Imágenes Magnéticas: Microscopía de Fuerzas Magnéticas

Agustina Asenjo

Dpto. Propiedades Opticas, Magnéticas y de Transporte

Instituto de Ciencia de Materiales de Madrid- CSIC

club español de magnetismo

Reunión del Club Español de Magnetismo

Esquema

Introducción:

- MFM frente a otras técnicas de observación de dominios.
- Fundamentos de la Microscopía de Campo Cercano, SPM
- Detección de fuerzas de largo alcance en SPM, MFM
- Interpretación de resultados

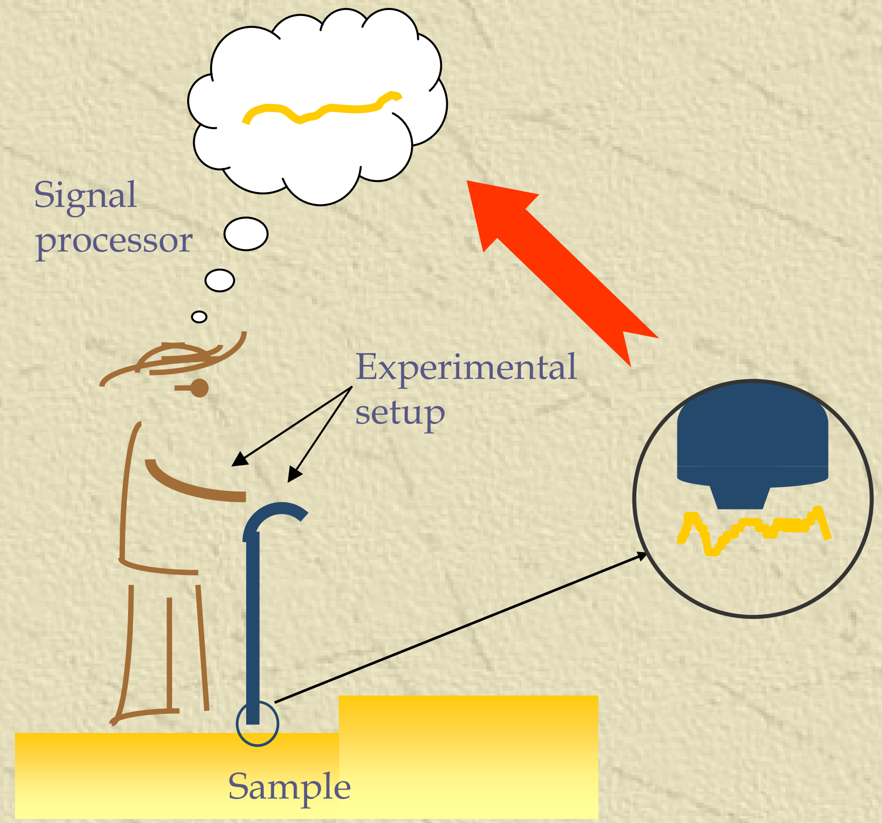
Aplicaciones del MFM:

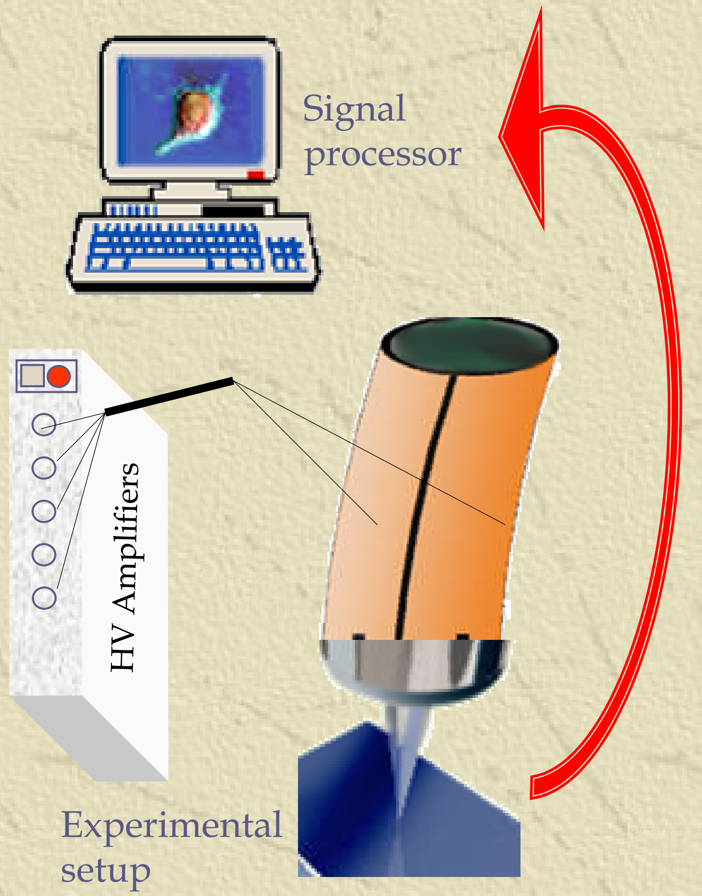
- Materiales duros, estructura de dominios.
- Interacción débil, dominios de cierre
- MFM aplicando campo magnético
- Nanoestructuras
- Procesos dinámicos

Magnetic Imaging Techniques

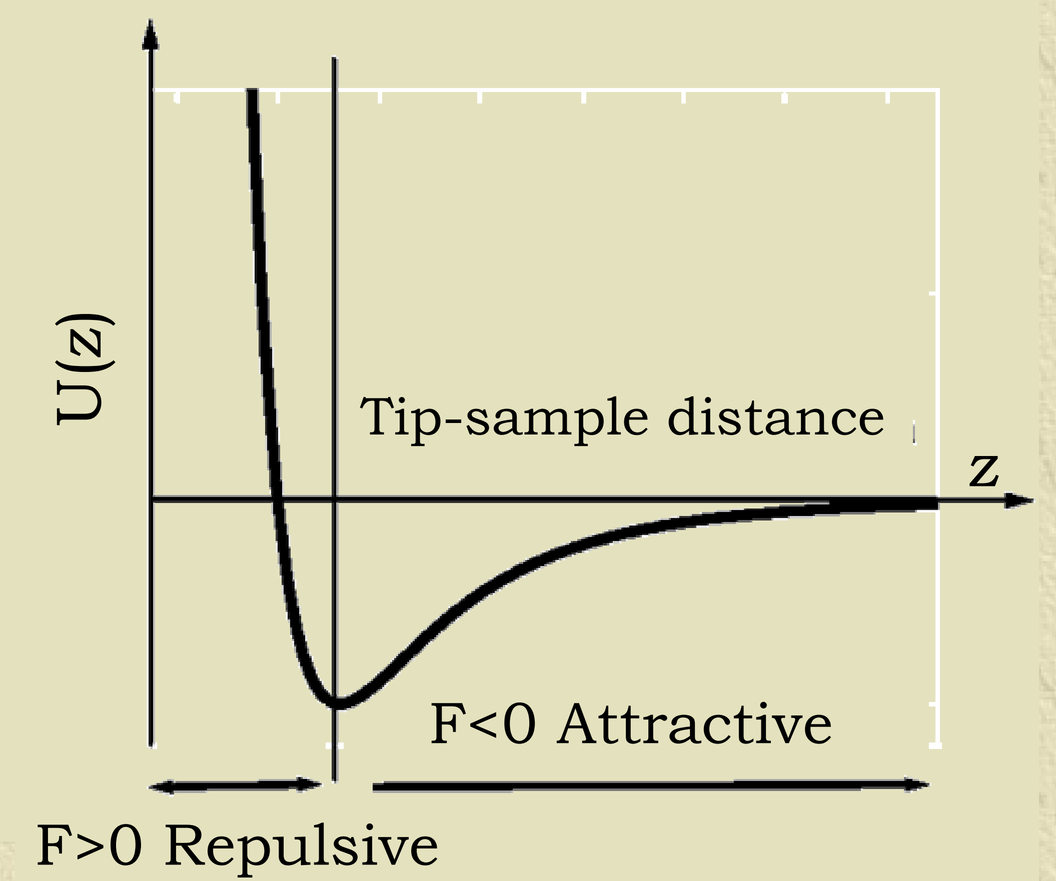
Technique	Signal	Sample preparation	Spatial resolution	Contrast	Materials	External field	Drawback
Magneto-Optical	Light polarization	Flat and Smooth surfaces	200nm	Walls and domains	K_{per} and $K_{in\text{-}plane}$	Available	Resolution
Bitter	Magnetic colloids distribution	None	100nm	Walls	High stray fields	Available (low speed)	Dirty Sample
SEMPA	Polarized S.E	HV cleaning	50nm	Domains	K_{per} and $K_{in\text{-}plane}$	Difficult	Cleanness
MFM	Charge density	None	20nm	Walls and domains	K_{per} and $K_{in\text{-}plane}$	Available	Tip-sample interaction
Lorentz	$F_{lorentz}$	UHV cleaning	~nm	Domains	$K_{in\text{-}plane}$	Difficult	Sample preparation

Scanning Probe Microscope

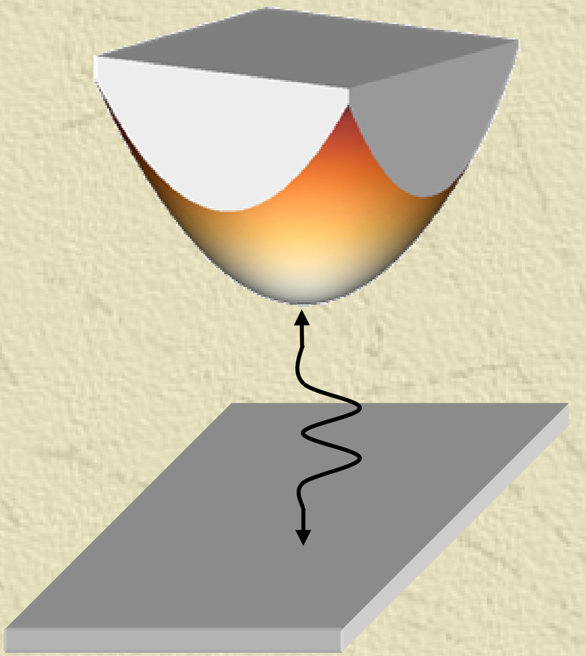




The interaction in the SFM

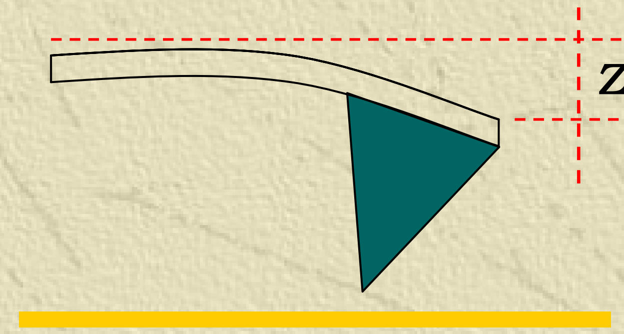


Potential near a surface:
attractive at large distances
repulsive for short distances



The microcantilever and the Hook's law

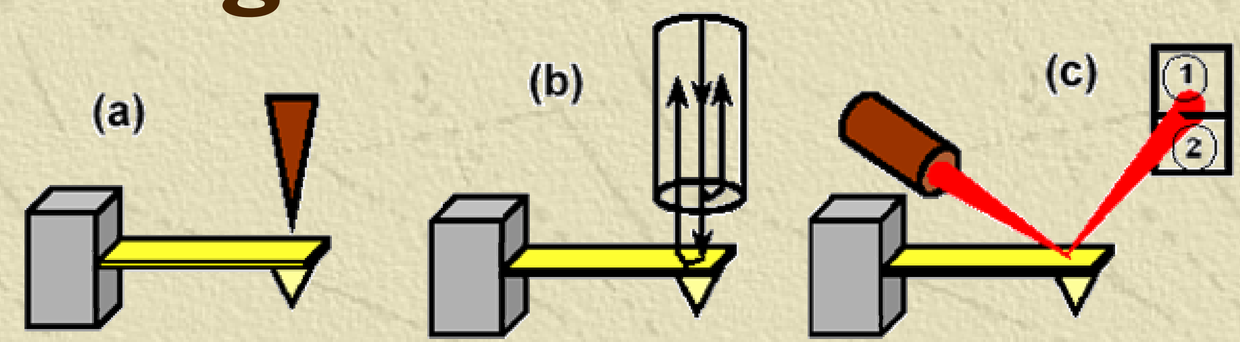
$$F = -kz$$



$k = E/4 \cdot W \cdot (T/L)^3$

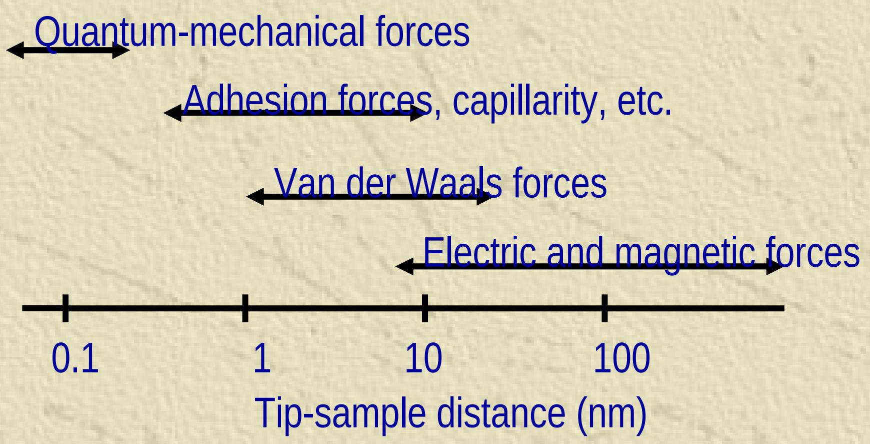
k depends on the geometry and material

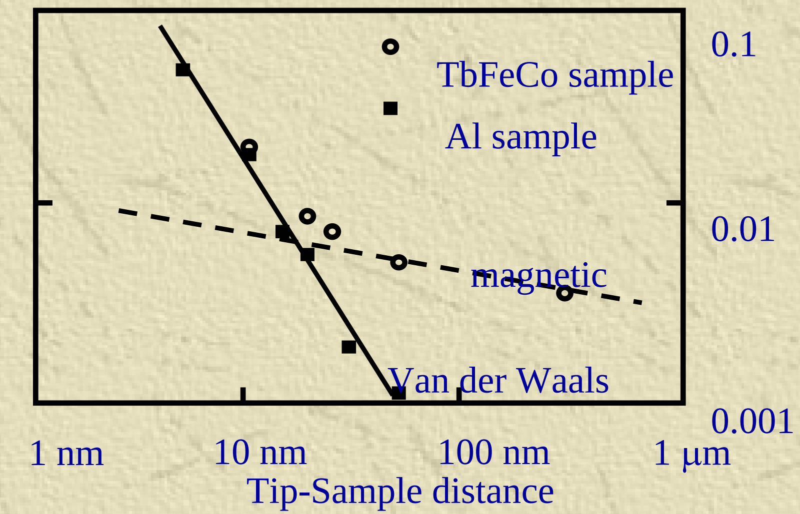
Detecting deflection



STM tip | Capacitance | **Beam reflection**

Tip-sample Interactions





$\mathbf{F}_{\mathbf{electrostatic}} = \dfrac{\partial C}{\partial z} V^2$ attractive

$\mathbf{F}_{\mathbf{vdW}} = -\dfrac{AR}{6z_0^2}$ spherical tip, $A=10^{-19}$J

Damping, amplitude decrease due to dissipation (magnetic and mechanical interaction, friction..)

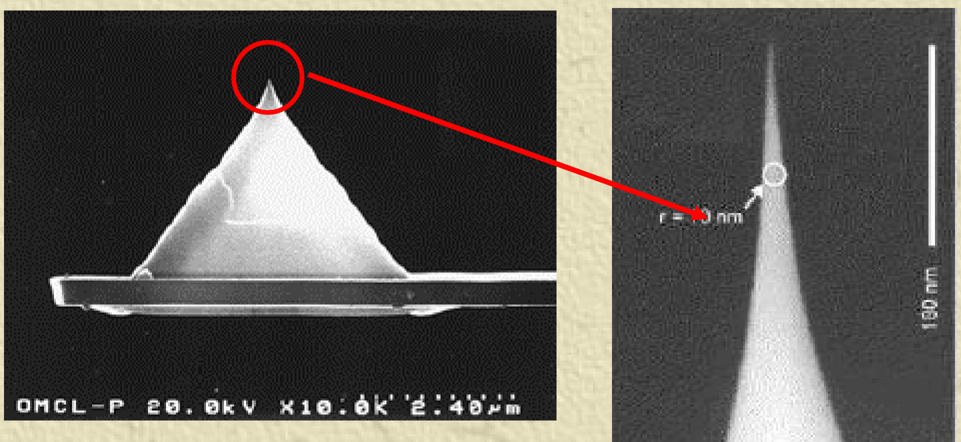
Capillarity, attractive force due to the meniscus between the tip and the sample .

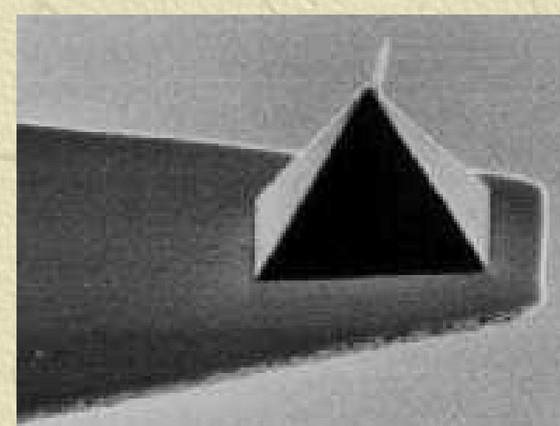
Quantum mechanical forces, down to 1nm, atomic resolution by UHV-AFM

Force sensor

MFM probes:

- Commercial tips covered with hard/soft magnetic thin film of Co , CoCr , permalloy, ...
- Axial magnetization due to shape anisotropy
- The resonance frequency, the force constant and the final radio change.





EBID tip grown on top of the pyramidal tip of a commercial Si_3N_4 cantilever. The needle is covered afterwards with 15 nm thick $Co_{80}Ni_{20}$ film

Contrast Mechanism

The interaction energy in MFM

$$E(\mathbf{r}) = -\mu_0 \int_{tip} \left[\mathbf{M}_{tip}(\mathbf{r}')\ \mathbf{H}_{sample}(\mathbf{r}+\mathbf{r}')\right] \mathrm{d}^3\mathbf{r}' = -\mu_0 \int_{sample} \left[\mathbf{M}_{sample}(\mathbf{r}')\ \mathbf{H}_{tip}(\mathbf{r}+\mathbf{r}')\right] \mathrm{d}^3\mathbf{r}'$$

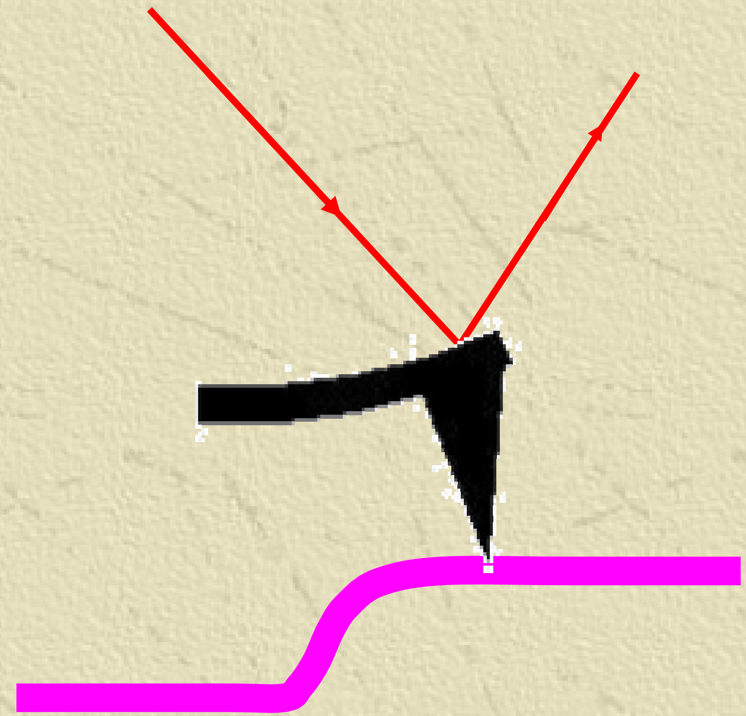
M_{tip} is the magnetisation of the tip, H_{sample} is the stray field from magnetisation of the sample
M_{sample} is the magnetisation of the sample, H_{tip} is the stray field from magnetisation of the tip

or $E = E_{volume} + E_{surface}$ → *Tip-sample distance, stray fields*

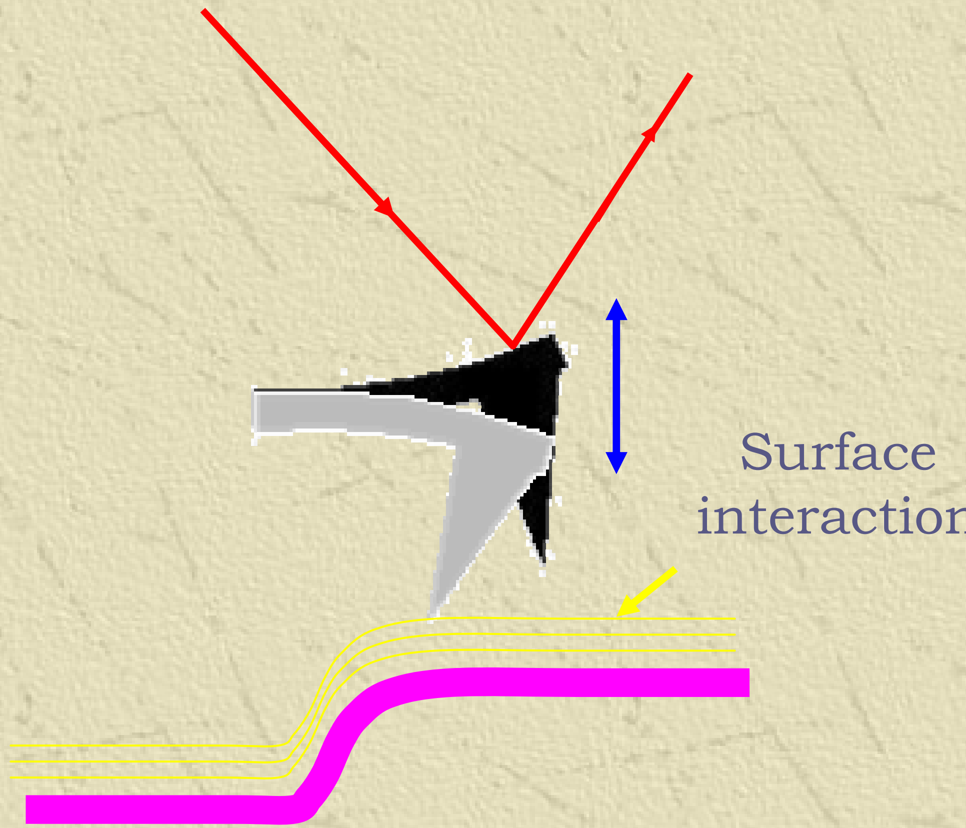
Contrast mechanism:

- Negligible interaction: magnetic charge
- Weak interaction: reversible effects
- Strong interaction: hysteresis effects

Contact mode and dynamic mode



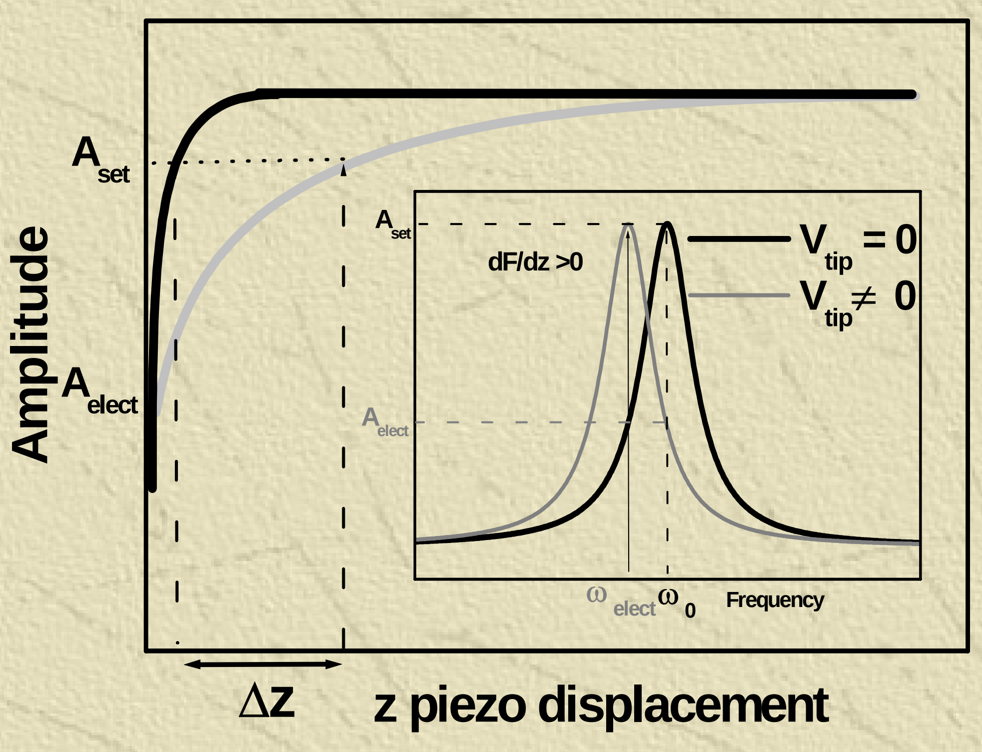
In contact mode the **deflection** of the cantilever is kept **constant**



In dynamic mode the tip is oscillated at the resonance frequency and the **amplitude** of oscillation is kept **constant**

Large Distance Interactions: Magnetic and Electrostatic

>10nm



$$\Delta\omega \propto \frac{\omega_0}{2k}\frac{\partial F_z^{ext}}{\partial z}$$

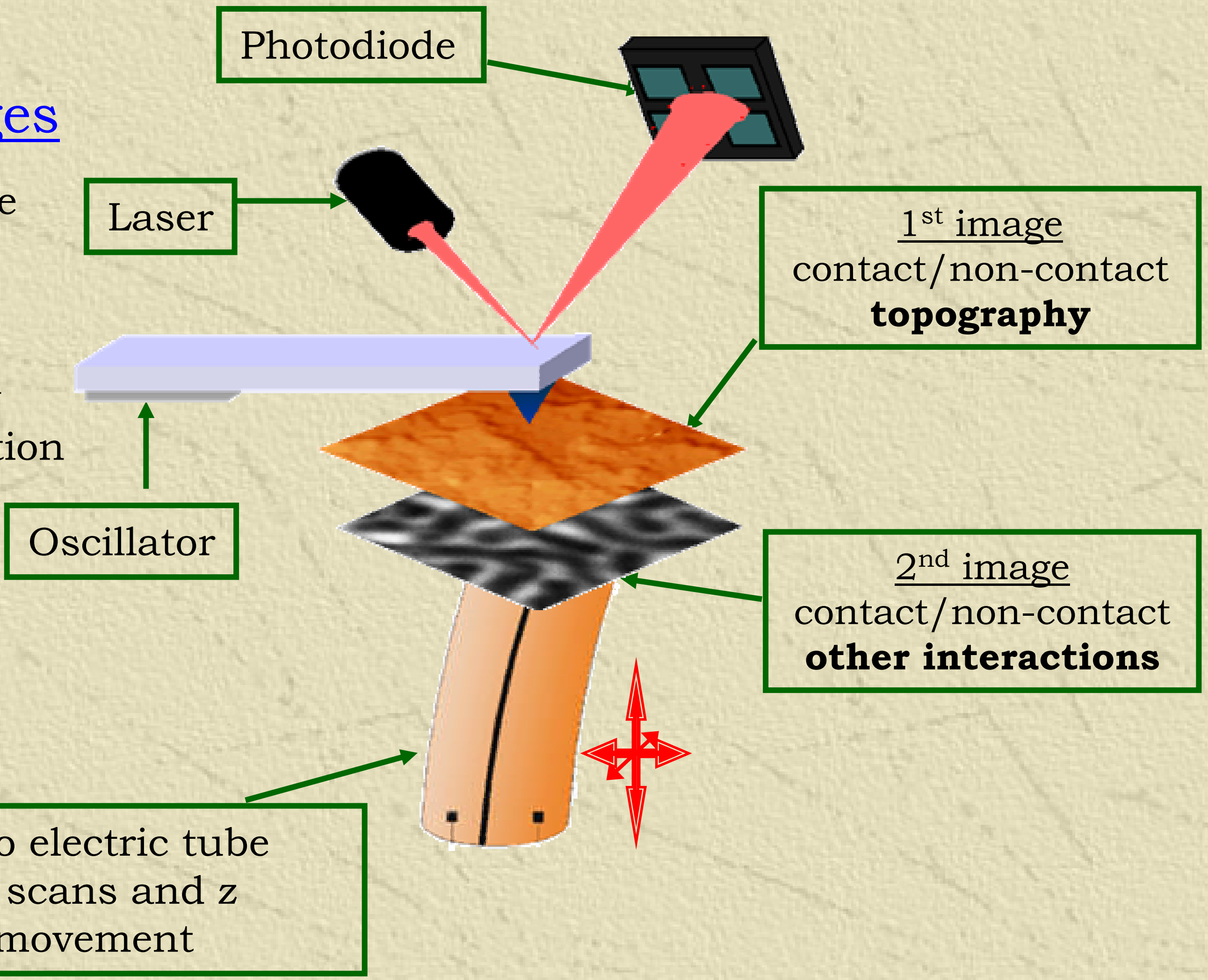
$$\Delta A = \frac{A_0 Q}{2k}\frac{\partial F_z^{ext}}{\partial z}$$

$$\delta \propto \frac{\omega_0}{\beta 2k}\frac{\partial F_z^{ext}}{\partial z}$$

MFM System

MFM Advantages

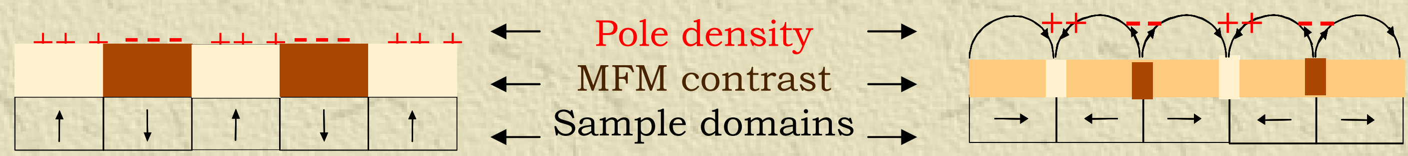
- Perpendicular and in-plane anisotropy
- High sensibility ~10^{-18}J/T
- Lateral resolution l~ 20nm
- Minimum sample preparation
- Topography



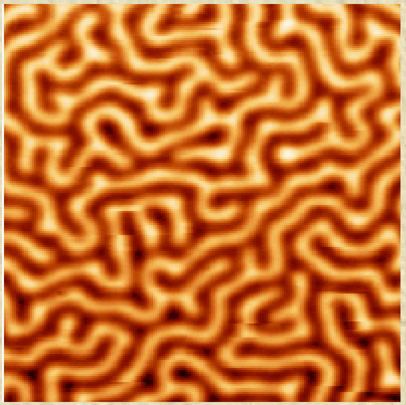
MFM Interpretation

Assuming that the tip-sample interaction is negligible:

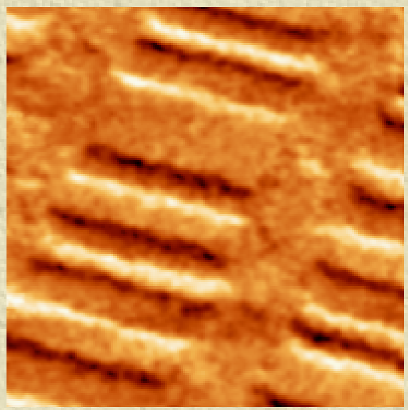
- The MFM is sensible to the magnetic poles.
- Perpendicular anisotropy: high pole density in the center of the **magnetic domains**.
- In-plane anisotropy: high pole density in the **domain walls**.



MFM image of a FePd thin film with perpendicular magnetic anisotropy. The bright and dark contrast corresponds to domains with up and down magnetization
Image size: 3 μm x 3 μm

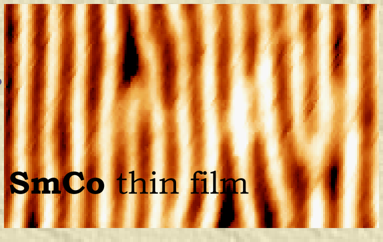


MFM image of tracks within a commercial hard disk. In longitudinal recording media, the anisotropy is in-plane. The bright and dark contrast corresponds to the domain wall.
Image size: 10 μm x 10 μm

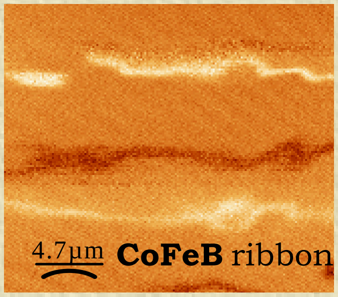


MFM Applications

- Hard magnetic material. Domain structure.



- Low anisotropy: Weak interaction
  Closure domains.



- MFM under an magnetic applied field.
- Nanostructures.
- Dynamic process

$Fe_{50}Pd_{50}$ Thin Film

Hard magnetic material with perpendicular anisotropy

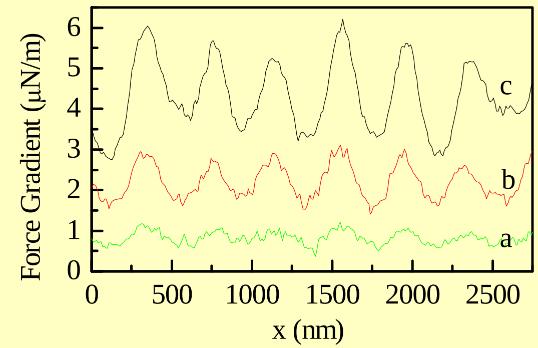
Stripe domains

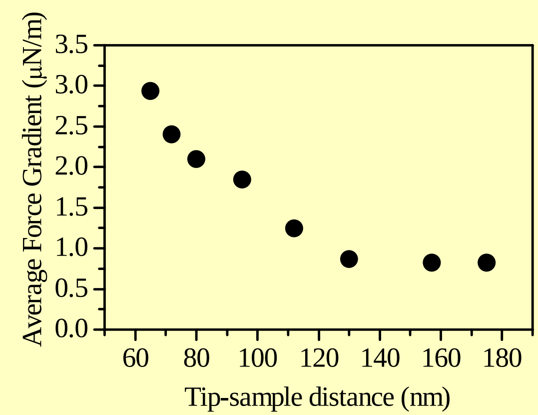
The domain width depends on the square root of the layer thickness for a Kittel structure

T	W	C	Order	$K_\perp$
1 nm	160 nm	0.6 mN/m	Disordered	
30 nm	200 nm	2.0 mN/m	Ordered	$0.91 MJ/m^3$
45 nm	260 nm	4.5 mN/m	Ordered	$1.17 MJ/m^3$

T: Pt buffer layer thickness, W: Domain width, C: MFM domain contrast,
$K_\perp$: Perpendicular anisotropy constant (VSM)

Image size: 5mm x 5mm
Acquisition Distance: 65nm
Magnetic structure: 160nm



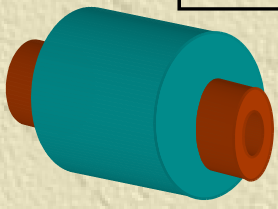


Acquisition Distance: 175nm
Domain size: 200nm

Zig-zag walls
Closure Domains

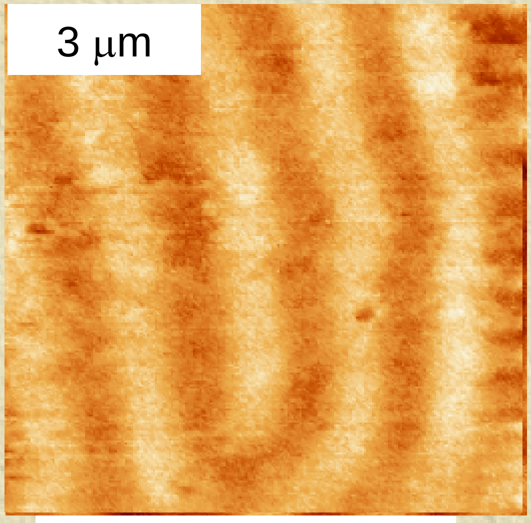
CoP microtubes

The anisotropy field is much smaller than the demagnetizing field

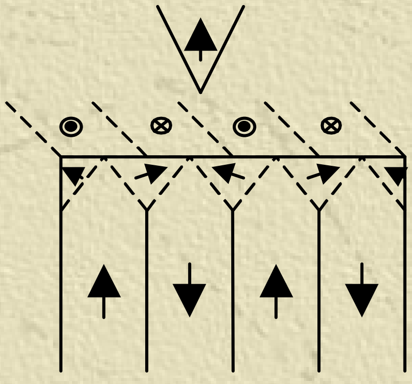


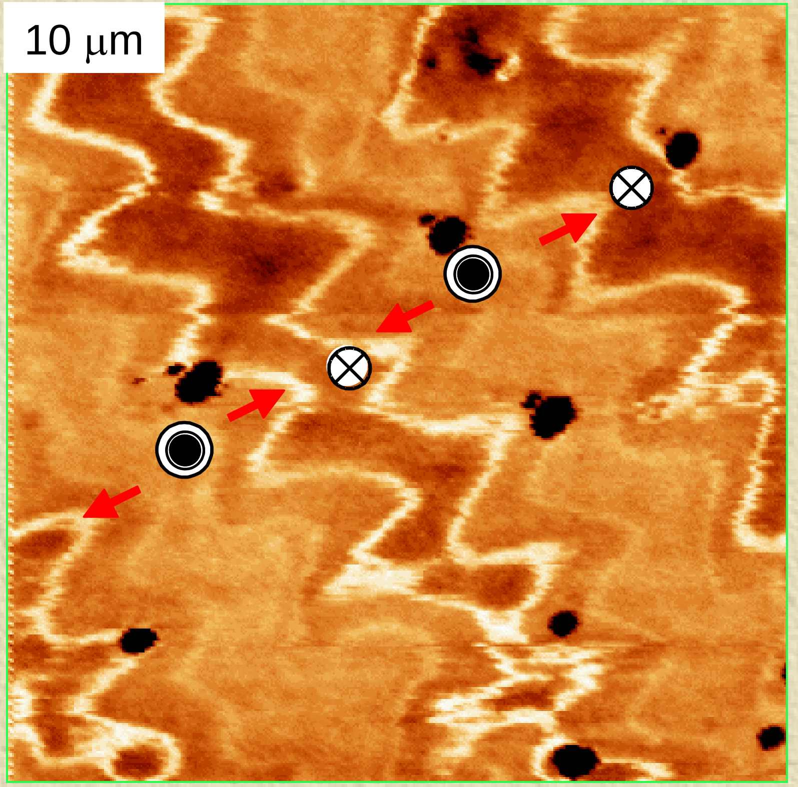
CoP electrodeposited onto 200μm diameter Cu wires

Closure domains



size: 18 μm x 18 μm





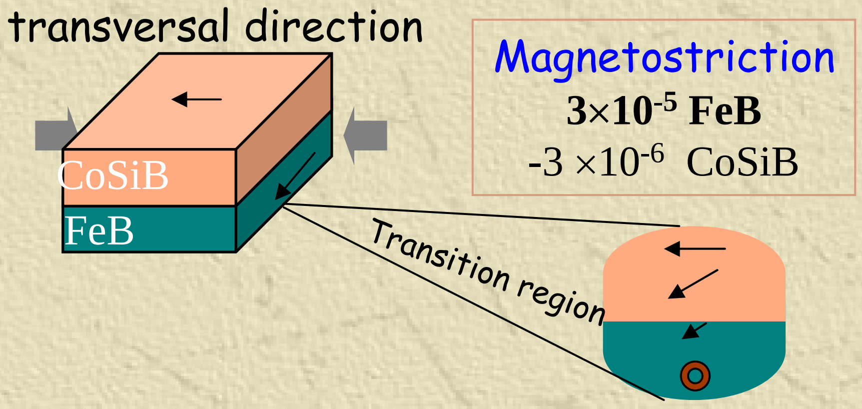
tip-sample distance: 25 nm
size: 12.5 mm x 12.5 mm

FeB/CoSiB multilayers

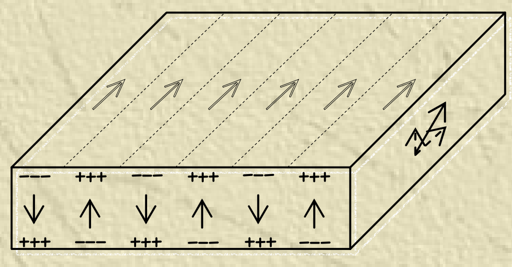
The magnetization is mainly in-plane (shape anisotropy), however, there are a weak anisotropy out of the plane

↓

"Dense stripe" domains

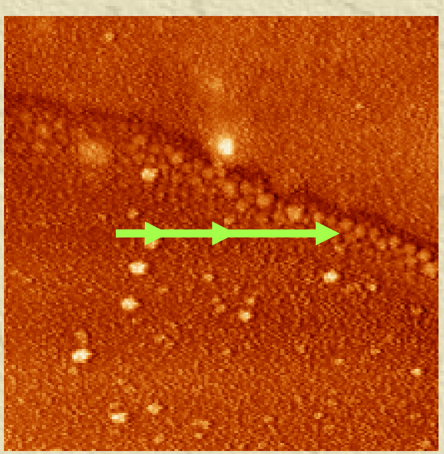


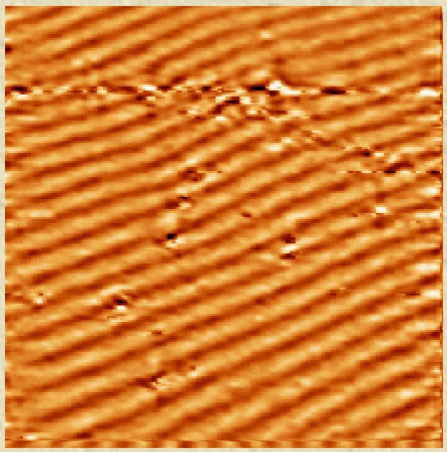
In order to reduce the magnetostatic energy, the magnetization oscillates periodically

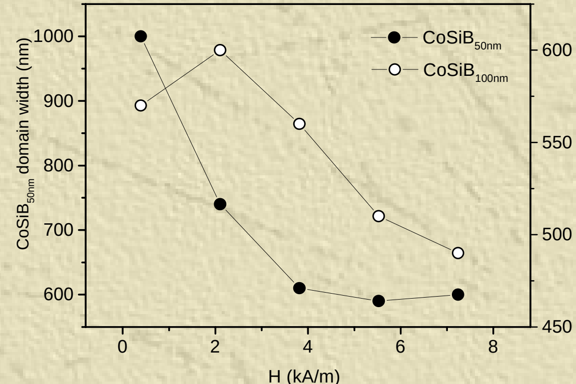


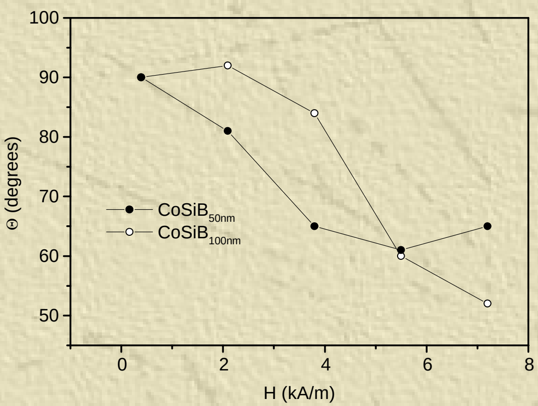
FeB/CoSiB multilayers under externally applied field

- An external magnetic field is applied to the samples growth onto **flat** substrates.
- The evolution of the structure is direct by the tendency to decrease the **Zeeman** energy



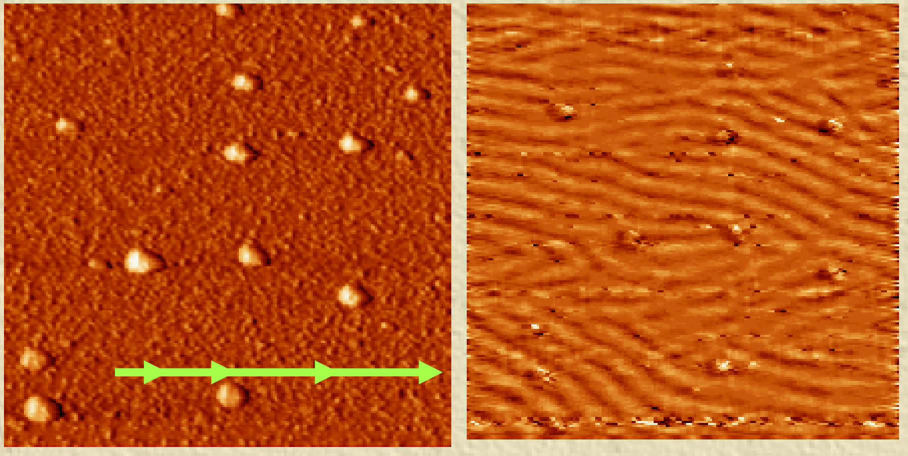


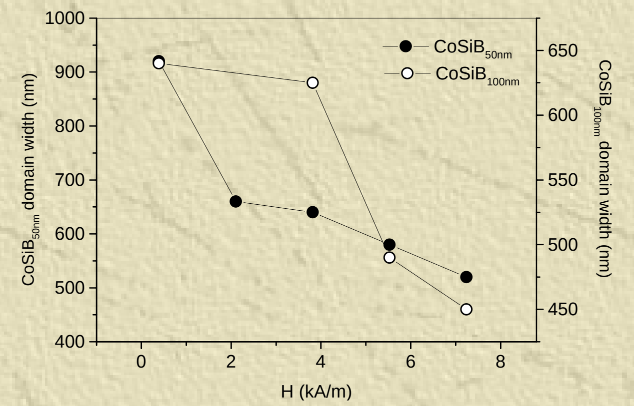


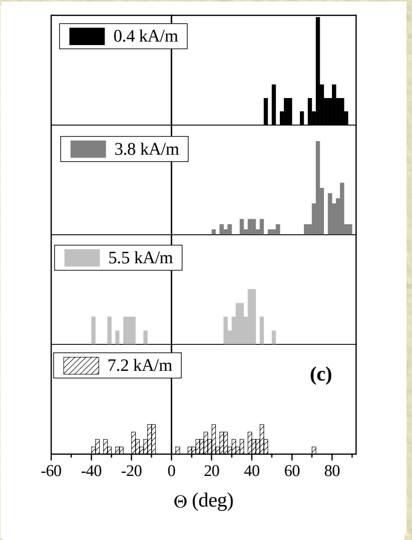


FeB/CoSiB multilayers under externally applied field

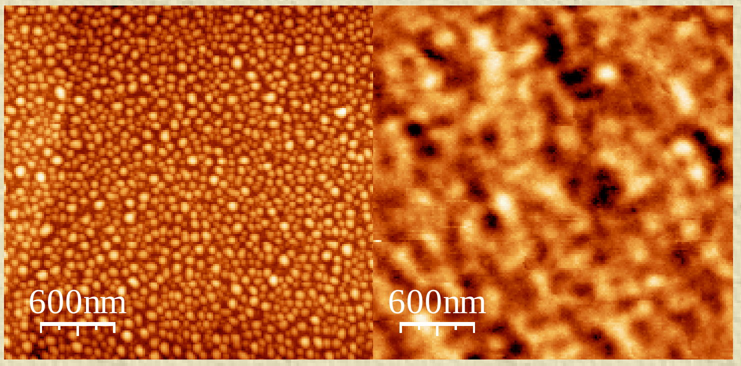
- An external magnetic field is applied to the samples growth onto **bowed** substrates.
- The evolution of the structure must be explained by **Zeeman** energy arguments and the existence of an **easy axis** in plane



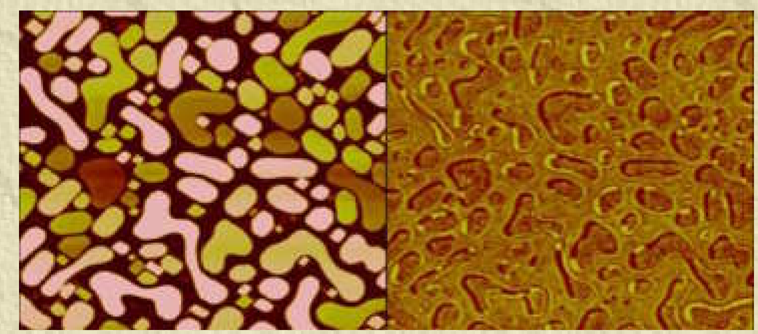




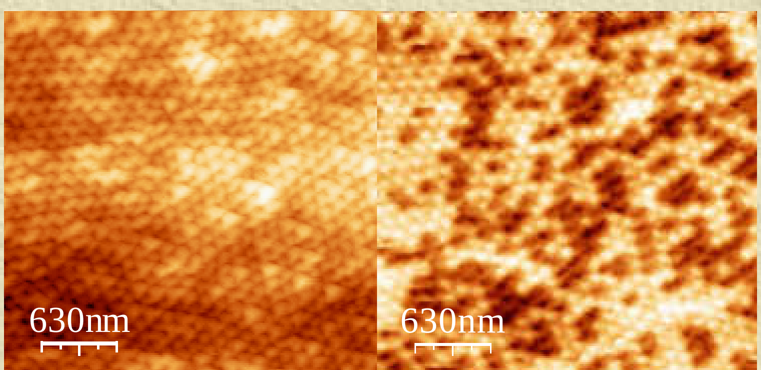
Nanostructures



$Co_{80}Cr_{20}$ nanostructures:
100nm thicker
Image size: 3μm × 3μm
Tip-sample distance: 40nm

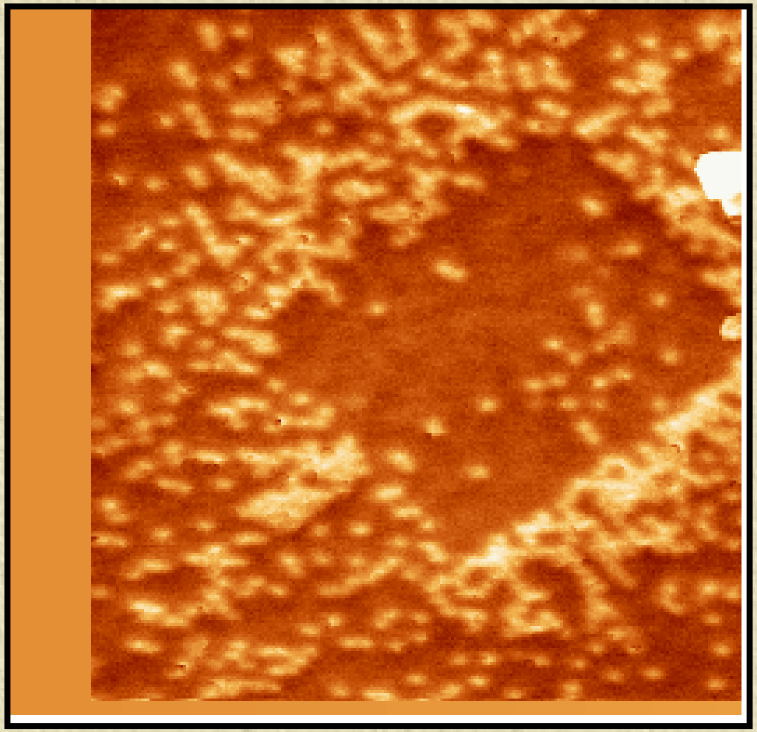


FePd nanostructures:
Pd 3nm/FePd 5nm/Pd 60nm/MgO
Image size: 8μm × 8μm
Tip-sample distance: 30nm

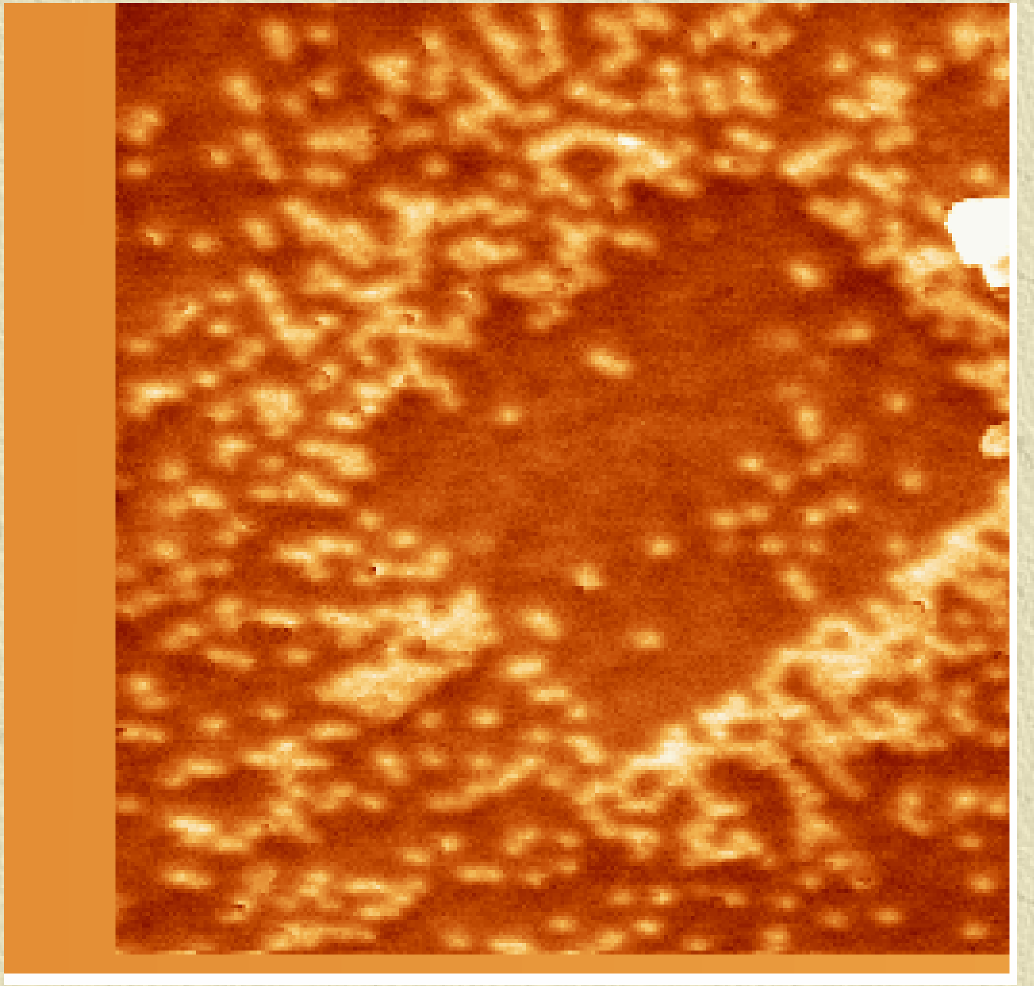


Electrodeposited Ni nanowires
Nanopores diameter: 15 to 90nm
Interpores distance: 80 to 500 nm
Nanopores length: 0.5 to 5 μm

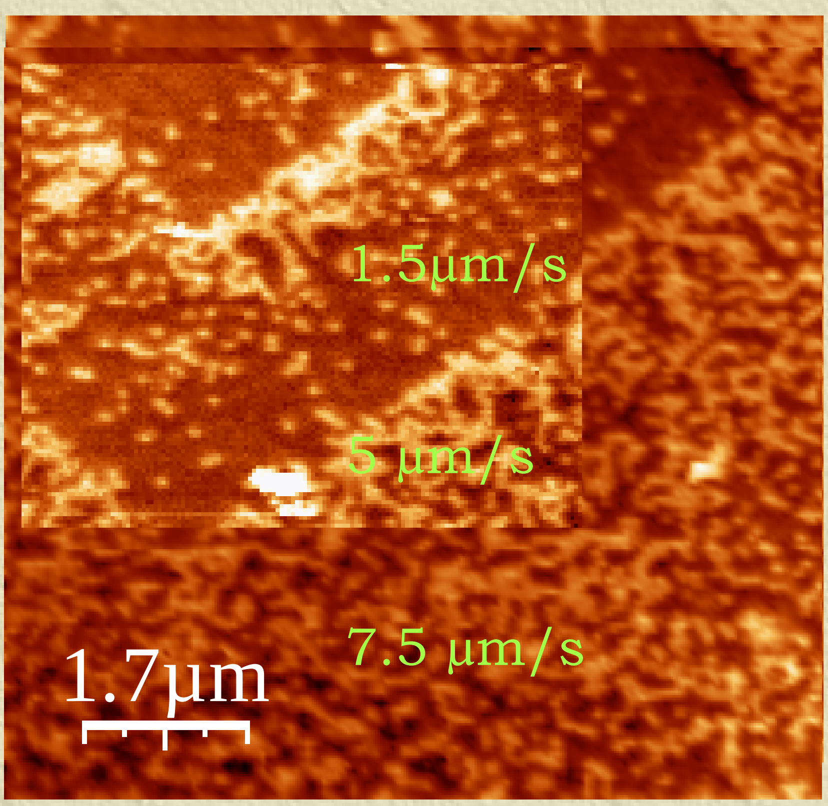
Dynamic studies



Dynamic studies

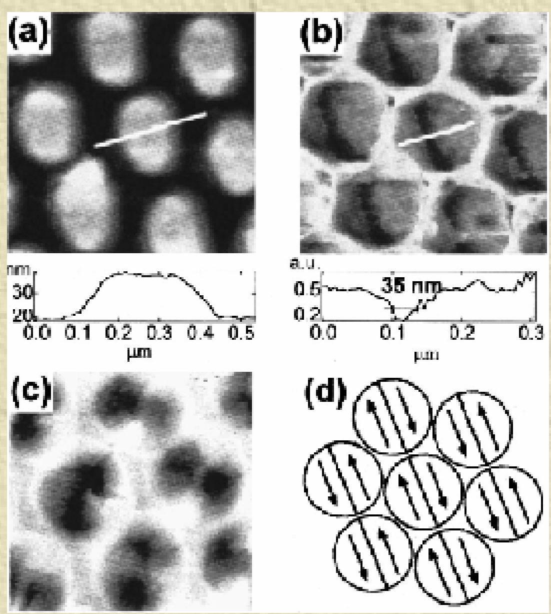


Tip-Sample interaction



Other applications

- ## Magnetic measurement with non magnetic tip



(a) Topographic AFM image,

(b) AFM image of the amplitude of the magnetostrictive response

(c) MFM image

(d) Schematic domain configuration

J. Wittborna et al. Dept. Materials Science, Royal Institute of Technology, Stockholm, Sweden

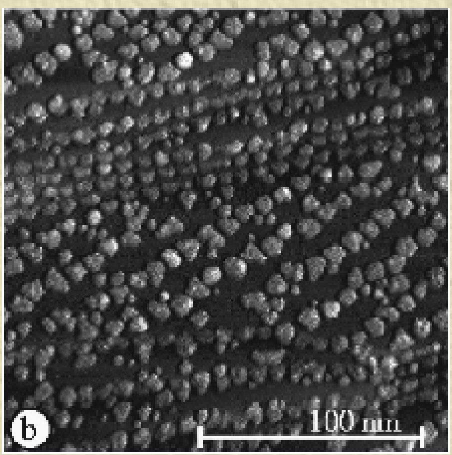
- ## Quantitative MFM

Quantitative measurement of MFM tip fields using Lorentz microscopy

Mc.Vitie Dept. Physics and Astronomy, University of Glasgow, Scotland, UK

Other applications

UHV MFM

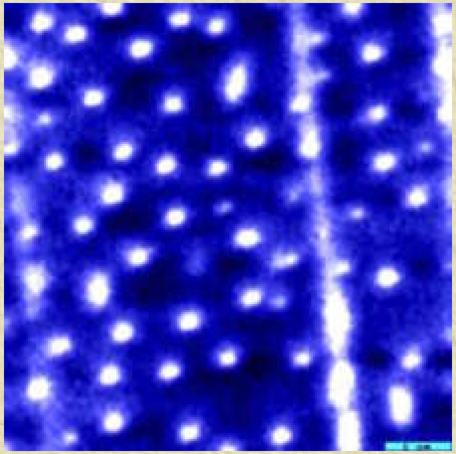


The Co islands of a height of two monolayers decorate the elbow sites of the underlying Au(111) *herringbone* reconstruction.

Scan size: 200 nm3200 nm.

R. Wiesendanger, University of Hamburg, Germany

Low temperature MFM



Vortices in High Tc-Superconductors

Image taken at 5.2 K vortices in an external field of 2 mT.

BSCCO single crystal.

A. Schwarz, University of Hamburg, Germany,

Conclusions

- The MFM is a helpful technique for the magnetic characterization. The main advantages are its high resolution and the versatility.
- Tip-sample interaction must be taken into account.
- In hard materials, the domain size obtained from the MFM images can be correlated with the anisotropy of the samples.
- The MFM is sensible to the surface magnetization
- The MFM reveals as a useful instrument for the study of magnetization process in the nanometer scale