Magnetic Force Microscopy
Illustration of the trilemma
Sensitivity – Spatial Resolution – Probe response

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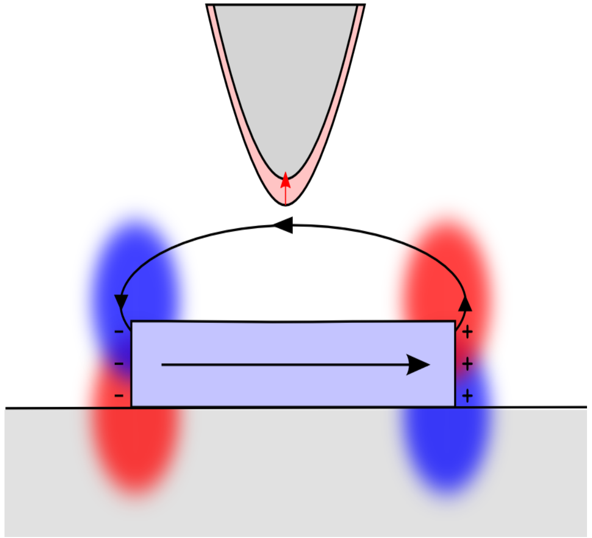
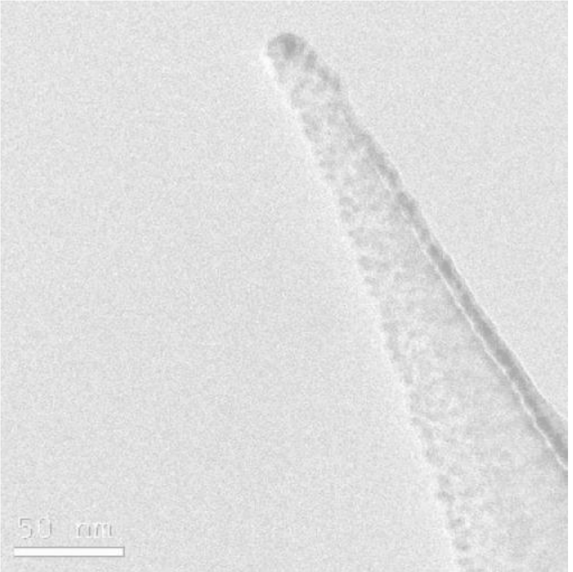
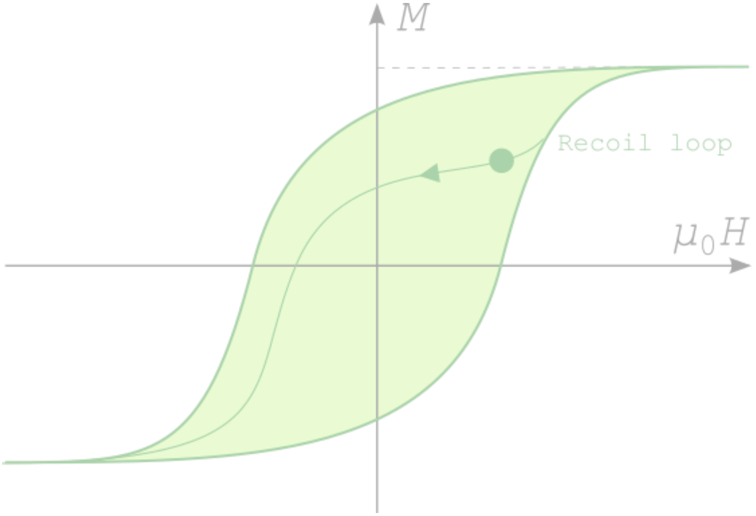
- MFM contrast



- MFM tips



- MFM in magnetic field

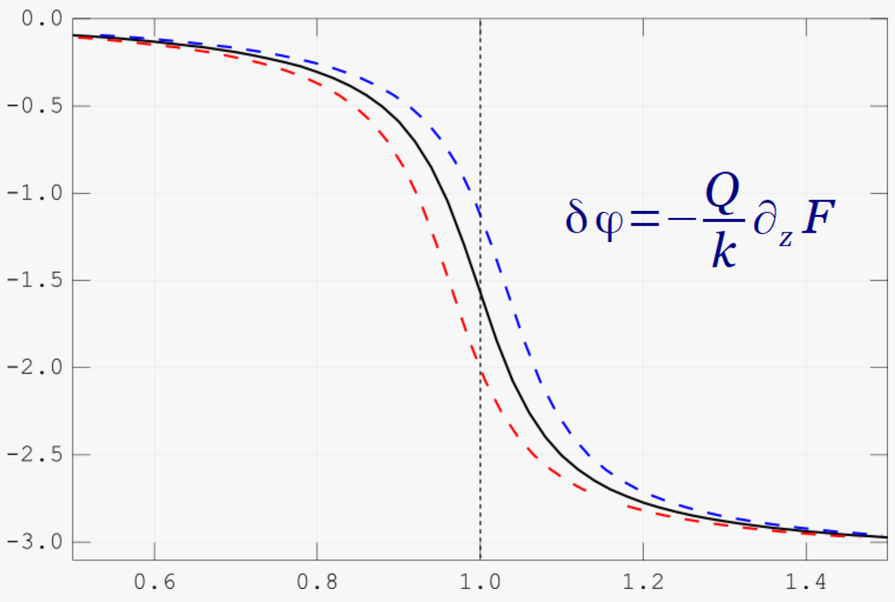


Tip-sample interaction treated as perturbation

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

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

Phase shift



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

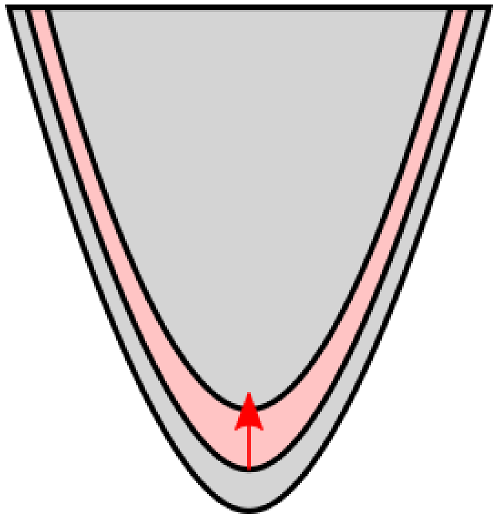
$$\omega_{exc}=\omega_o$$

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 contrast – Standard tips



AFM tip + magnetic coating

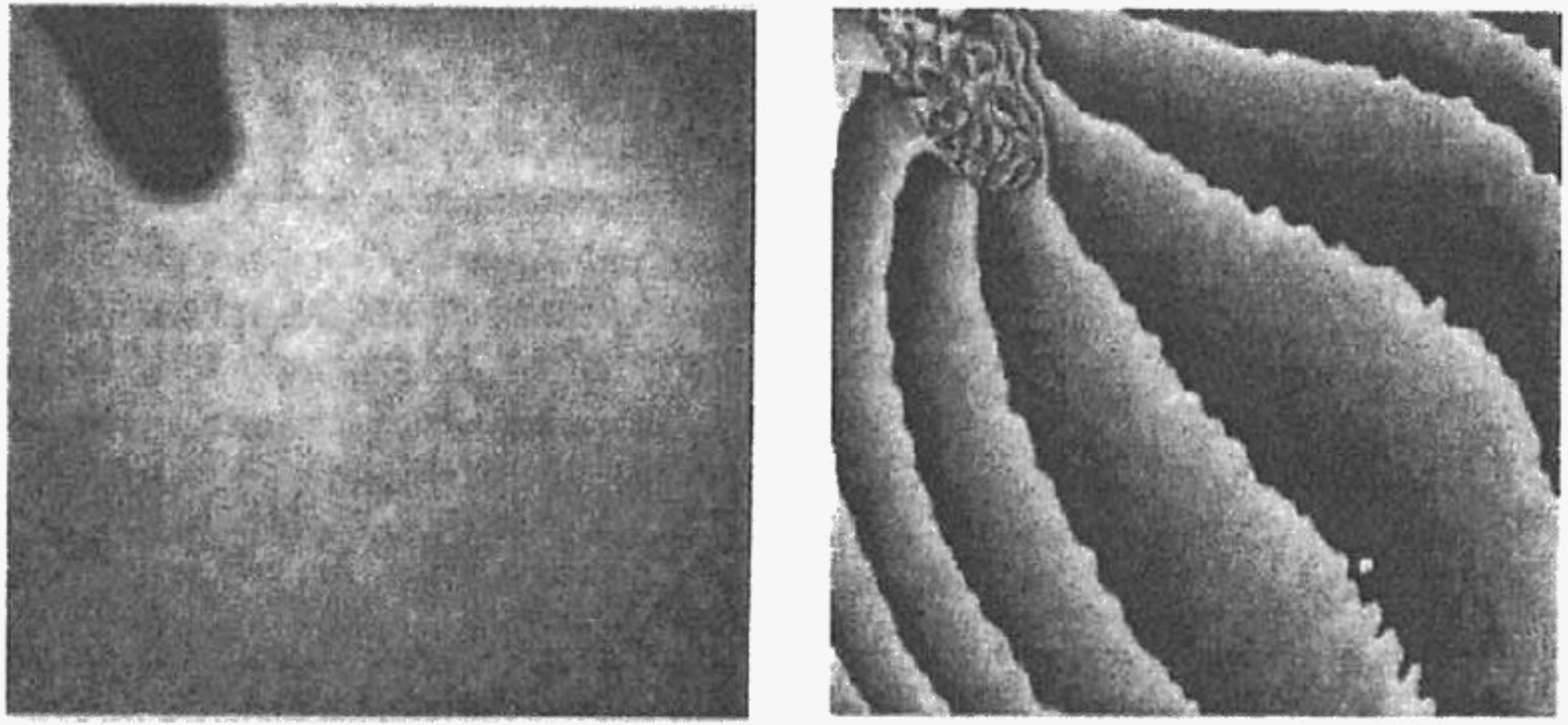


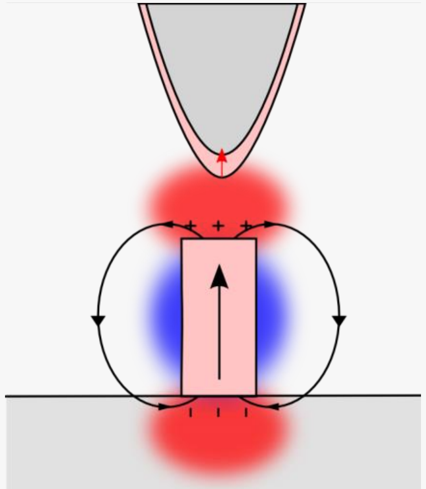
Figure 11-20: The electron amplitude (left) and phase (right) near an MFM tip visible as a dark shadow on the upper left corner of the left image.

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

MFM contrast – Tip/sample interaction

Tip is a dipole

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

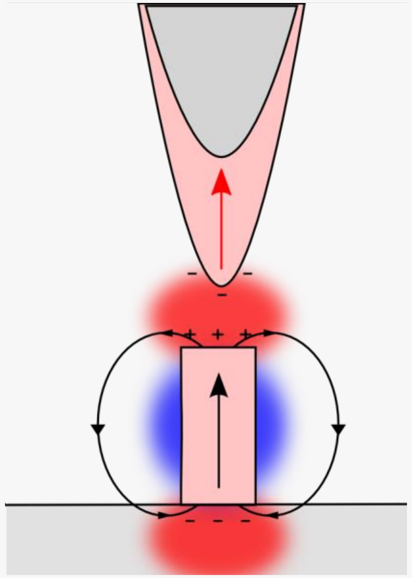


$$E_{1,2} = -\mu_0 \left(\mu_x . H_{\mathrm{d},x} + \mu_y . H_{\mathrm{d},y} + \mu_z . H_{\mathrm{d},z} \right)$$

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

Tip is a monopole

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



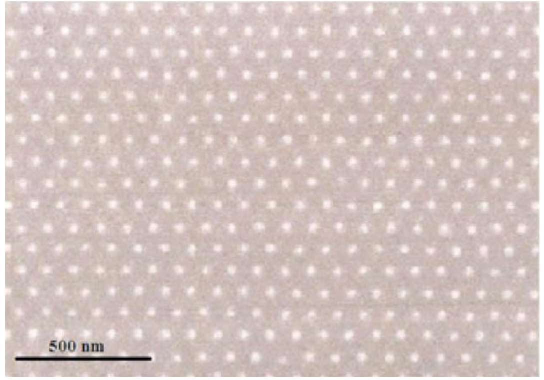
$$F_z = -\mu_0 \sigma H_{\mathrm{d},z}$$

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

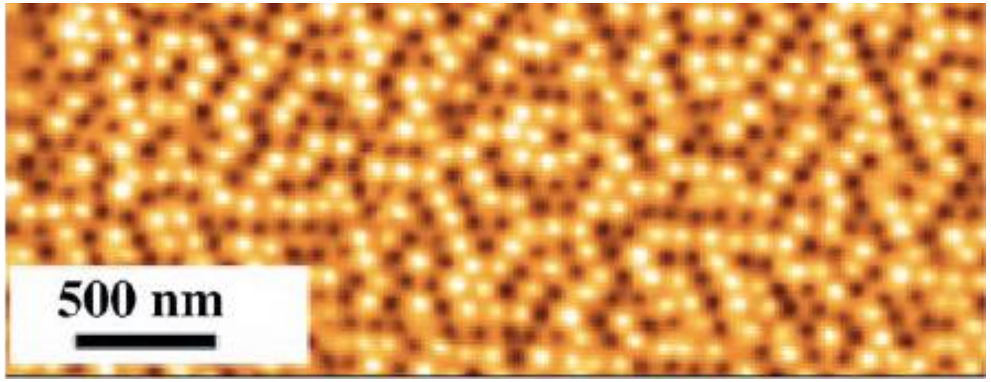
- In practice, a combination of both models is best suited (dipole is more important)
- MFM is sensitive to some derivative(s) of the stray field from the sample
- MFM may be sensitive to in-plane field, depending on the tip magnetic moment

MFM contrast – Single-domain (perpendicular)

Structure (SEM)

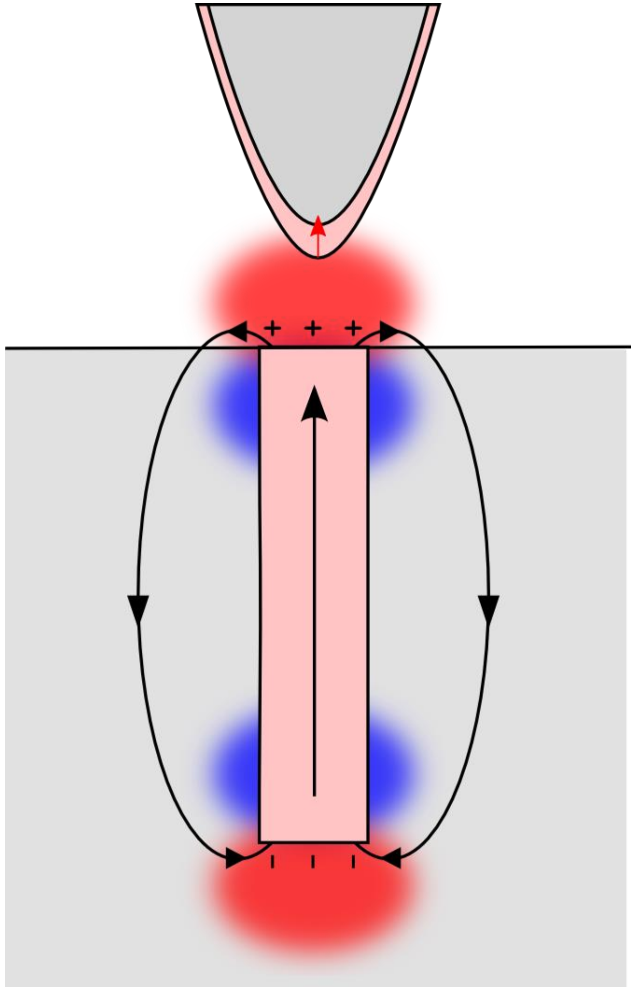


MFM, partly reversed



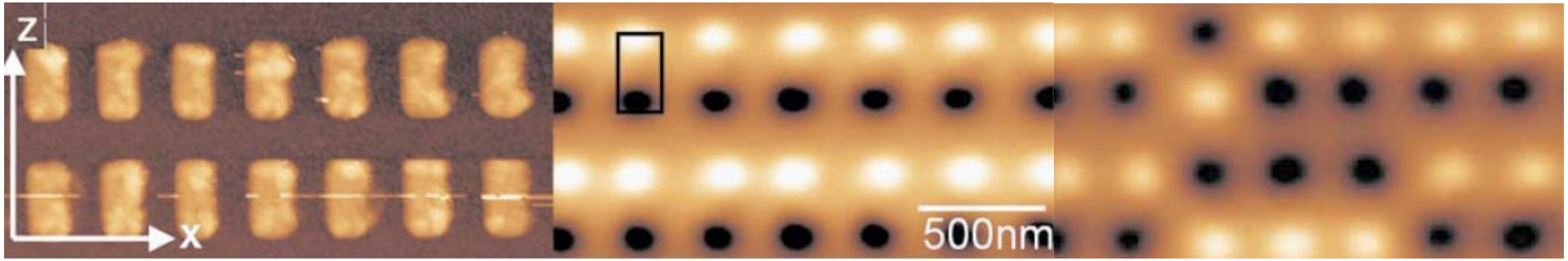
T. Wang et al., APL 92, 192504 (2008)

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

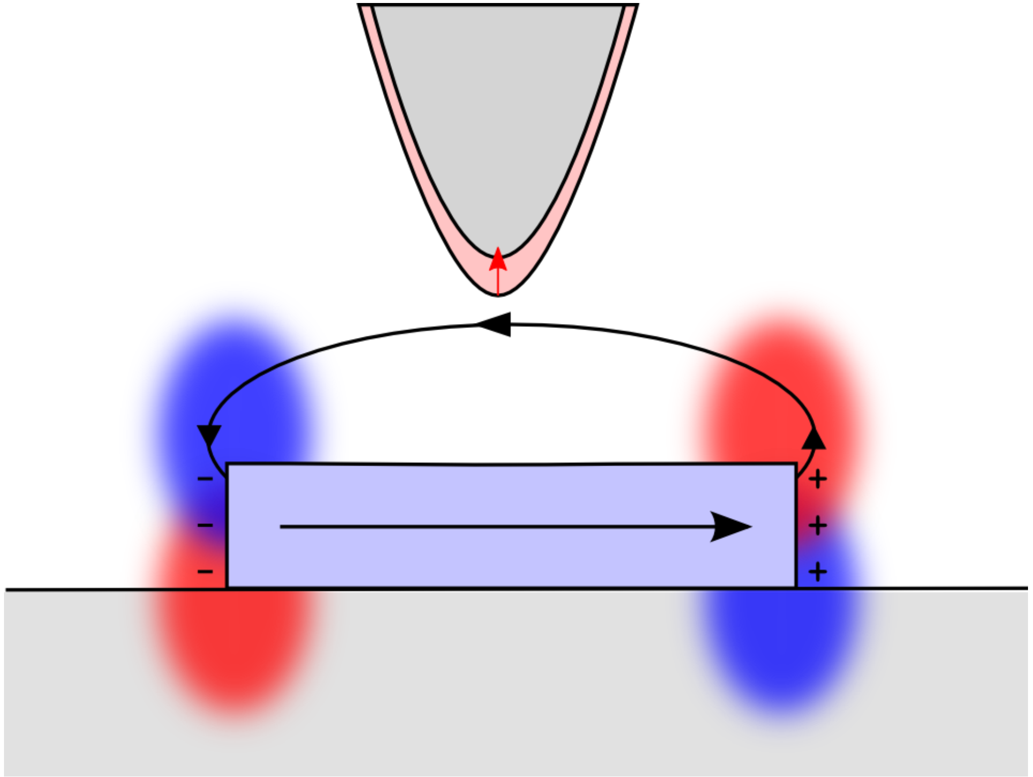


MFM contrast – Single-domain (planar)

Topography MFM, saturated MFM, partly reversed



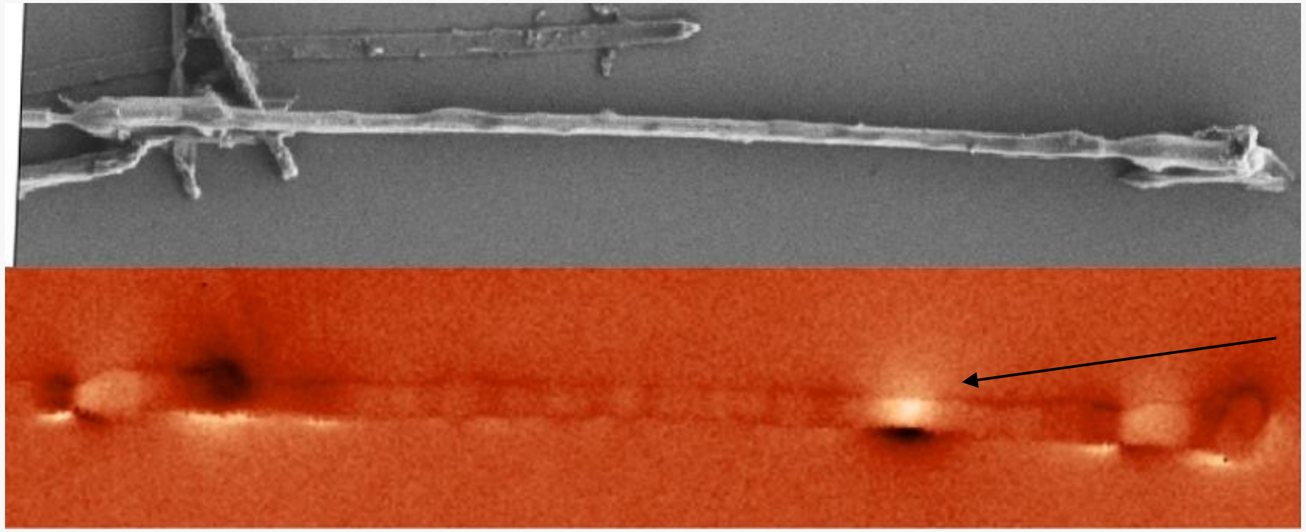
S. Y. Suck et al., APL95, 162503 (2009)



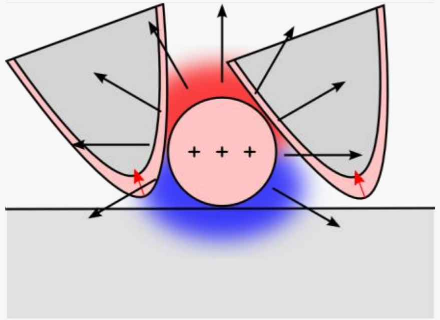
- Single-domain in-plane magnetized dots appear as dipoles

MFM contrast – Effect of tilted cantilever and tip

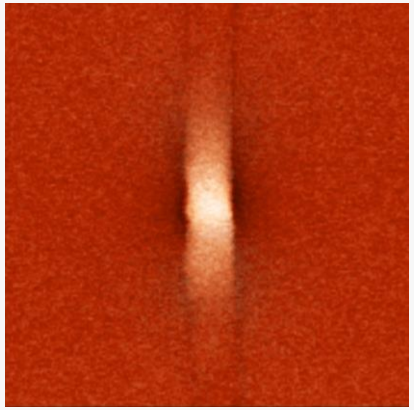
Tilted cantilever, across wire

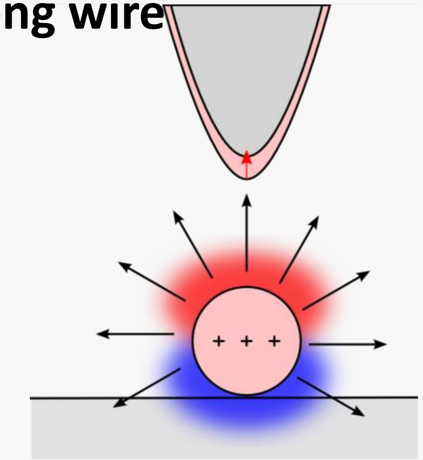


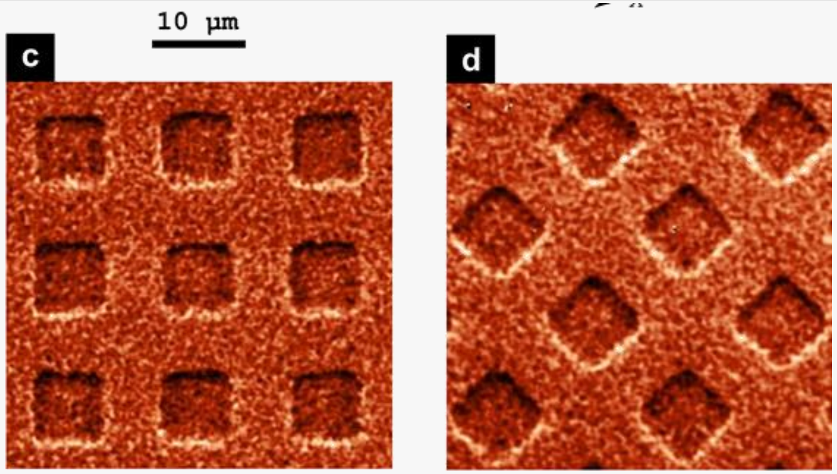
S. Da Col et al., APL109, 062406 (2016)



Tilted cantilever, along wire



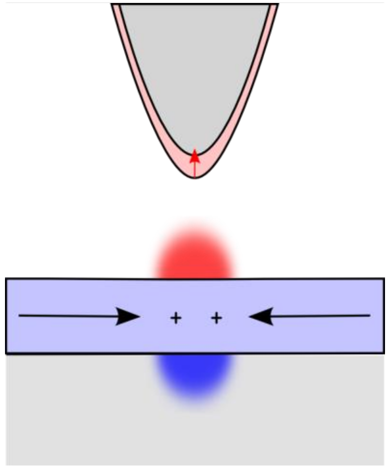


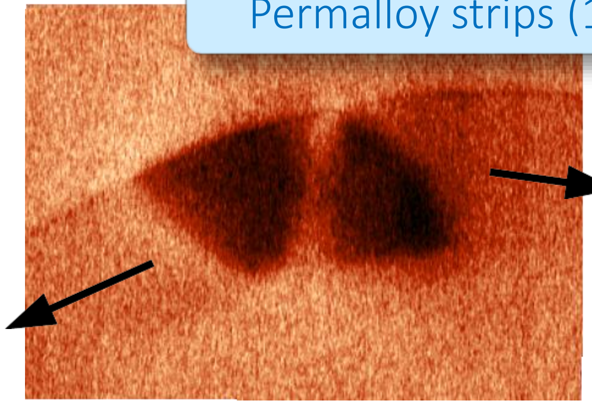


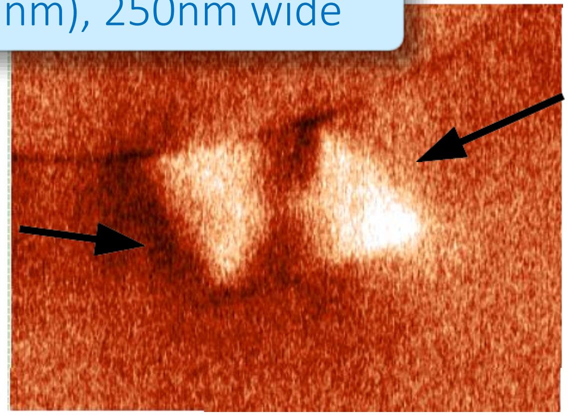
G. Ciuta, IEEEtm 52, 6500408 (2016)

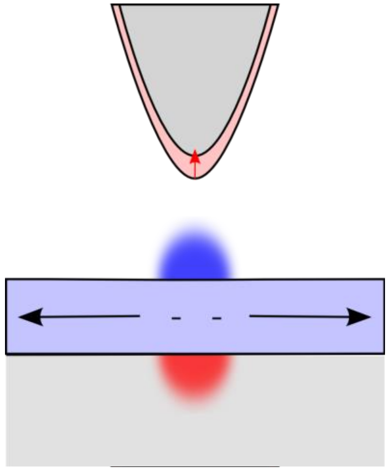
MFM contrast – Domain walls

Permalloy strips (15nm), 250nm wide



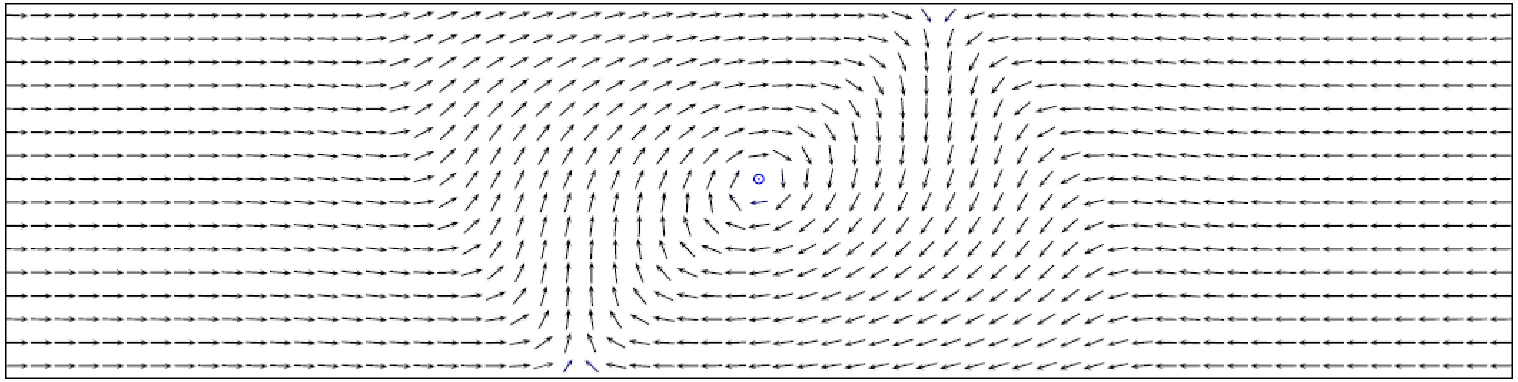






Contrast : ±0.3°,
tip 5nm CoCr

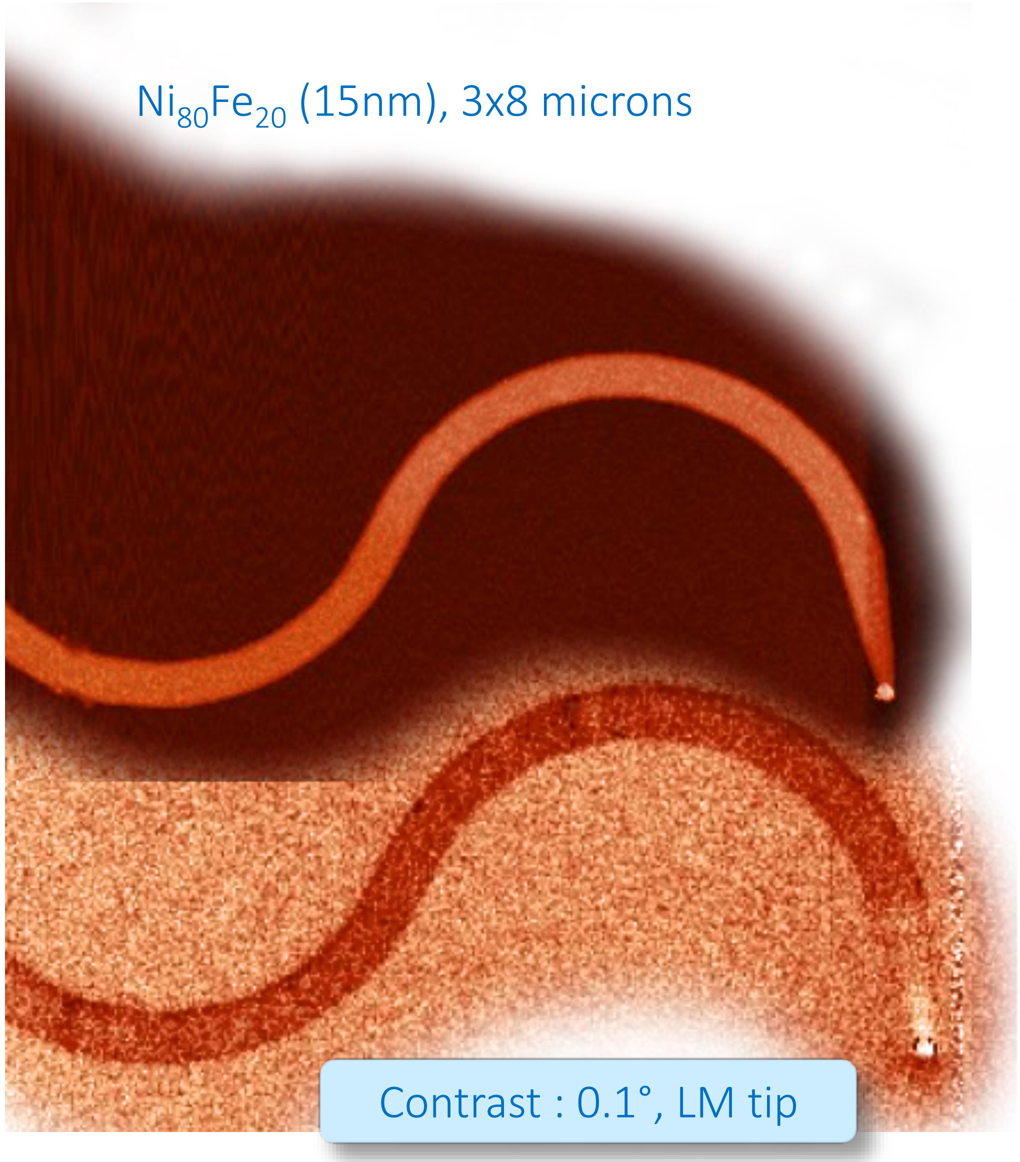
Known as vortex domain wall



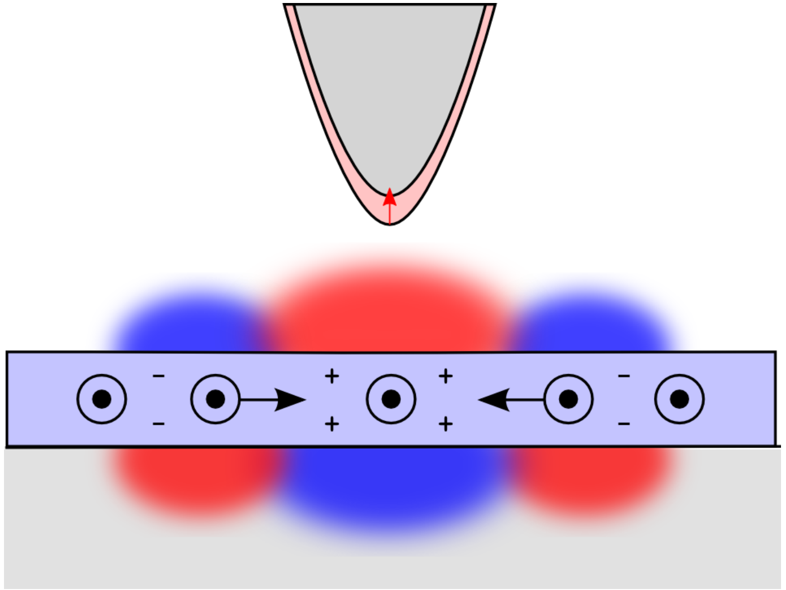
R. McMichael and M. Donahue, IEEE Trans. Magn. 33, 4167 (1997)

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

MFM contrast – In-plane domains (mutual interaction)



Lithography : S. Pizzini (Institut Néel)

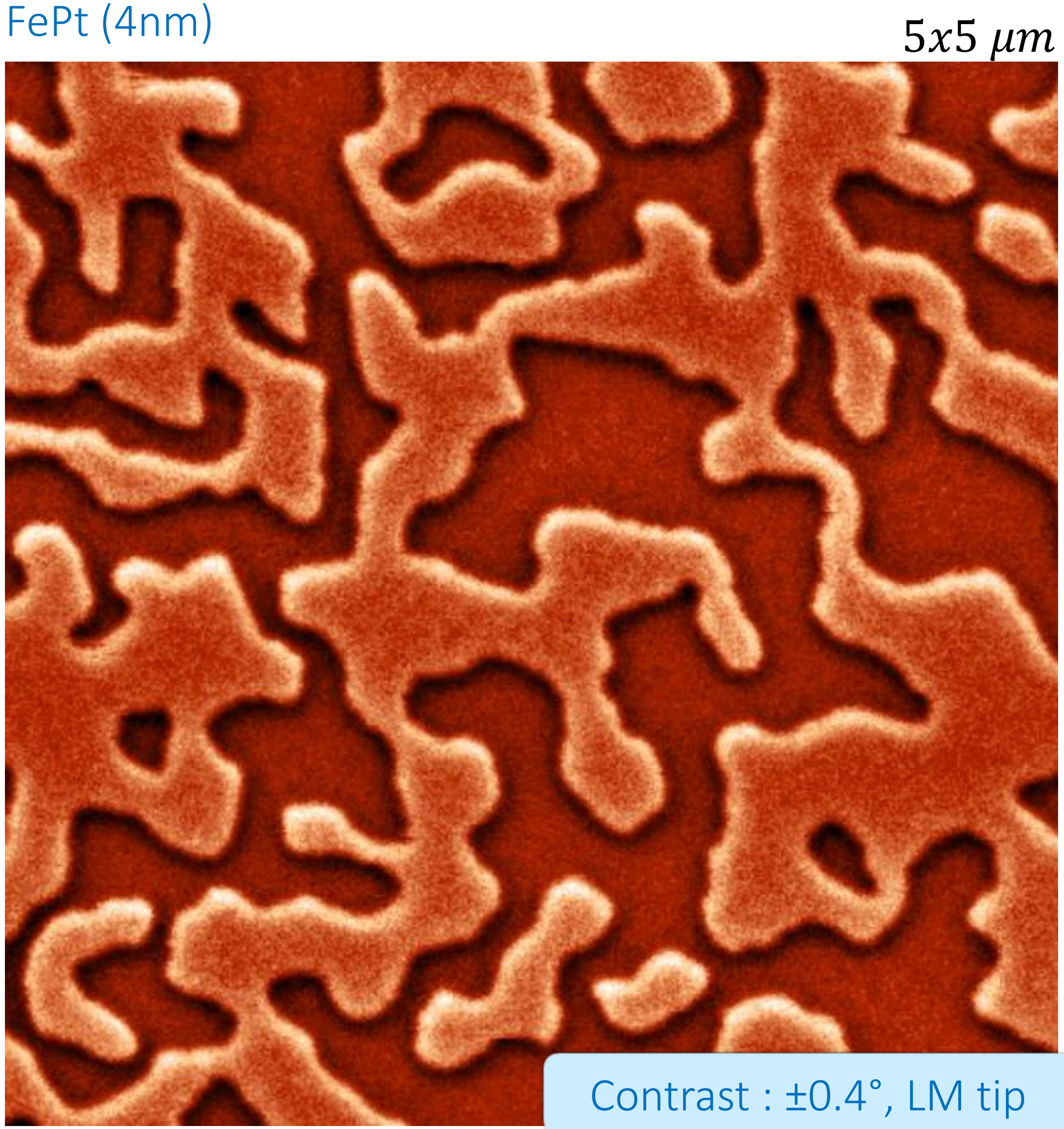


Principle :

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

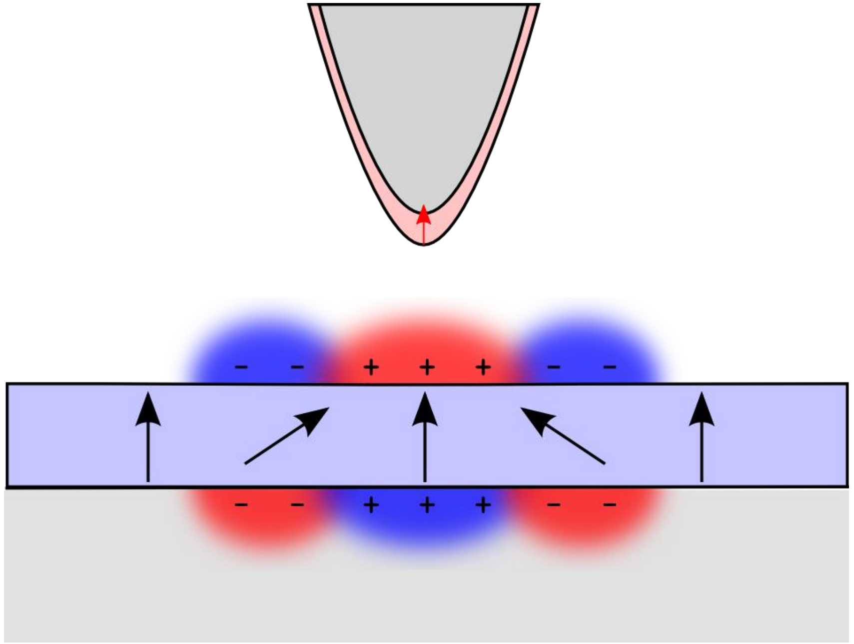
- It is a DOMAIN contrast
- Interaction is ALWAYS attractive : red shift
- Contrast proportional to squared tip moment
- Direction of magnetization not measured

FePt (4nm)



Contrast : ±0.4°, LM tip

Sample : A. Marty (SPINTEC)



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

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

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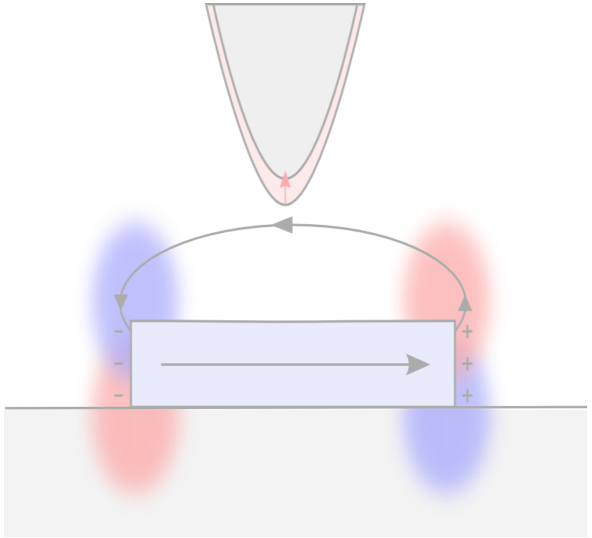
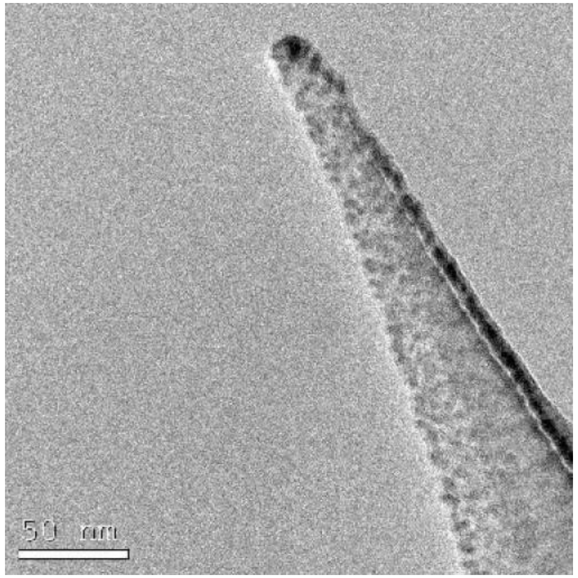
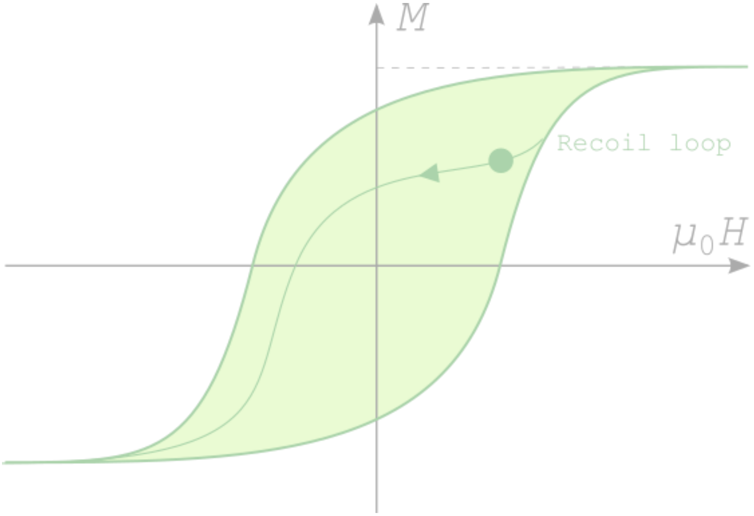
- MFM contrast



- MFM tips



- MFM in magnetic field

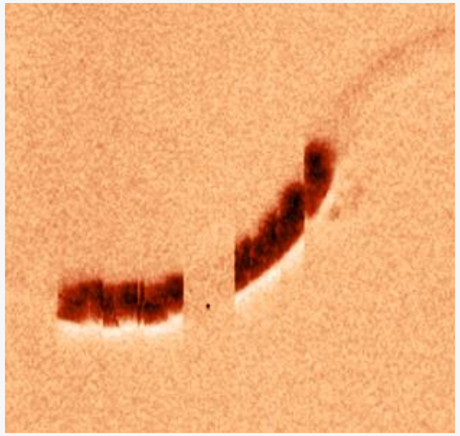


MFM tips – Tip influencing samples

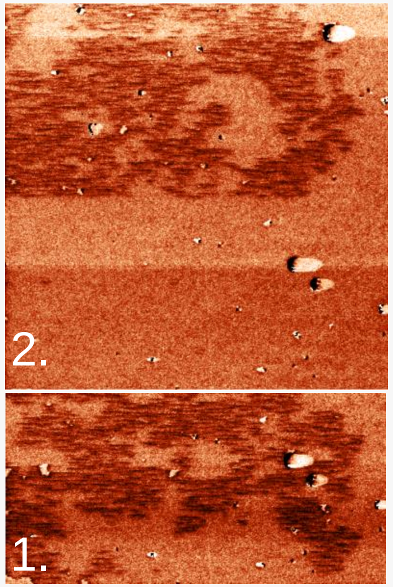
High

Scanning

Attraction



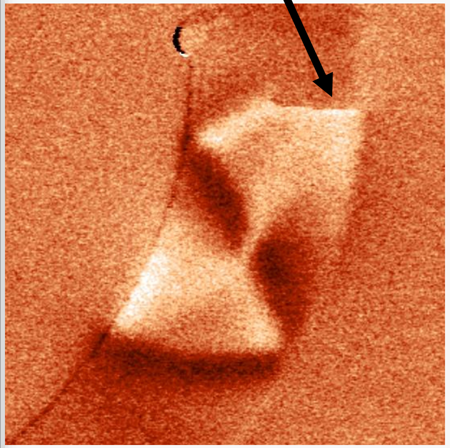
Permalloy (15nm)
500nm strips
Sample : S. Pizzini



Co (0.6nm)/
graphene (20 mic)

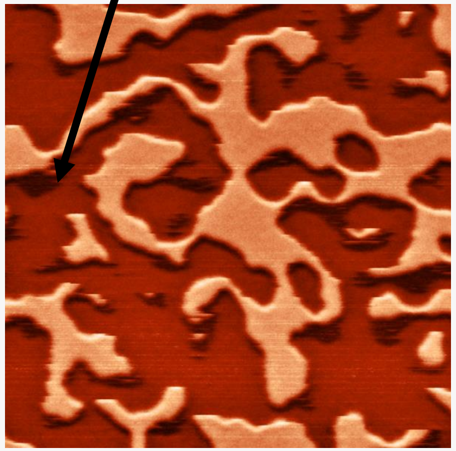
Moderate

Repulsion



Permalloy (15nm)
500nm wide
Sample : S. Pizzini

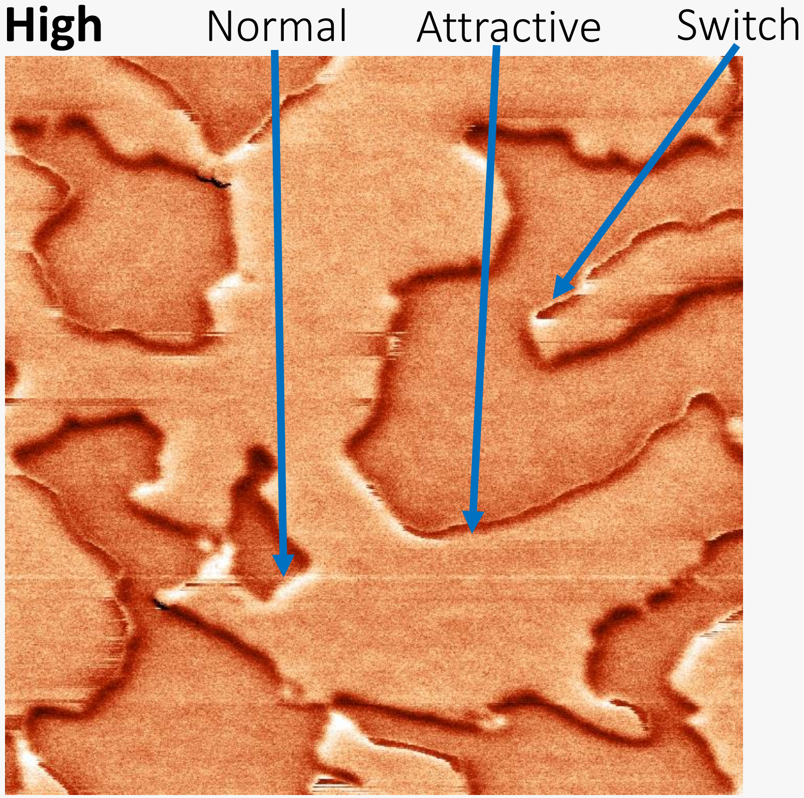
Attraction



FePt (4nm)
Image 5 microns
Sample : A. Marty

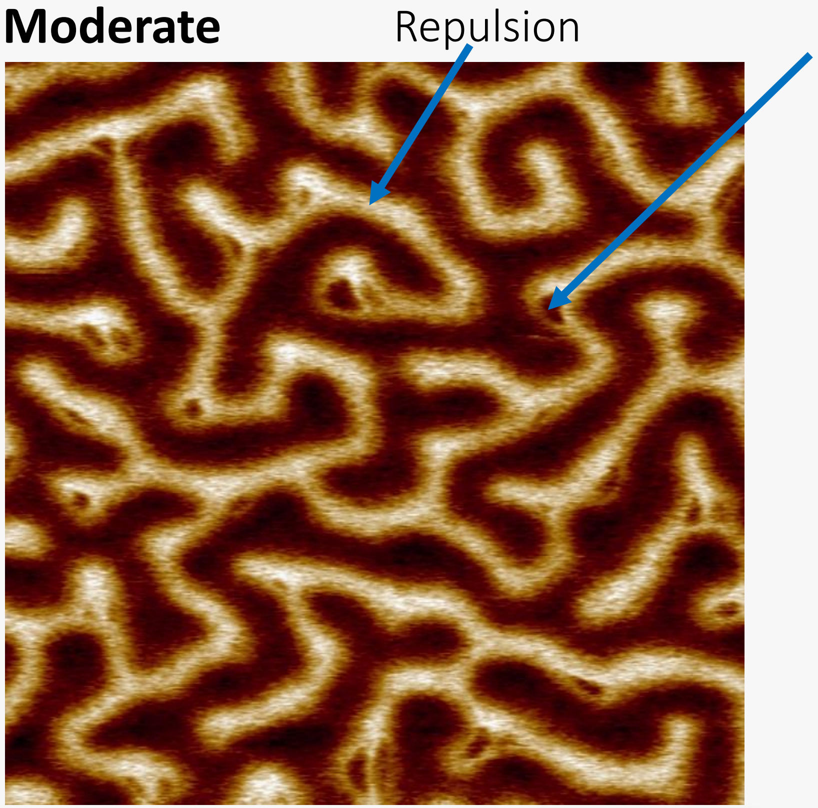
- Repeat measurement and/or change scanning direction
- Low-coercive samples require low-moment tips
- Commercial 'low-moment' may not be low enough

MFM tips – Sample influencing tips



FePt(001) 4nm
Sample: Alain Marty

2x2 µm

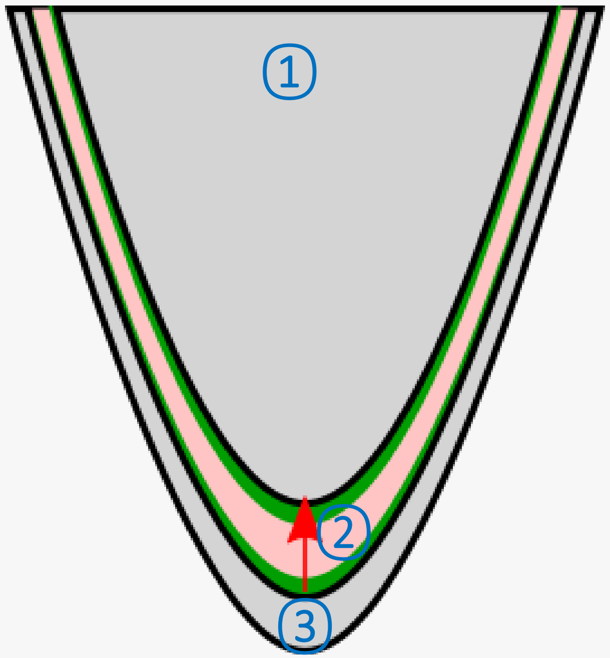


Pd/Co/Au multilayers
Sample: Chloé Bouard

2x2 µm

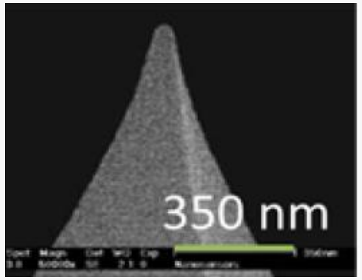
- Sharp reversal features, and/or streaks parallel to fast direction
- Occurs at the highest repulsive fields

AFM tip + magnetic coating

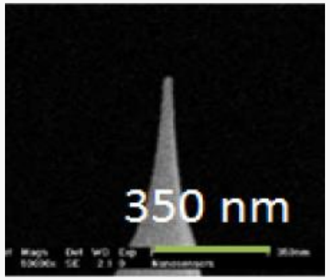


1 Non-magnetic tip

- Cantilever stiffness/inertia/frequency: sensitivity, scanning speed…
- Tip sharpness
  Spatial resolution



Asylum 240TS
Radius : 10 nm



Nanosensors PPP-SSS
Radius: 2-5 nm

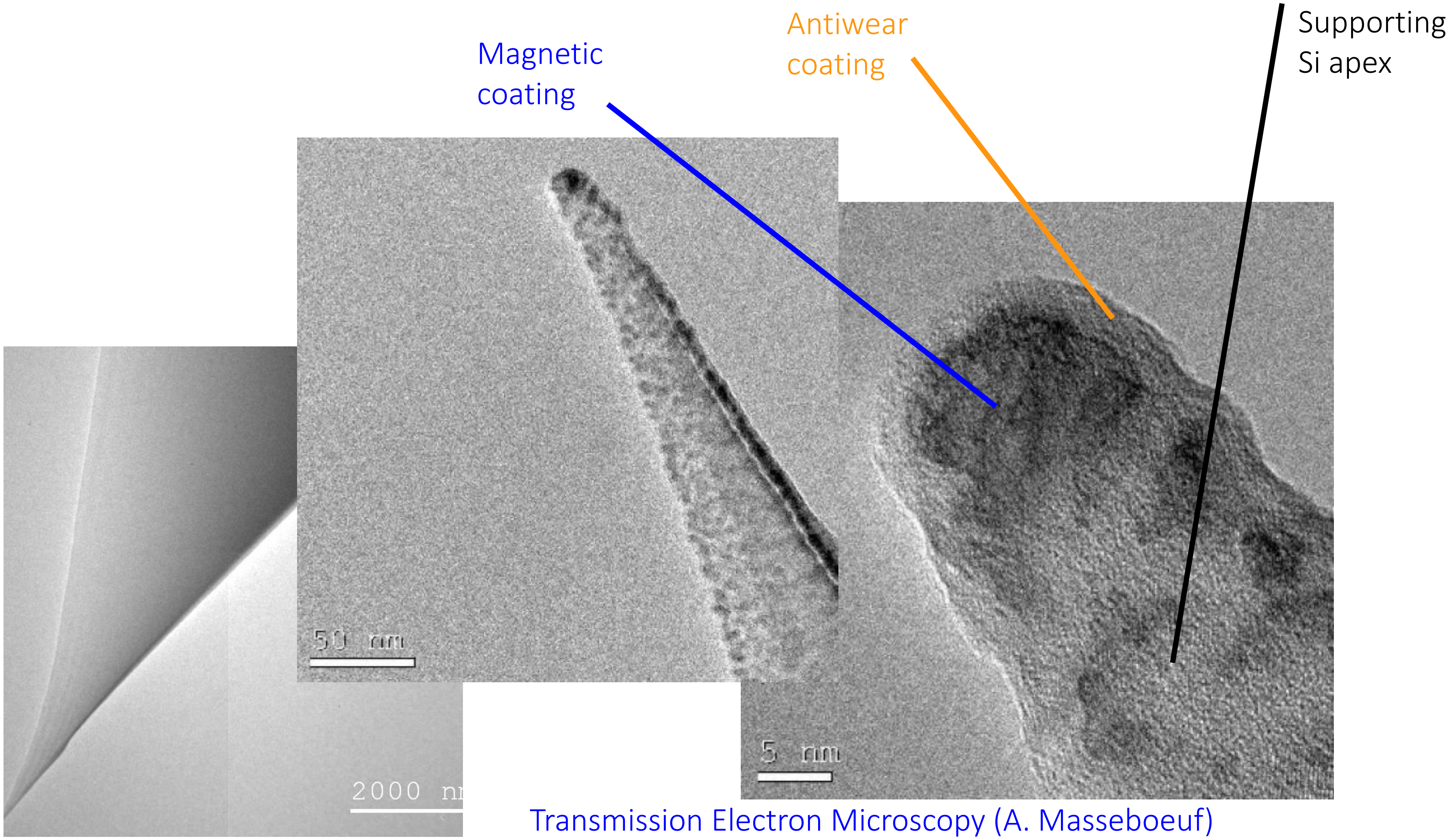
2 Magnetic material

- Alloy and under/overlayers determine properties
- CoCr (≈80/20%) usual choice
  Co grains with exchange-decoupling Cr boundaries
- Pt: enhance coercivity
- NiFe (≈80/20% permalloy).
  Soft-magnetic alloy
  Reduced stray field (less perturbation)
  Possibility of in-plane magnetized tip

3 Non-magnetic coating

- Protection: oxidation, mechanical wear
- Reduce tip-sample interaction

MFM tips – High-resolution tips

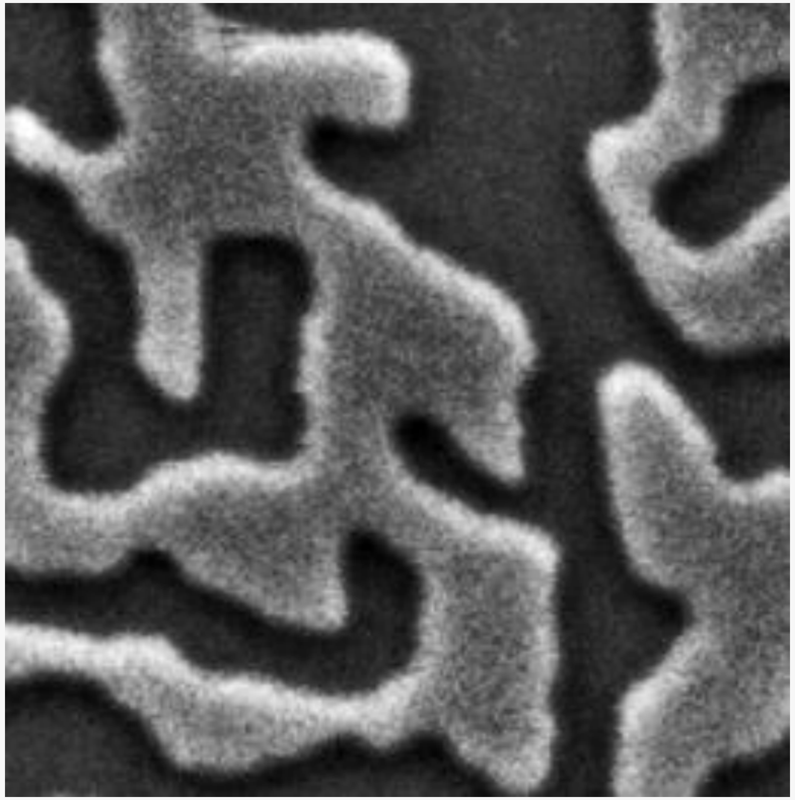


Transmission Electron Microscopy (A. Masseboeuf)

MFM tips – Coating thickness and susceptibility contrast

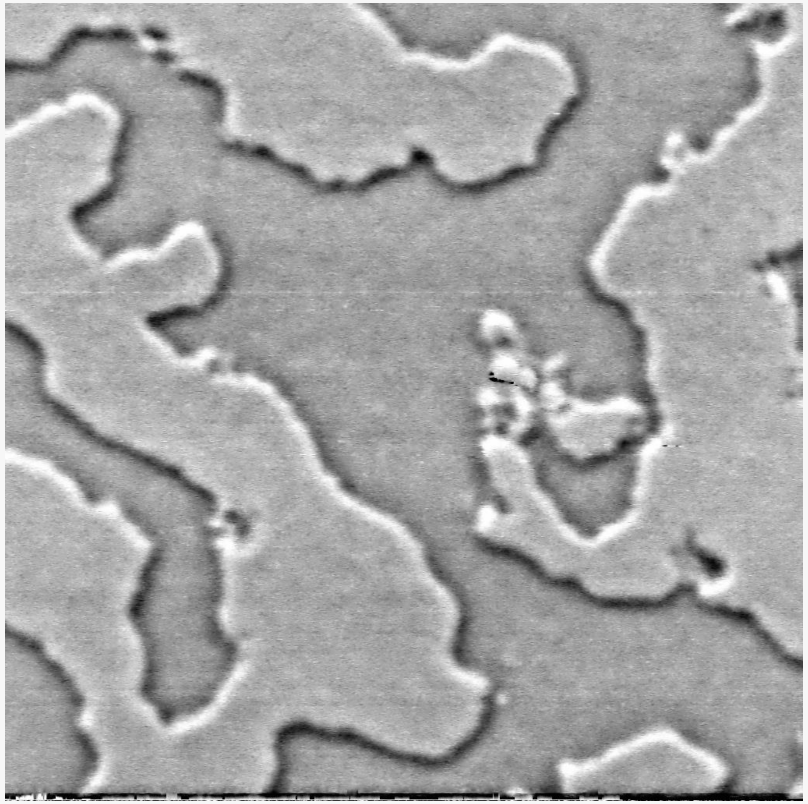
spintec SPIN IN ELECTRONICS

Medium coating



Tip : « Low-moment » commercial tip

Thin coating



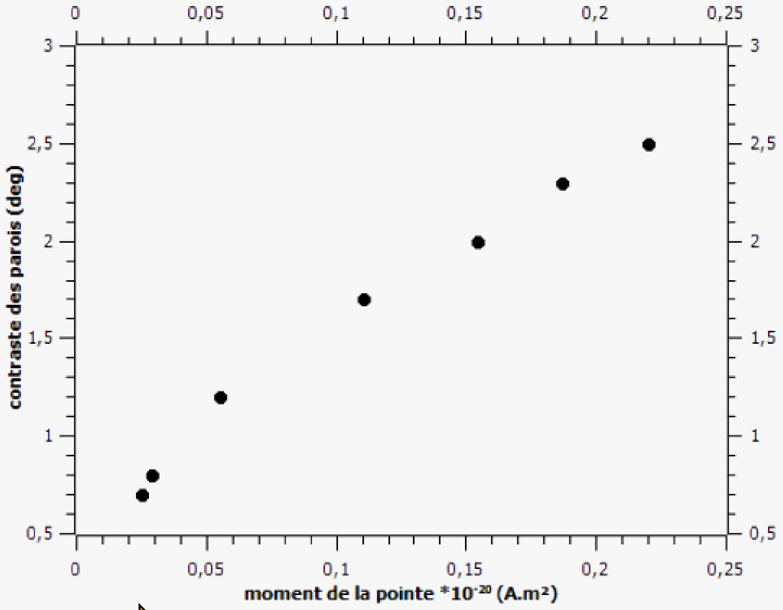
Tip : Nanosensors SSS \ 5nm CoCr
Fly height <10nm, amplitude 10nm

Sample: FePt[4nm]
-> Up/down domains
FoV: 2x2 µm

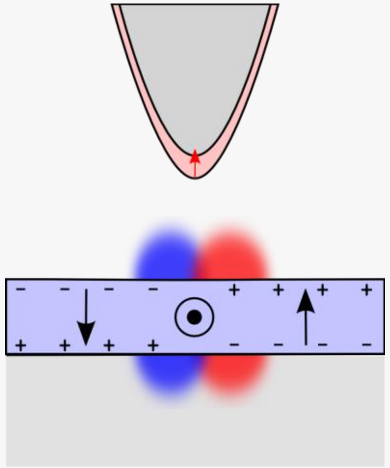
- Low-moment tips decrease the mutual-interaction contrast

MFM tips – Coating thickness and susceptibility contrast

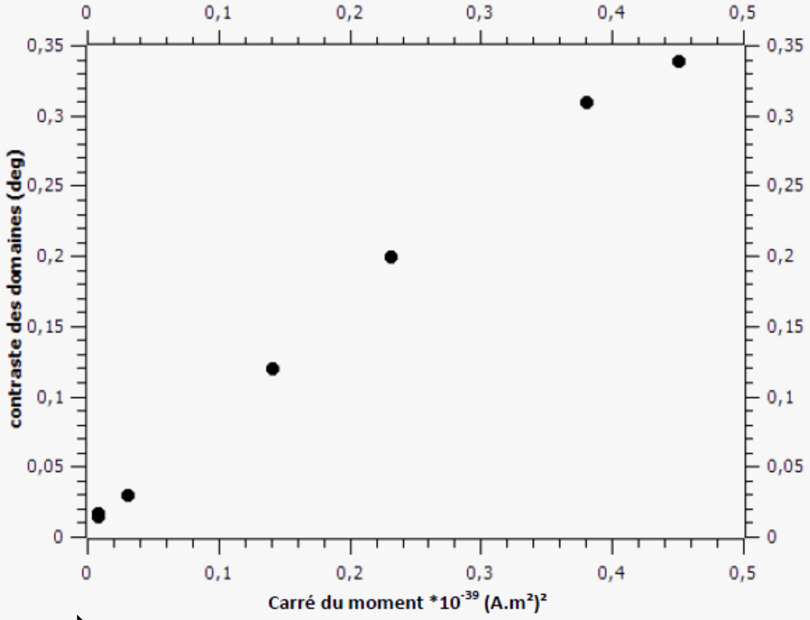
Domain-wall contrast



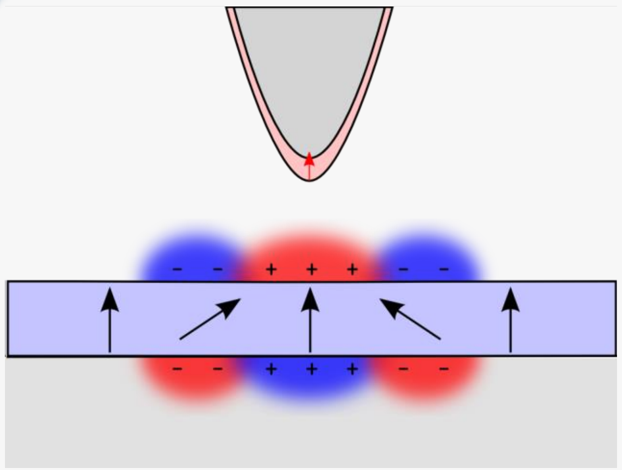
Linear with tip moment



Domain contrast



Linear with square of tip moment



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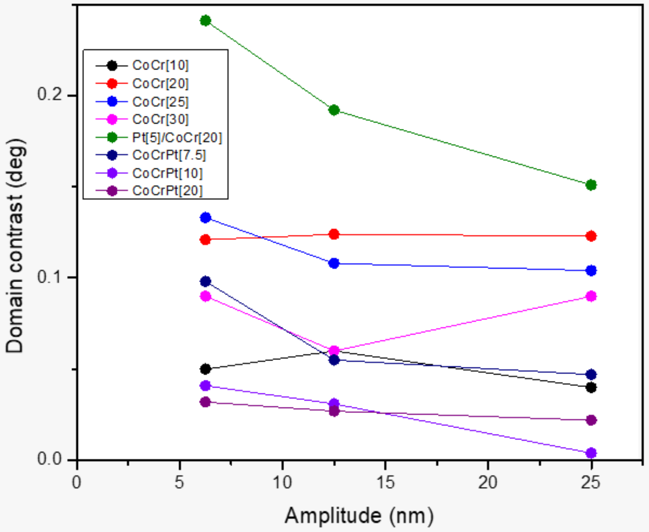
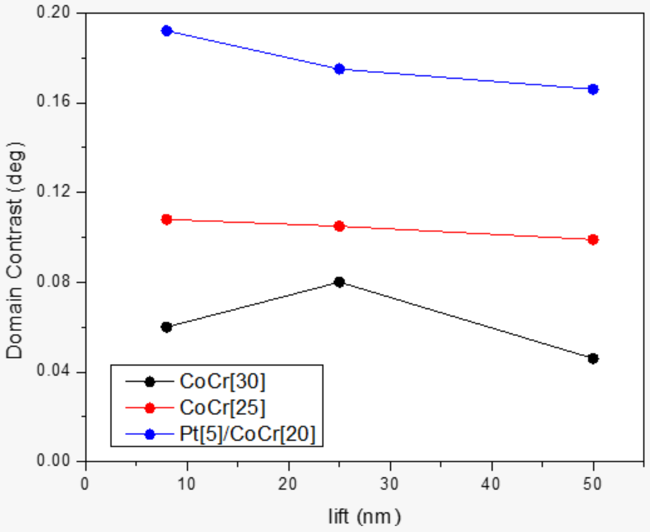
SPIN IN ELECTRONICS

Oscillation amplitude

Lift height

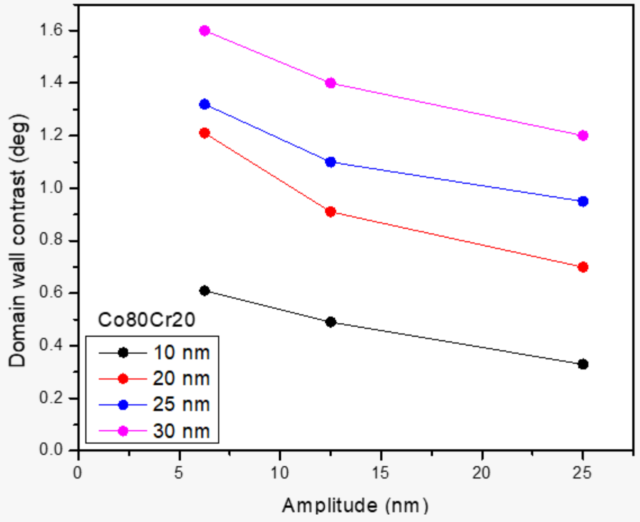
Domain contrast

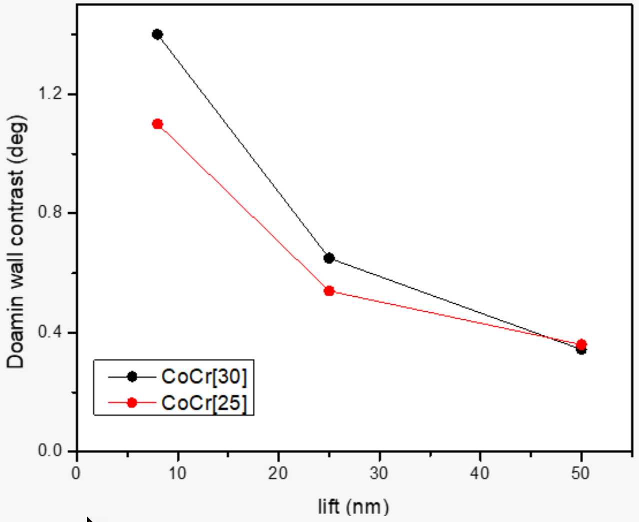




Weak variation with distance

Stray-field contrast

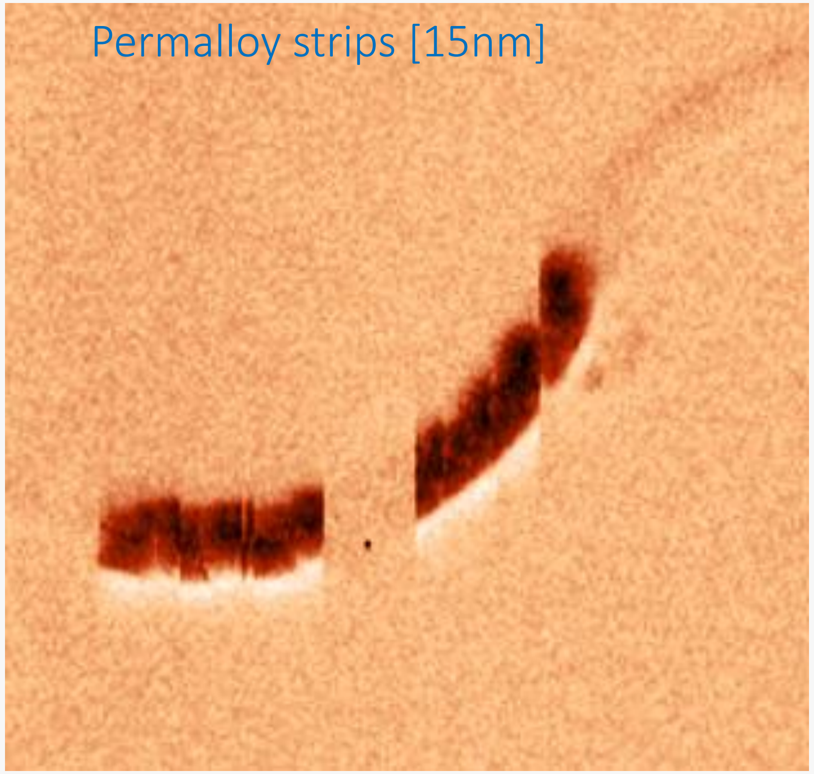




Significant variation with distance

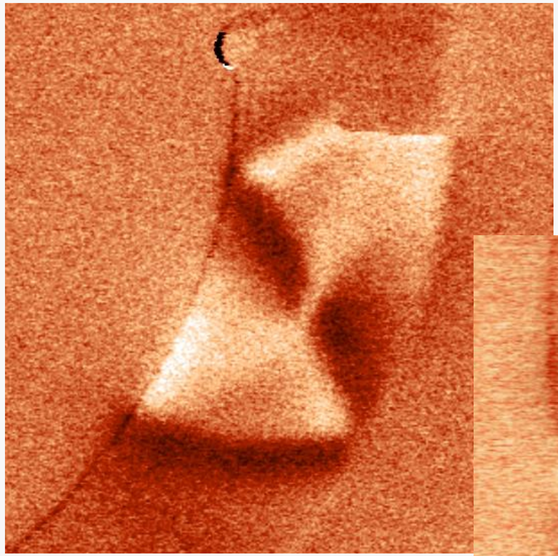
MFM tips – Coating thickness and sample disturbance

Commercial tips, “low moment”

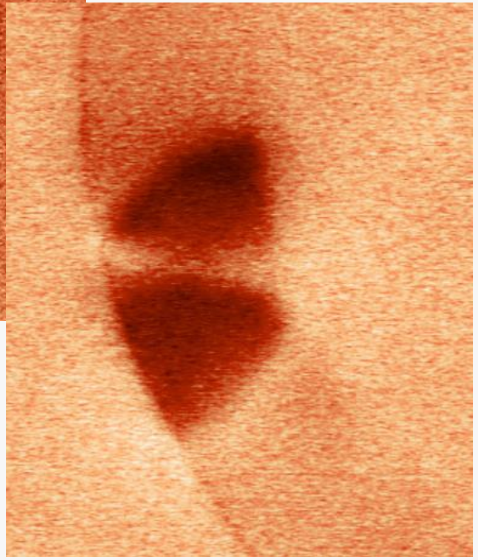


Sample: S. Pizzini

Home-made tips, lower moment



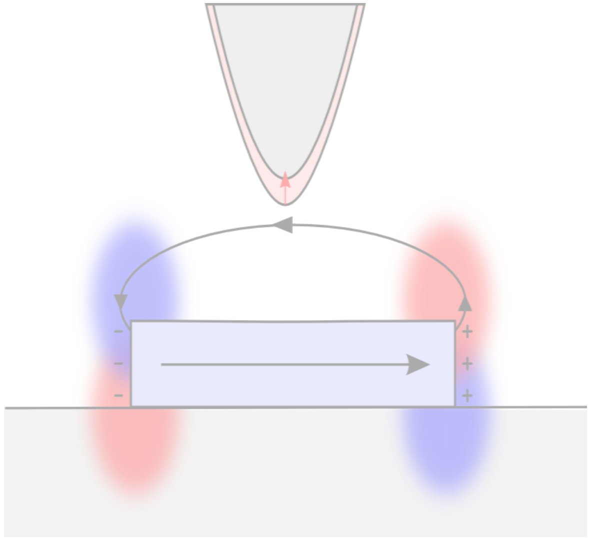
Tip : CoCr[10nm]
500nm strips
15nm permalloy



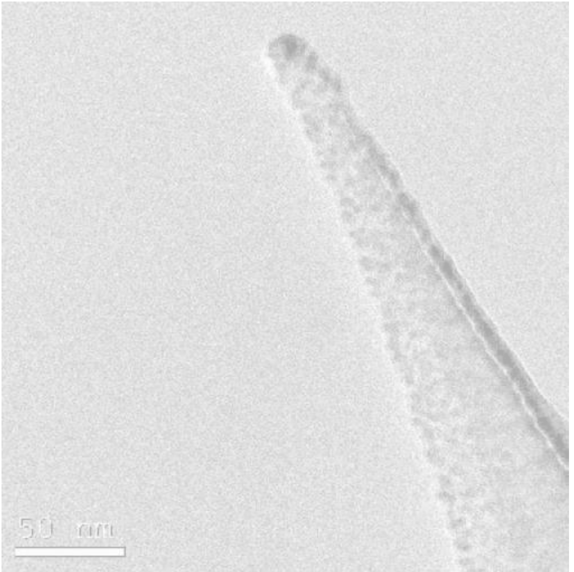
Tip : CoCr[5nm]
300nm strips
15nm Permalloy

- Application: domain walls, skyrmions, which may move under magnetic field
- Note: each case may require a specific optimization

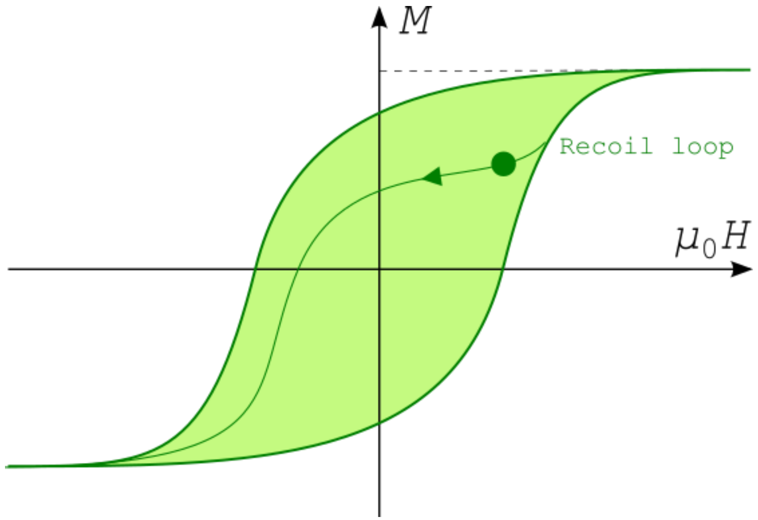
- MFM contrast



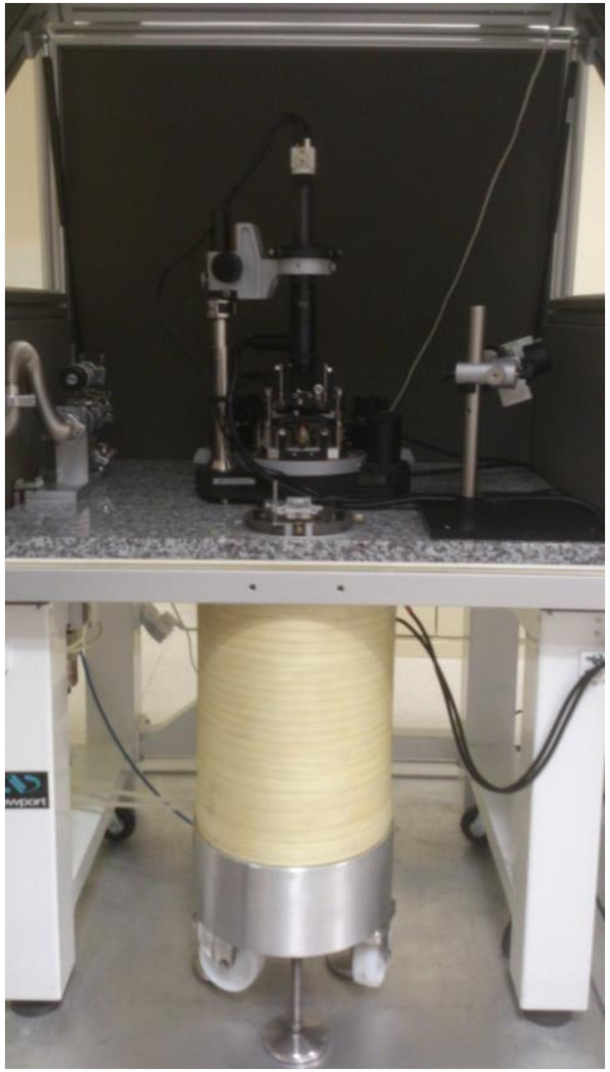
- MFM tips



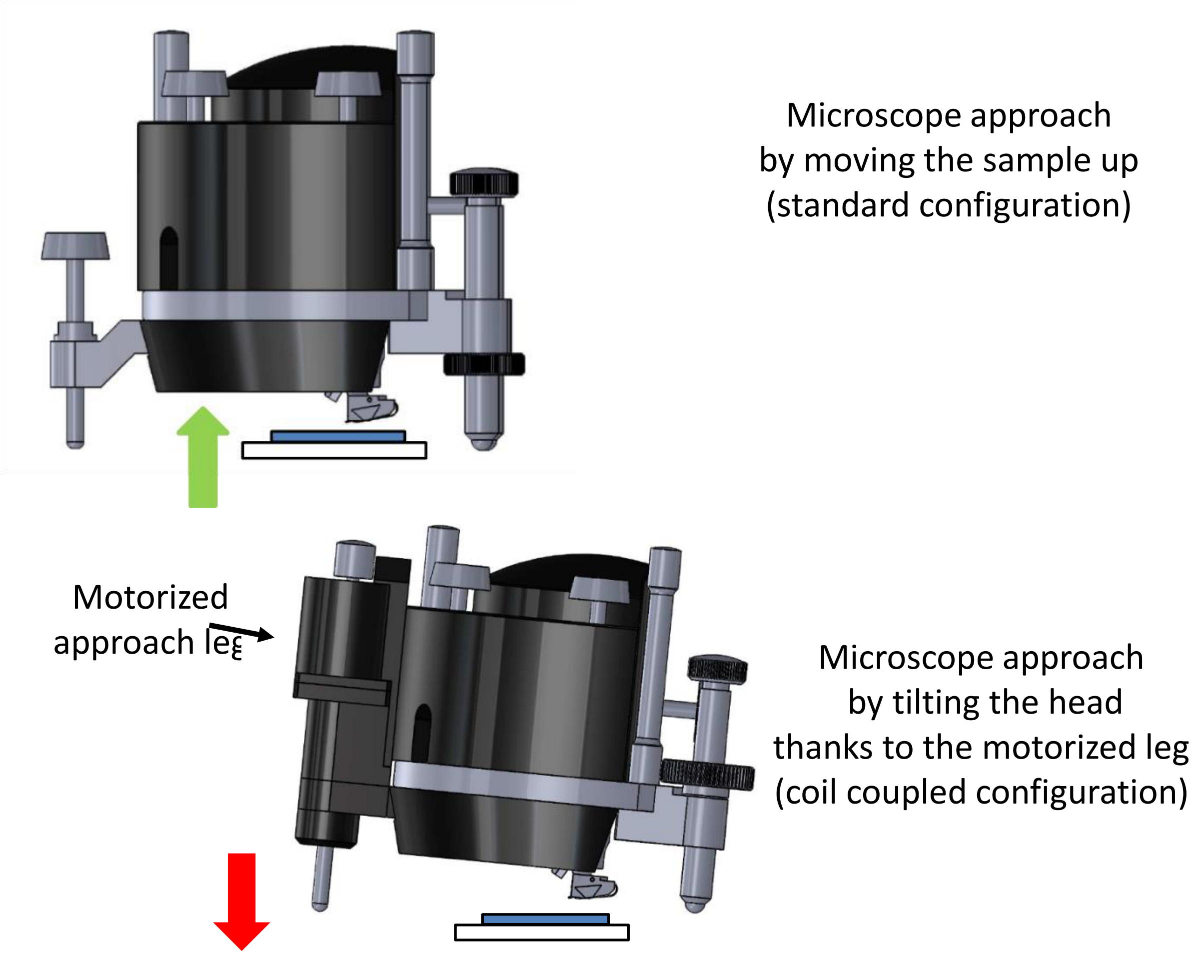
- MFM in magnetic field



MFM under magnetic field – Setup



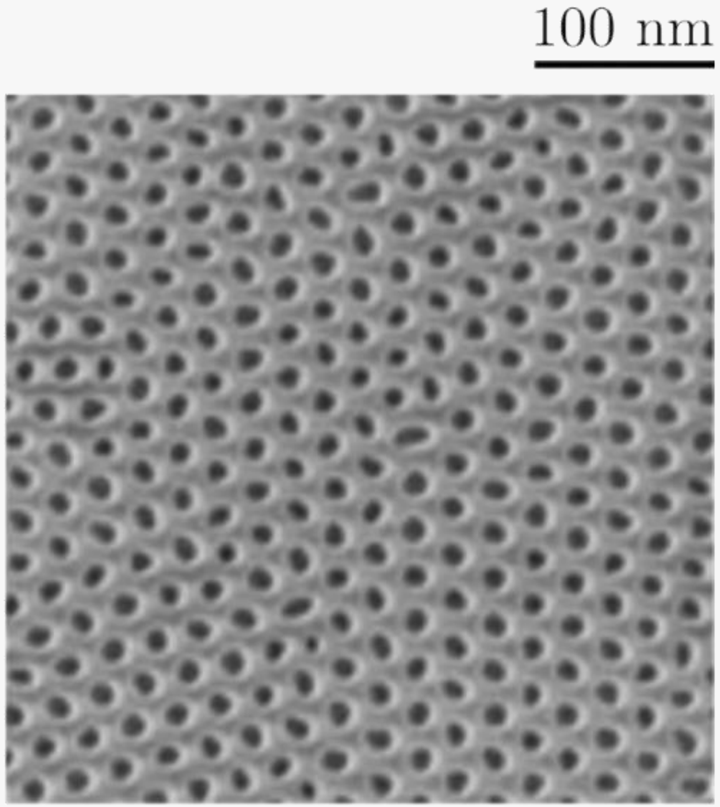
Field >1T (custom-made)
Optimized cooling

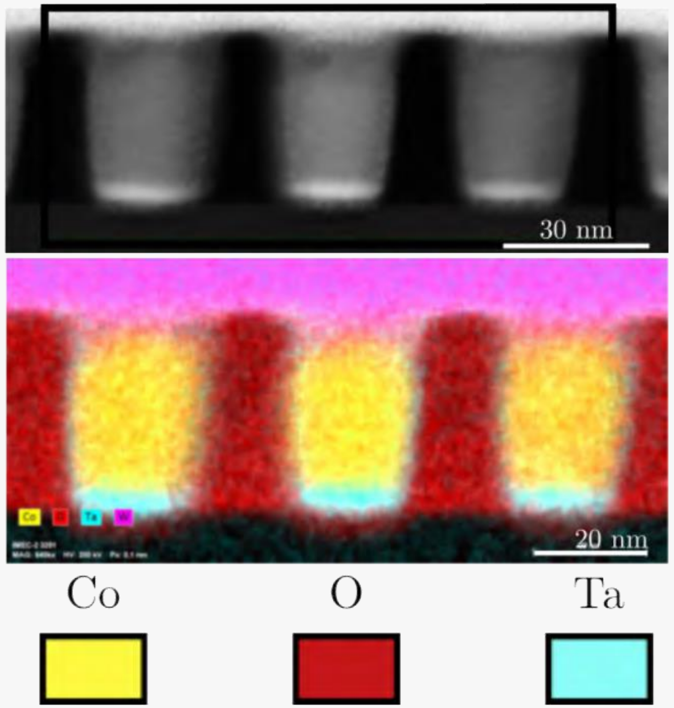


- Scanning & approach by head (motorized leg)
- Dedicated in-field sample holder

MFM under magnetic field – A system

Physical system: magnetic nanopillars embedded in SiO2 vias





- Diblock copolymer lithography
- Etching transfer to SiO2
- Co electroplating
- Chemical Mechanical Polishing

Motivation

- Perpendicular-shape magnetic tunnel junctions
- High-density on-chip magnetic memories

Patent EP23798223

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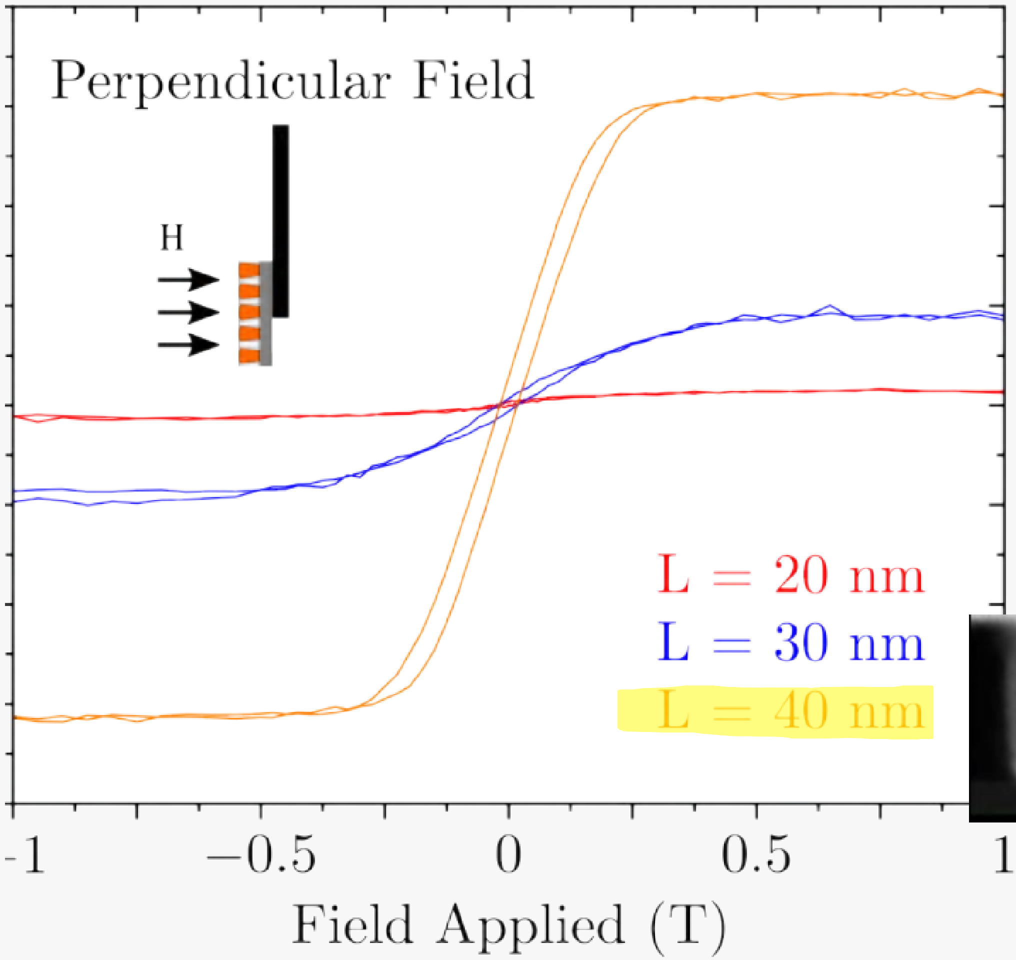
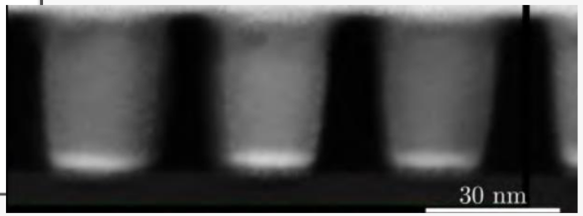
MFM under magnetic field – A system

Macroscopic measurements





Motivation

- Does this reflect individual cells?
- Do cells interact?

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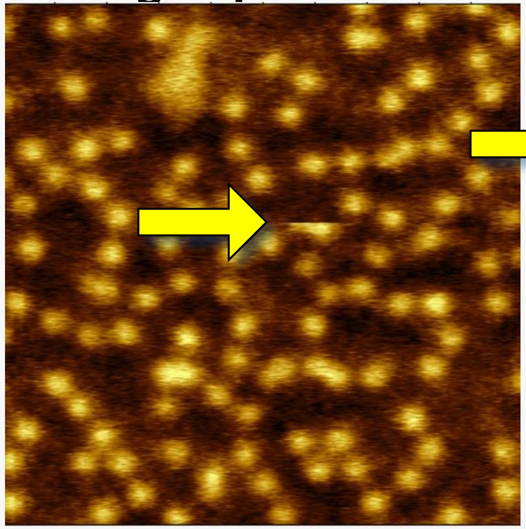
MFM under magnetic field – Tip-induced switching

Choice of tip

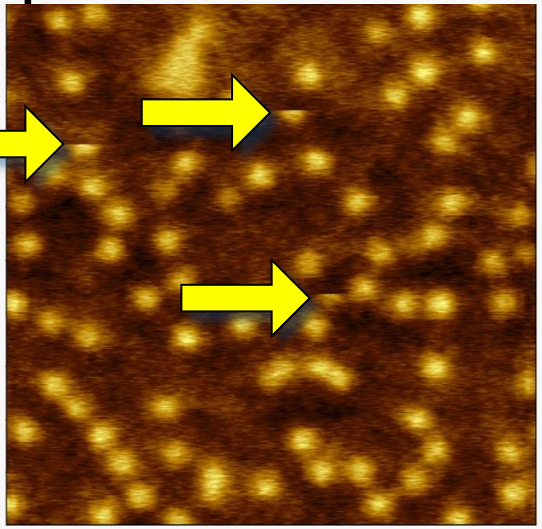
- 43 nm pitch: good spatial resolution needed
- Avoid tip switching in external + stray field of nanopillars
- Avoid pillar switching in external + stray field of tip

Choice: CoCr[20nm]

Manage tip-induced sample disturbance



+400 mT



+450 mT

1x1 µm FoV, 0.5° phase contrast

Operating conditions

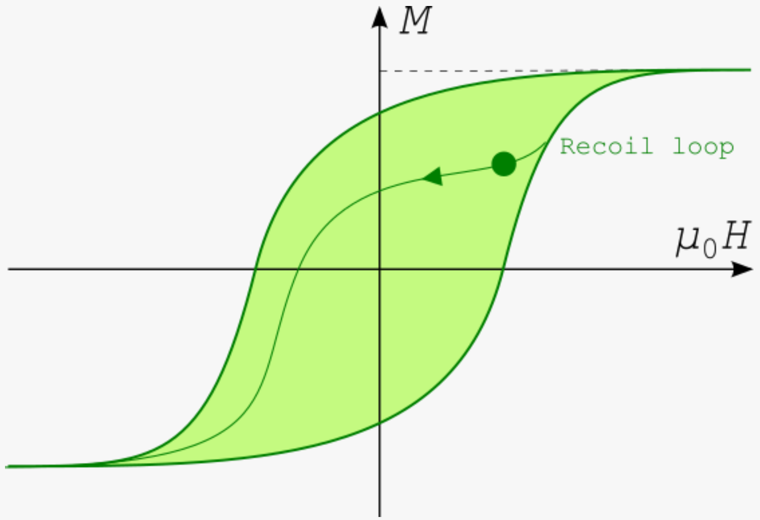
- Oscillation magnitude: 18nm peak-to-peak
- Lift height: 8nm
- Fast scan axis: x
- Slow scan from bottom to top

- Pillars close to their switching field are influenced by the tip
- Cannot be avoided with any kind of tip

→ Workaround needed

MFM under magnetic field – Recoil loops to avoid disturbance

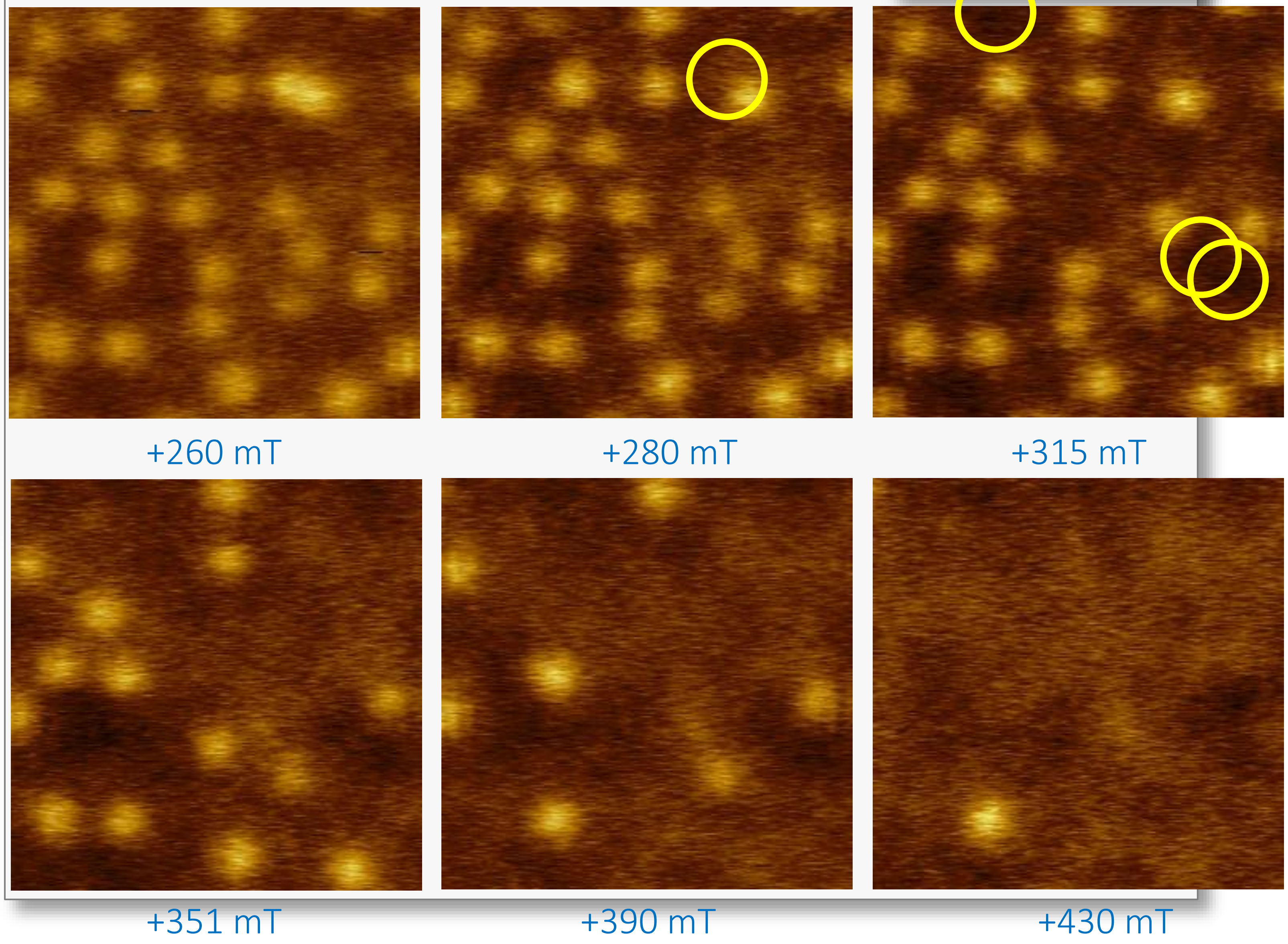
Protocol Small recoil loops



- Sufficiently small to not switch pillars
- Larger than tip stray field on sample

Tip-independent imaging at any applied field

400x400 nm FoV



Learn about

- Interaction with neighbors
- Distributions, incl. rare events

Thank you for your attention !

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