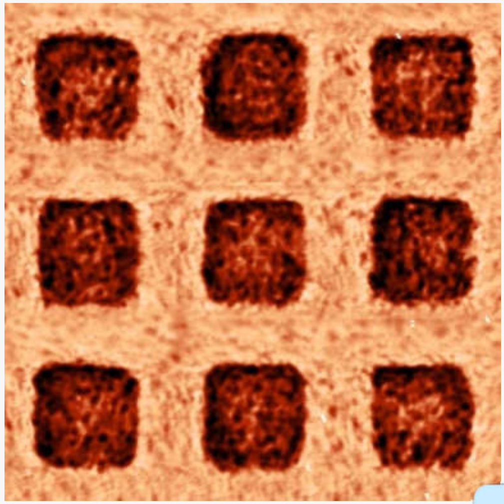
FePt, epitaxial (4nm)



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

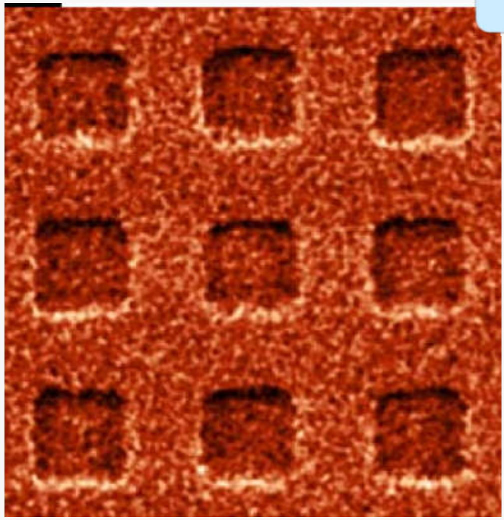
Quantitative analysis, see e.g.: H. Hug, J. Appl. Phys. 83, 5609 (1998) and followers

May require hard tip coating



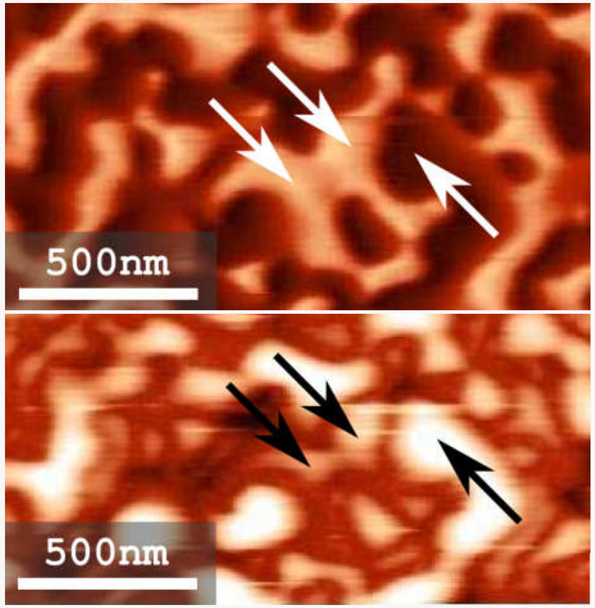
Soft coating

50x50 µm



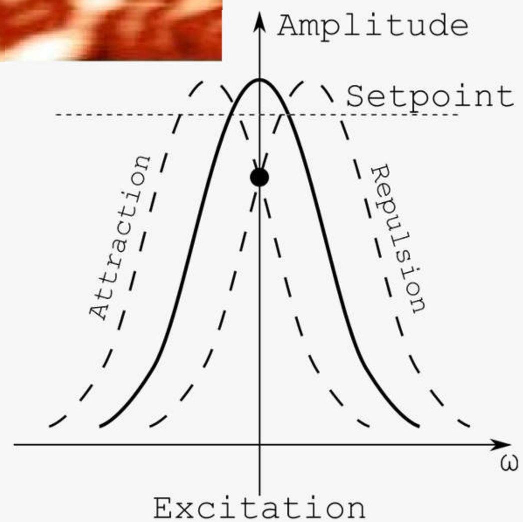
Hard coating

May require stiff cantilevers



MFM

Topography (artefacts)



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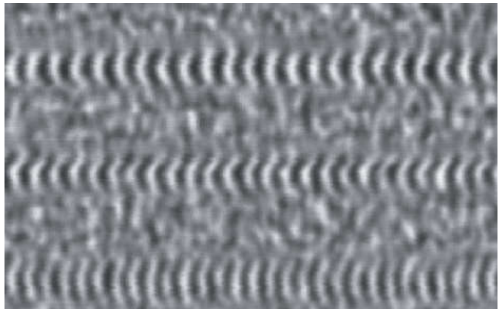
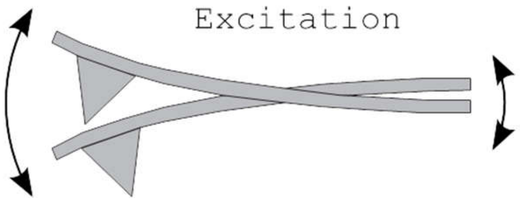
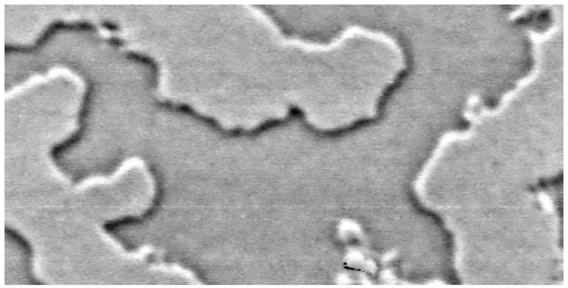
- Motivation and criteria



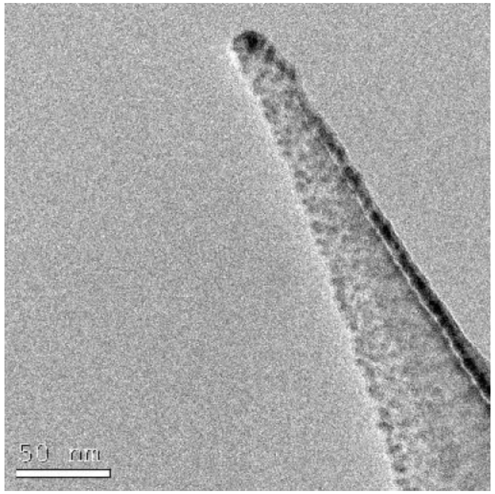
- Working principle



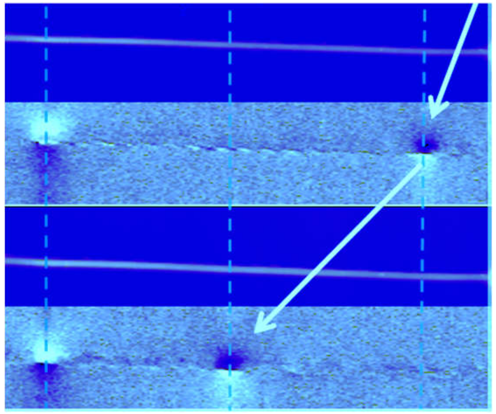
- Image analysis



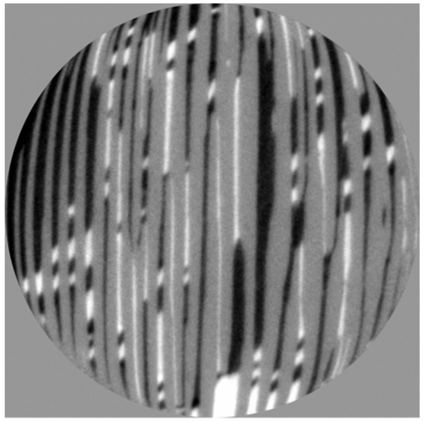
- Choice of tips

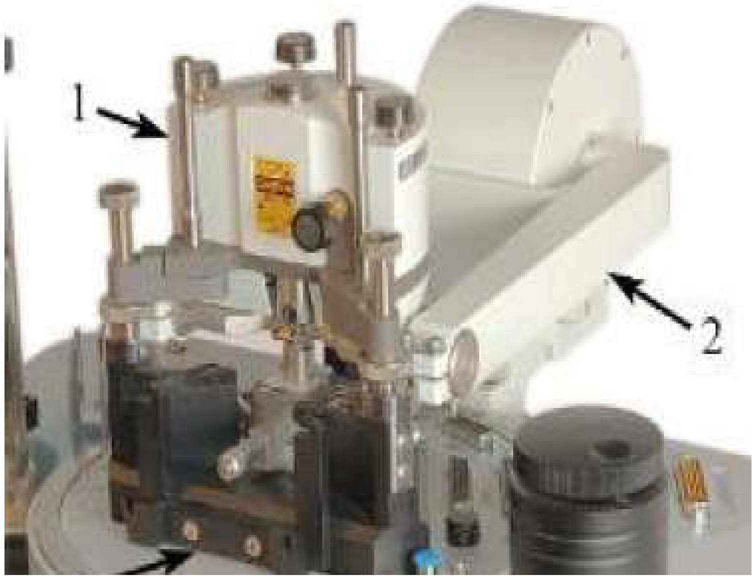


- Operando imaging

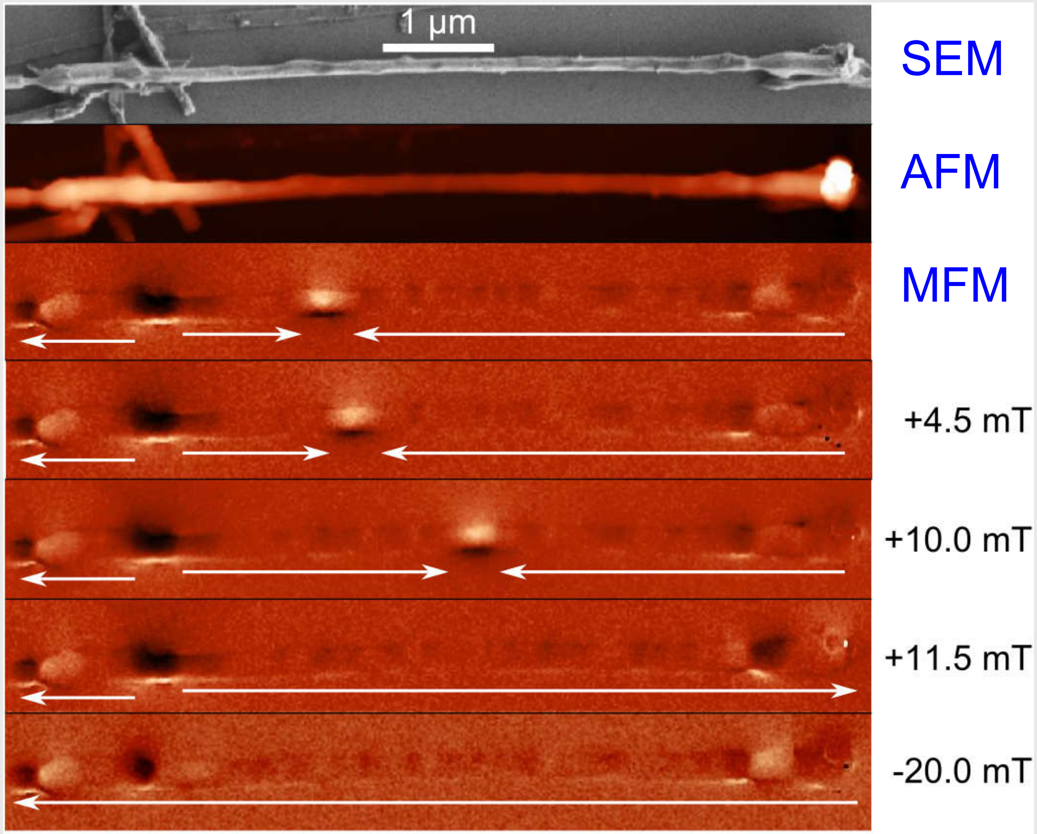


- Panorama of other microscopies



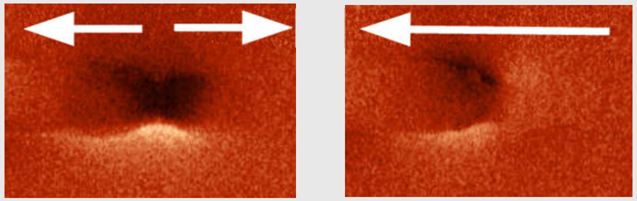


Domain wall motion



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

Protrusions and constrictions

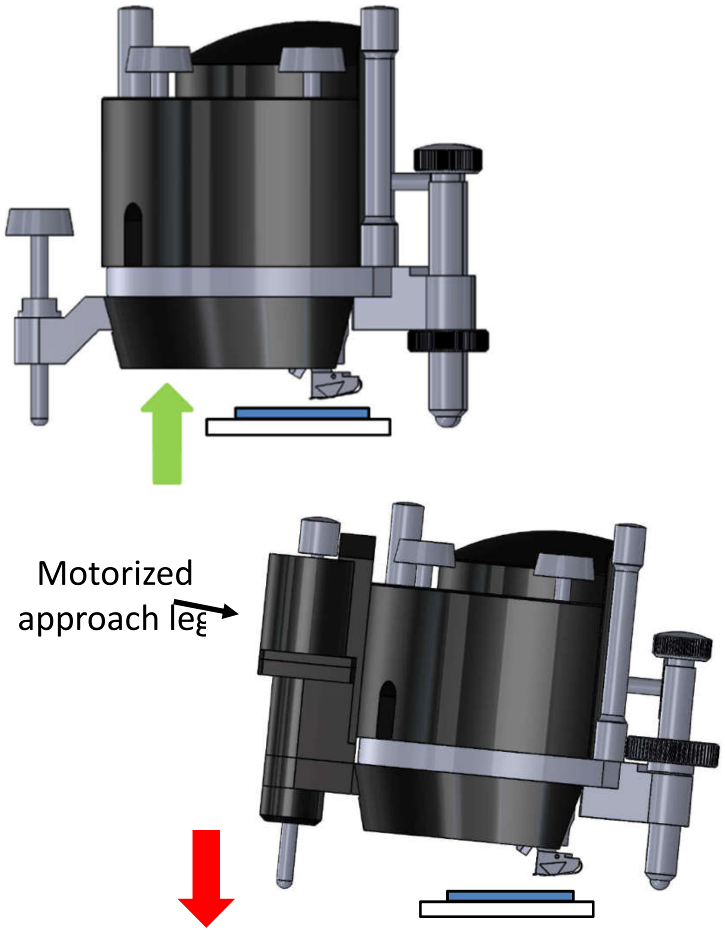


⇨ Pinning field ~30mT

- Imaging under field
- Magnetization processes

OPERANDO. Out-of-plane field

Field >1T (custom-made)
Optimized cooling



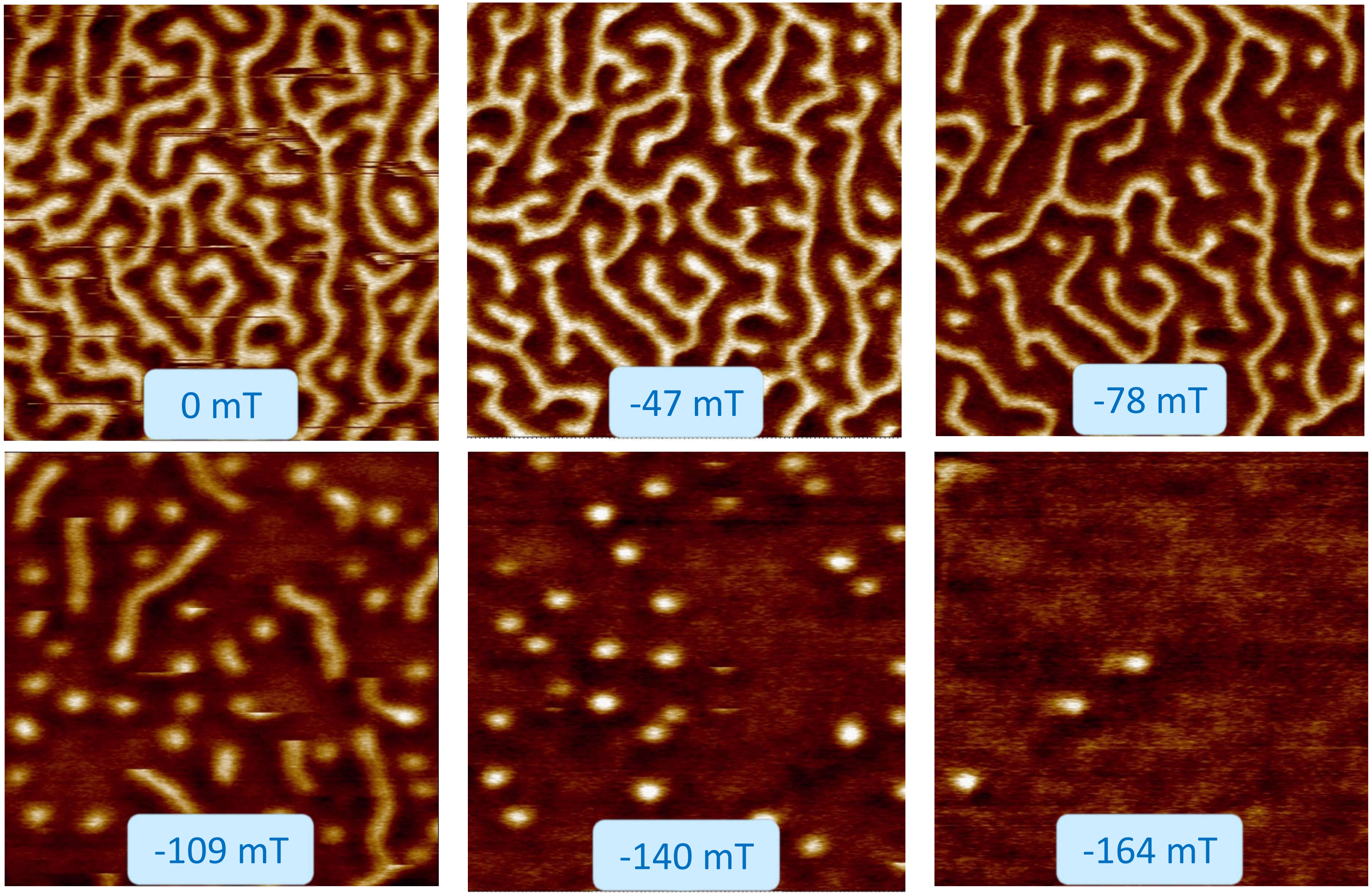
Microscope approach
by moving the sample up
(standard configuration)

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/W multilayers, 2x2µm

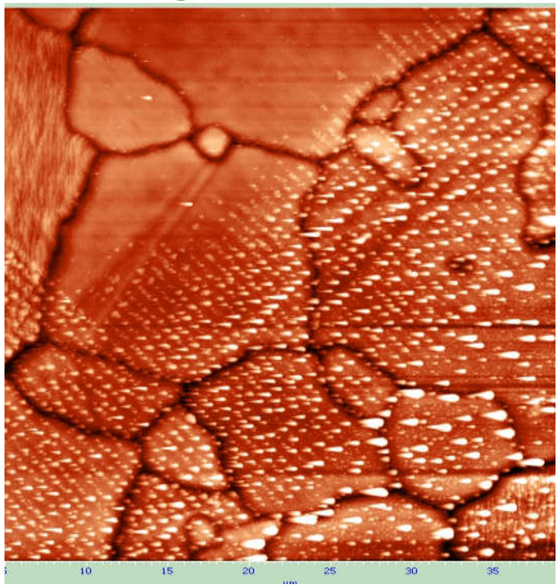


Sample: Chloé Bouard

OPERANDO. Out-of-plane field

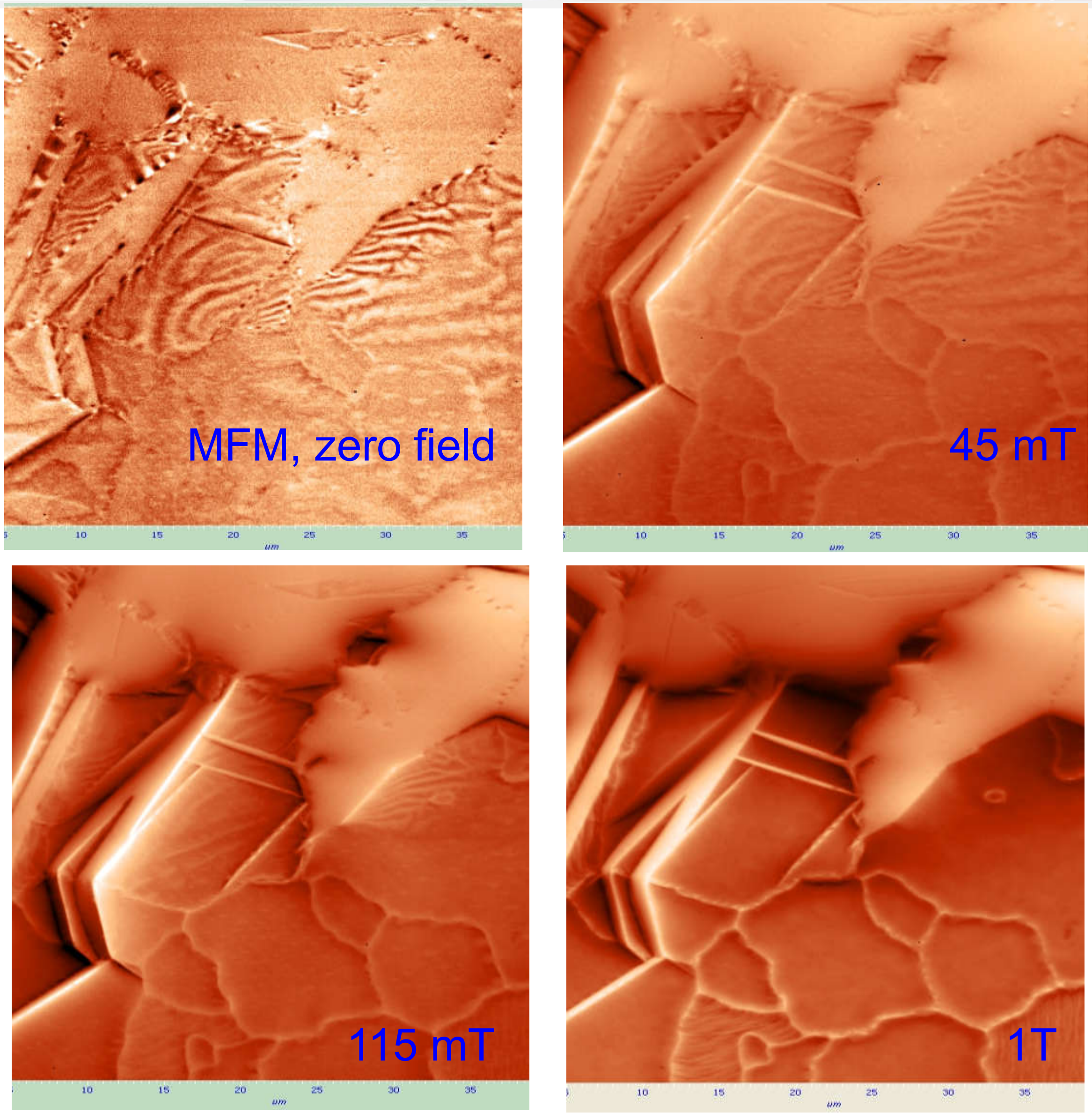
Magnetic shape-memory alloy

G. Crouigneau et al.

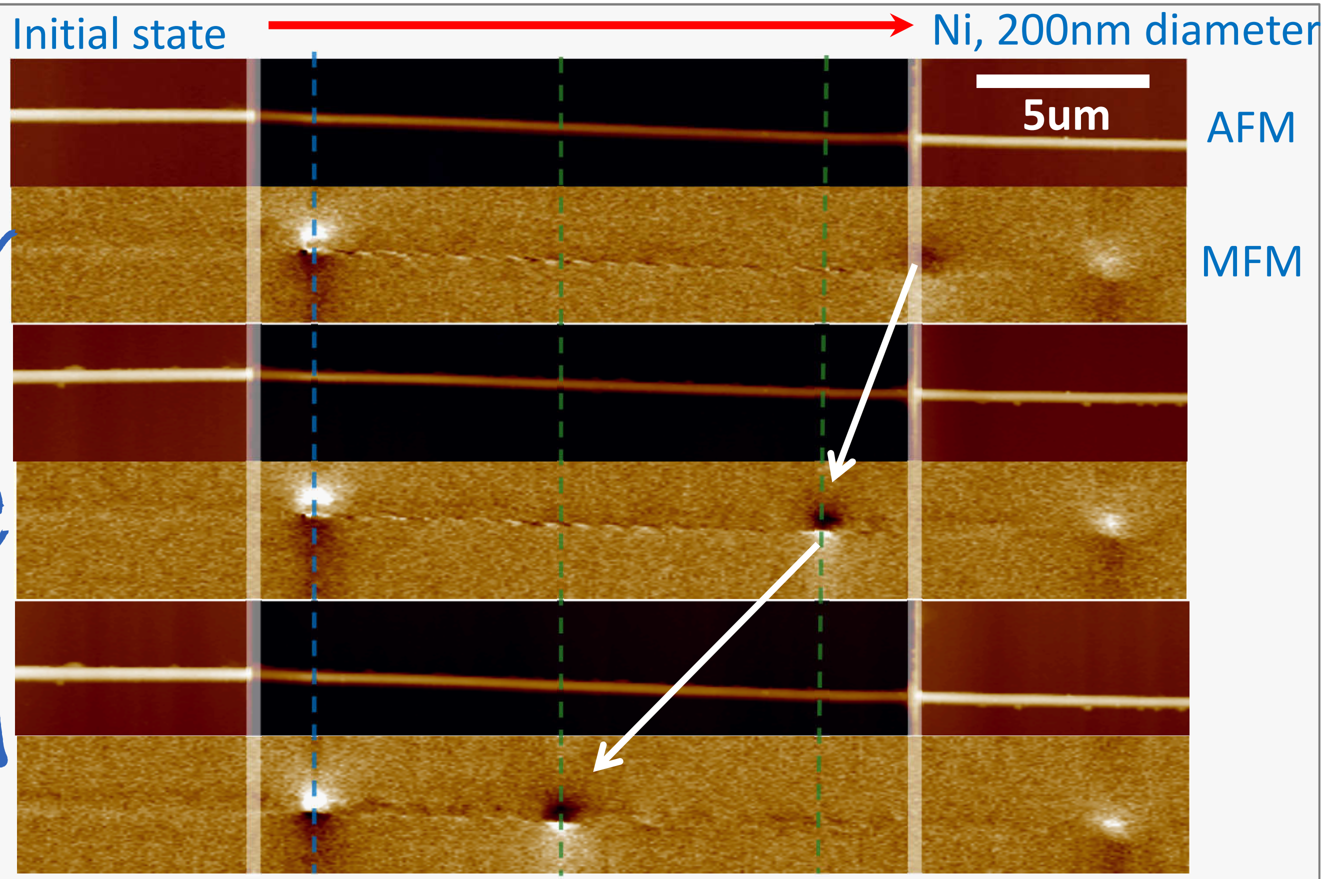


Topography (grains)

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



Domain-wall motion

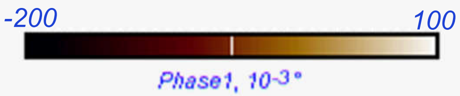


$j \quad 1.5 \cdot 10^{12} \mathrm{A/m^2}$

during 30 ns

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

during 30 ns



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

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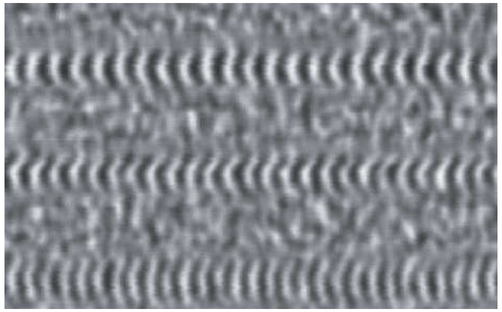
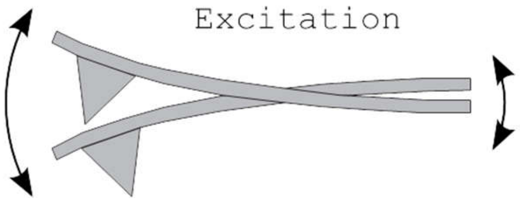
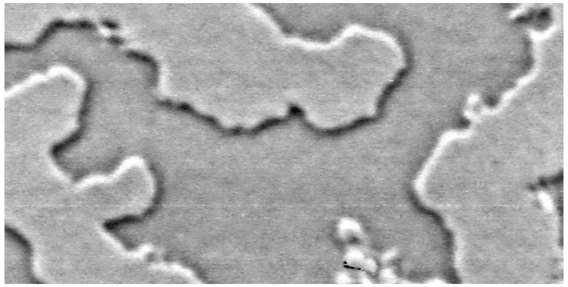
- Motivation and criteria



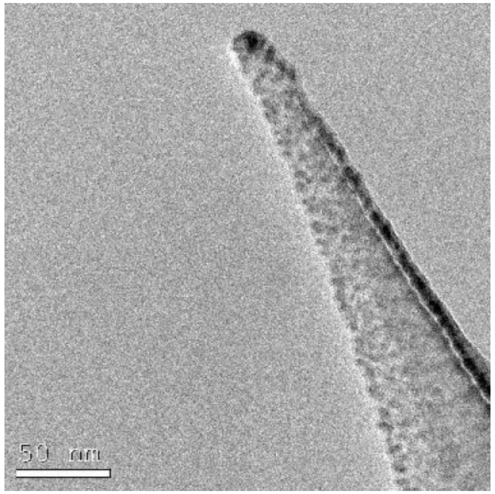
- Working principle



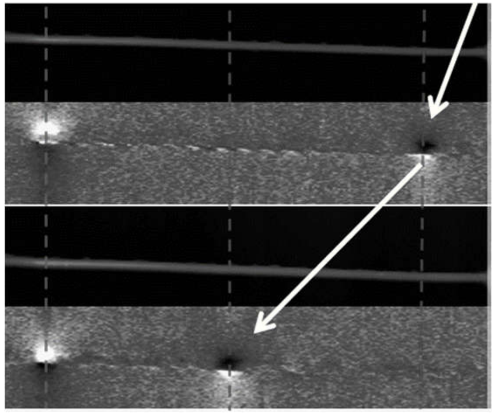
- Image analysis



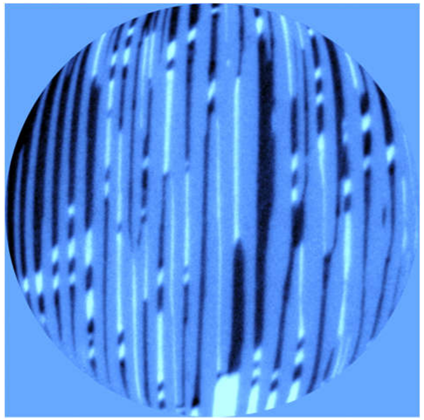
- Choice of tips



- Operando imaging



- Panorama of other microscopies



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 ?

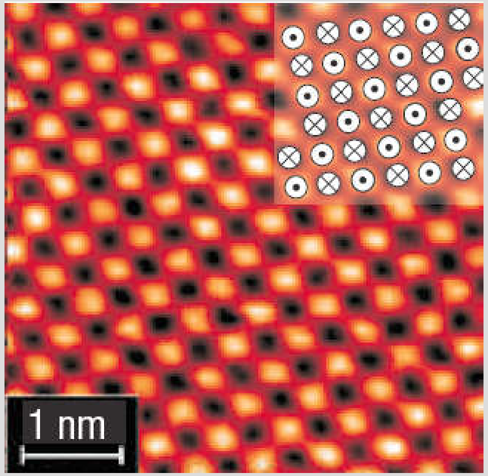
Conclusion

No universal technique

Many criteria to be balanced

Spin-polarized STM

Fe(1ML)/W(001)



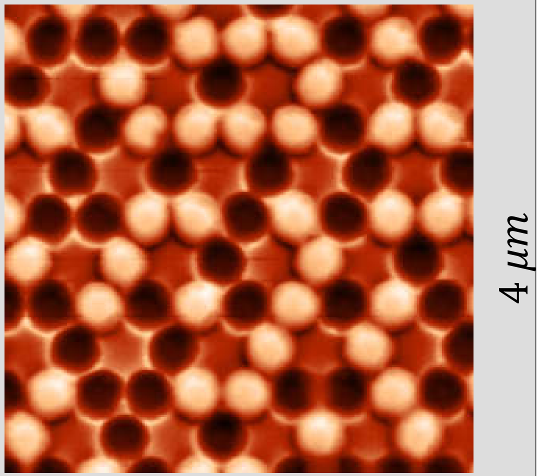
Antiferromagnetic domain

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

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

Magnetic Force Microscopy

Array of dots



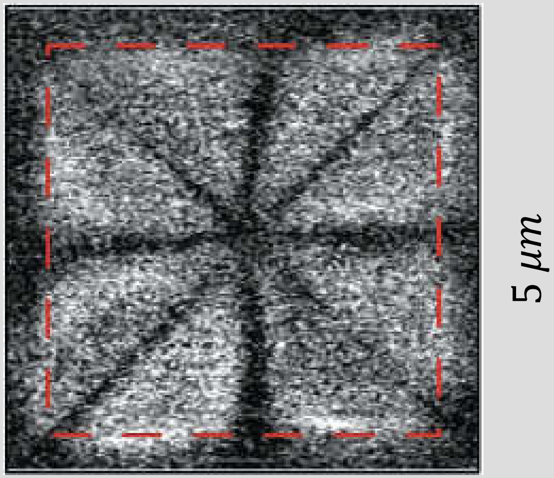
Up-and-down 'single-domains'

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

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

NV center microscopy

Square Fe20Ni80 dot



Signature of flux-closure

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

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

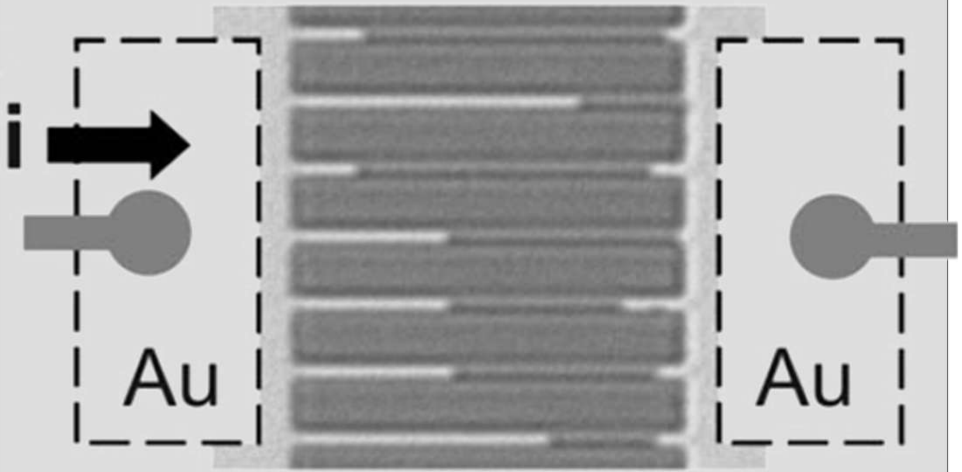
Overview
- Large variety
- Rather slow

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



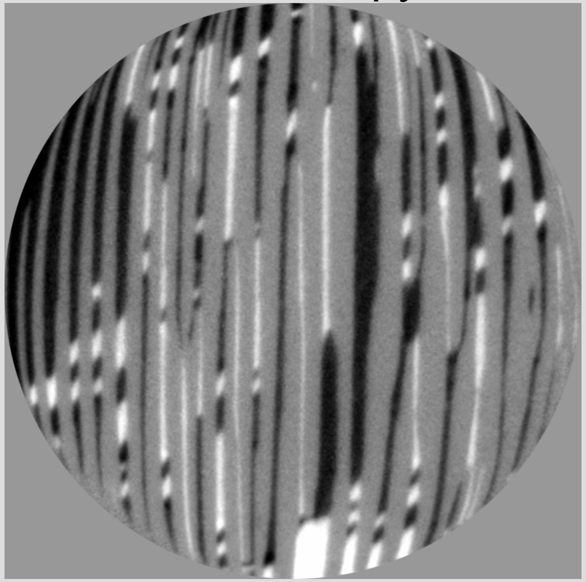
@NEEL : T. A. Moore et al., Appl. Phys. Lett 93, 262504 (2008)

Overview

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

SPLEEM

Spin-Polarized Low Energy Electron Microscopy

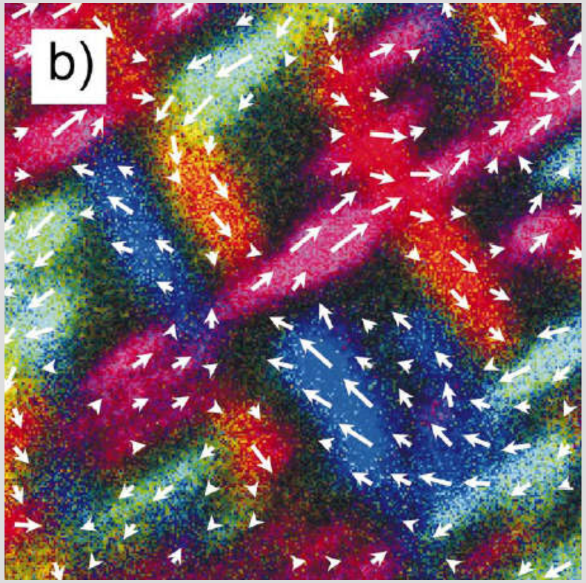


Stripes of Fe/W(110)

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

SEMPA

Scanning Electron Microsc. with Polarization Analysis

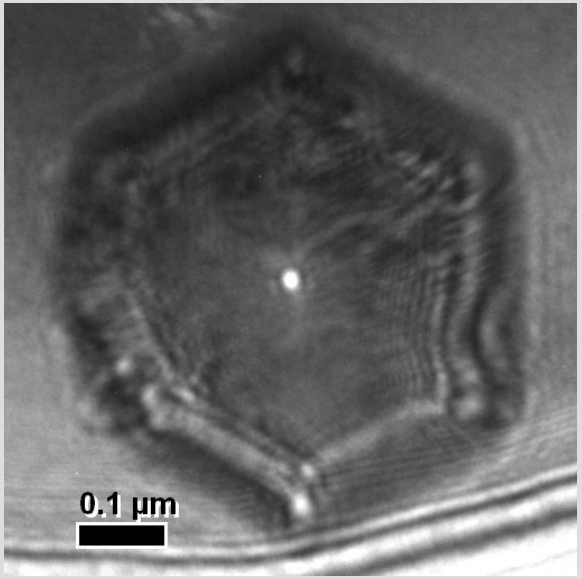


Maze of Fe/W(001) $1.5\ \mu m$

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

Lorentz, holography etc.

TEM - based



Self-assembled Co/W(110)

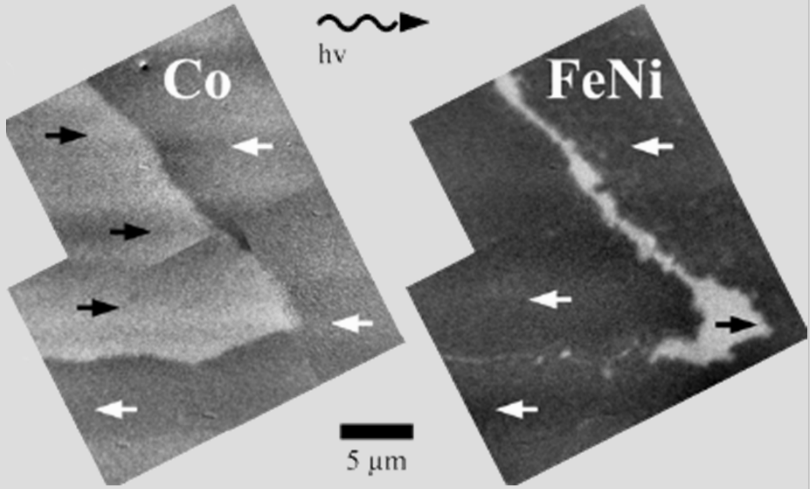
@NEEL :
O. Fruchart et al., J. Phys. Condens. Matter 25, 496002 (2013)

Overview

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

XMCD-PEEM

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

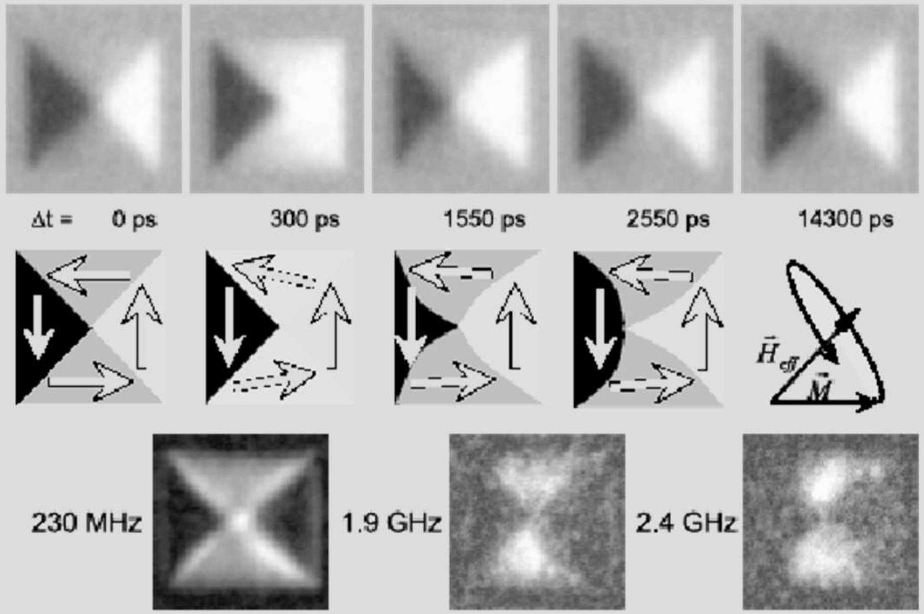


Co\Cu\FeNi trilayer
→ elemental resolution

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

TXM

Transmission X-ray Microscopy

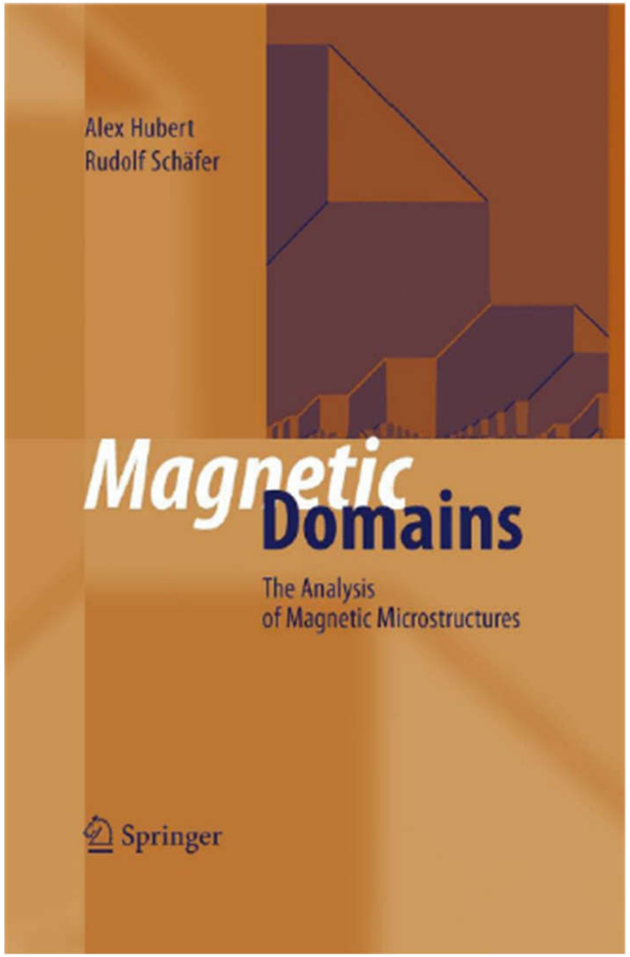


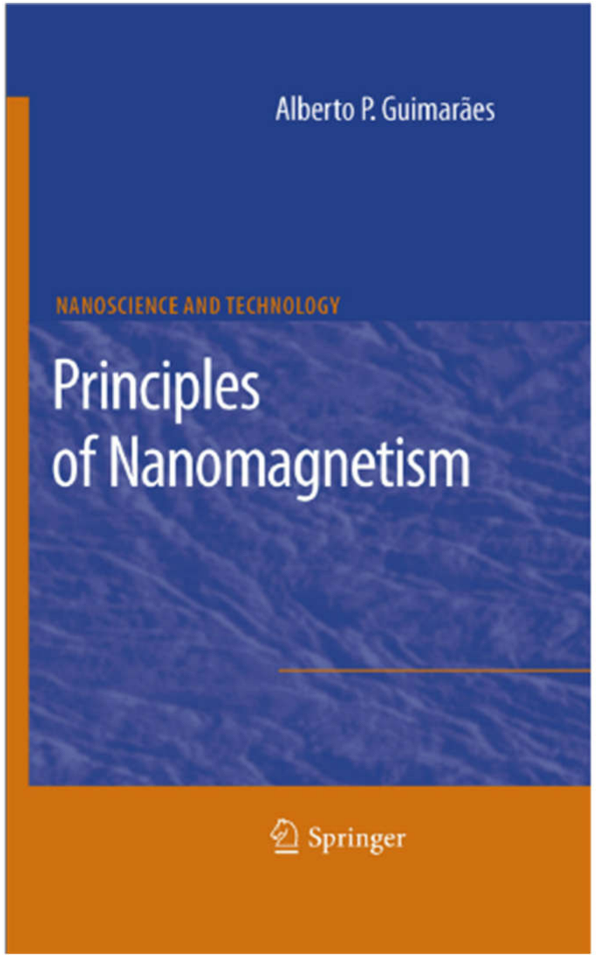
FeNi 6µm square dot → time resolution

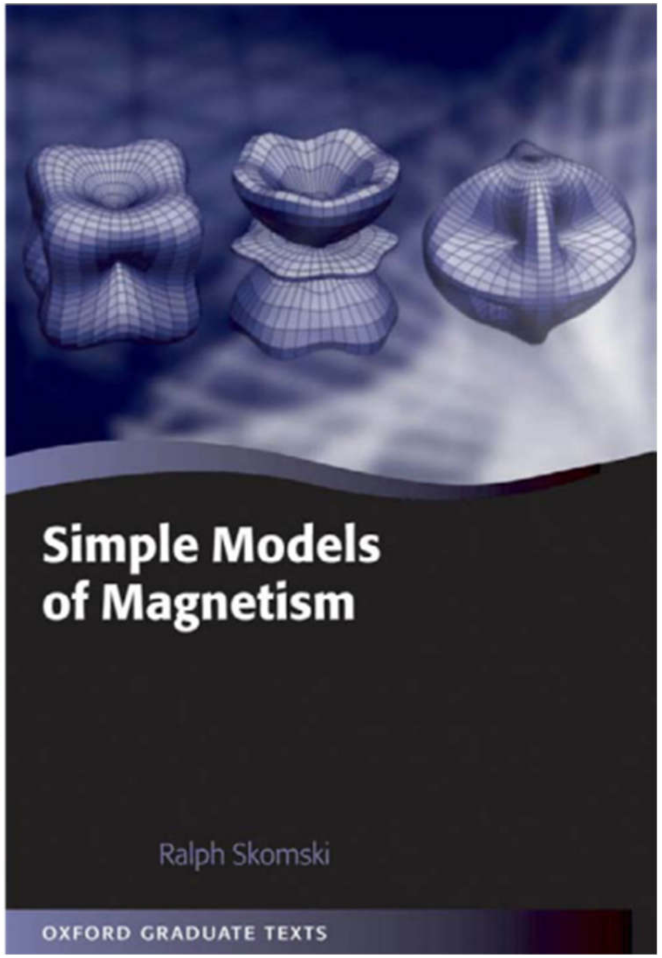
J. Raabe et al., Phys. Rev. Lett. 94, 217204 (2005)

Others : holography, scattering

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


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

Thank you for your attention !

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http://fruchart.eu/slides