Scanning probe microscopies for magnetism

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A volunteer to track my mistakes?

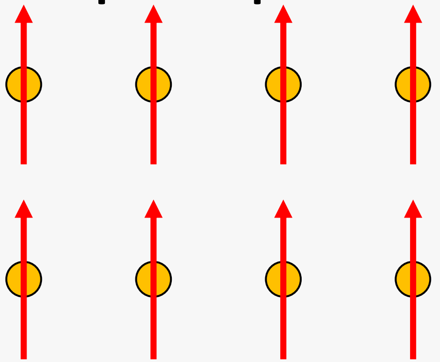
(Please)

Quizz #0

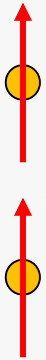
Dipolar energy is positive

$$\mathcal{E}_\mathrm{d} = \frac{1}{2}\mu_0 \iiint_{\mathcal{V}} \mathbf{H}_\mathrm{d}^2 \,\mathrm{d}\mathcal{V}$$

Dipolar energy results from dipole-dipole energy



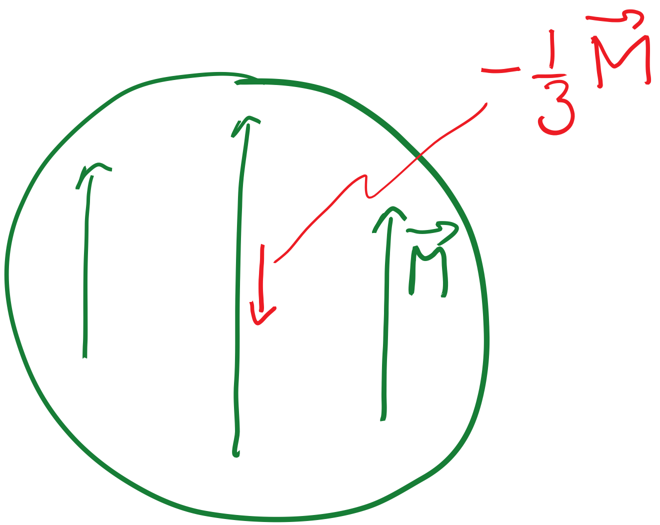
Dipole-dipole energy may be negative

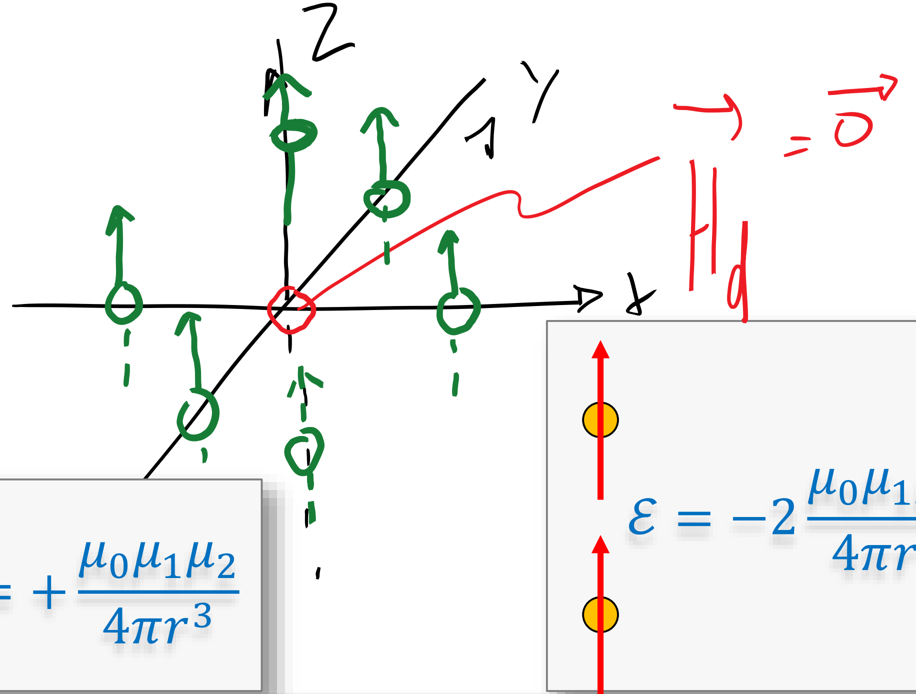


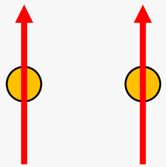
$$\mathcal{E} = -2\frac{\mu_0\mu_1\mu_2}{4\pi r^3}$$

Quizz #1

I can prove that demagnetizing field does NOT exist!





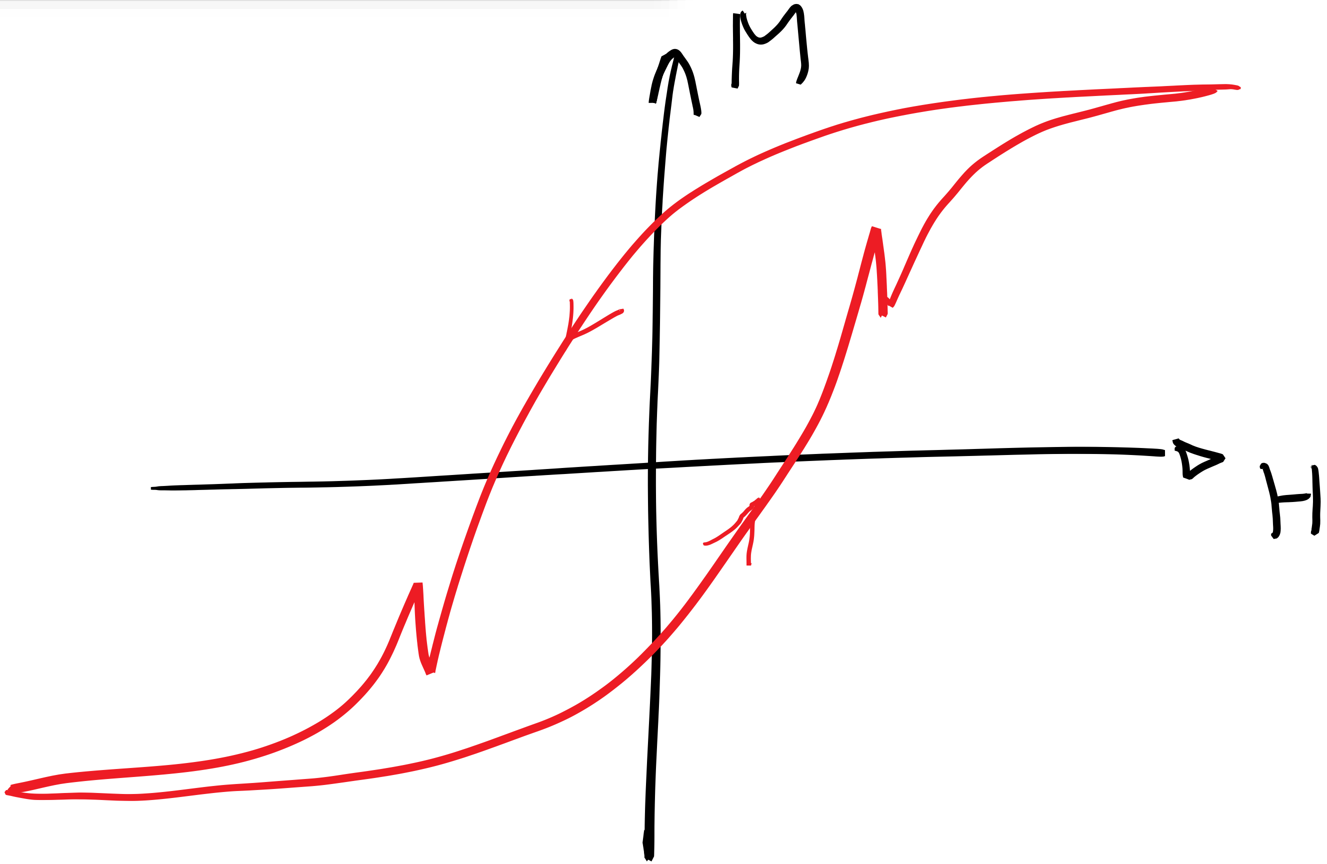


$$\mathcal{E} = +\frac{\mu_0 \mu_1 \mu_2}{4\pi r^3}$$

$$\mathcal{E} = -2\frac{\mu_0 \mu_1 \mu_2}{4\pi r^3}$$

Quizz #2

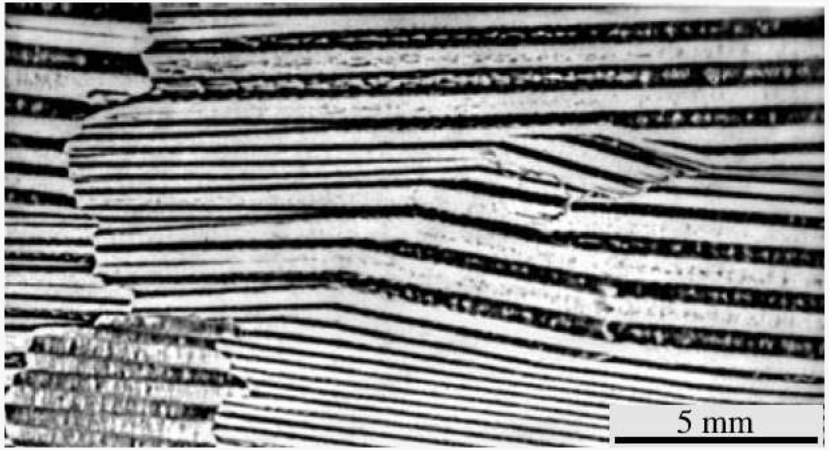
Is such a hysteresis loop possible ?



Motivation for microscopy

Magnetic domains

- Numerous and complex shape of domains



History: Weiss domains

Magnetic length scales

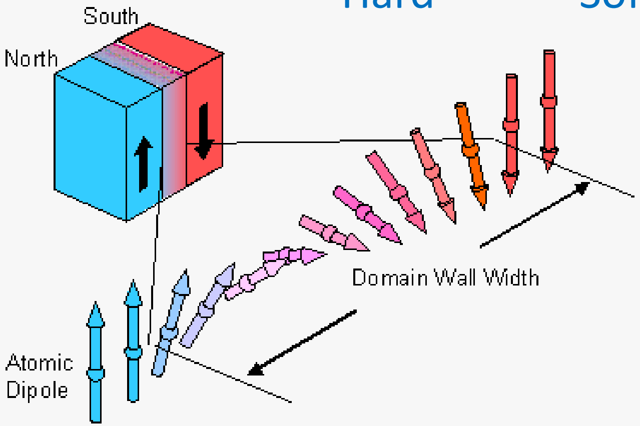
$$E = A\left(\frac{\partial m_i}{\partial x_j}\right)^2 + K\sin^2\theta$$

Exchange: $\mathrm{J/m}$ — Anisotropy: $\mathrm{J/m^3}$

- Anisotropy exchange length

$$\Delta_\mathrm{u} = \sqrt{A/K} \quad 1\ \mathrm{nm} \rightarrow 100\ \mathrm{nm}$$

Hard → Soft



Motivation for microscopy

Versatility

- Samples made with lithography or ex situ OK ?
- Need for sample preparation ?
- Compatible with various environments ? (temperature, field etc.)

Imaging speed

- Sample preparation needed ?
- How much time for one image ?

Access

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

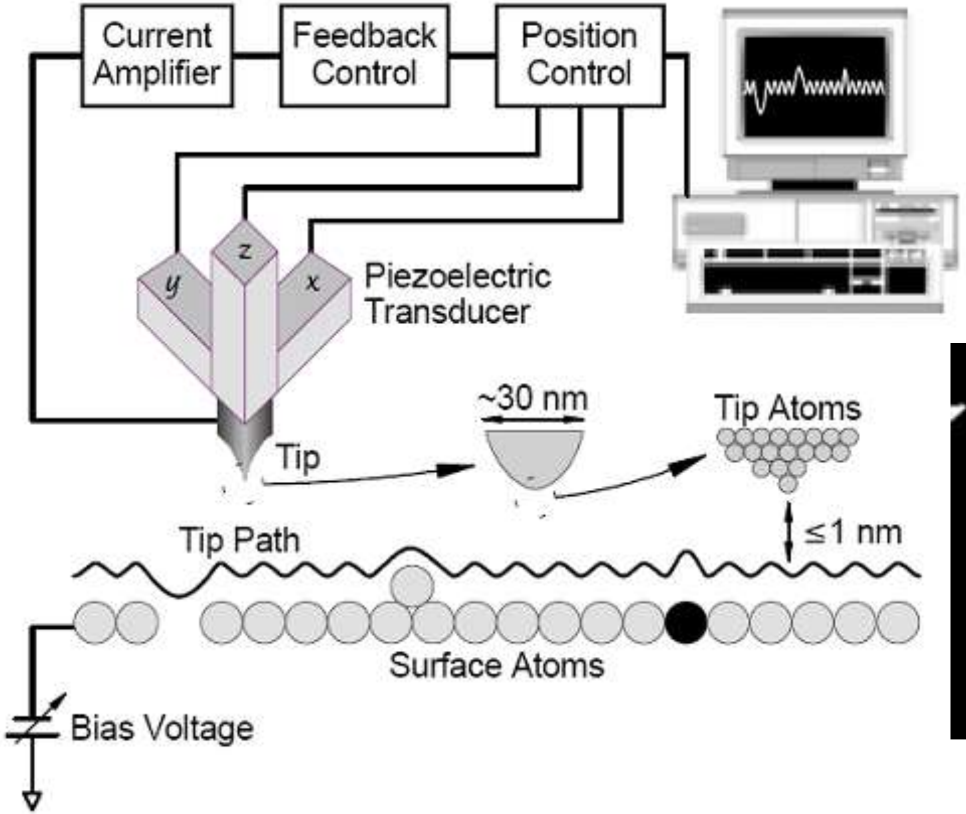
What is probed

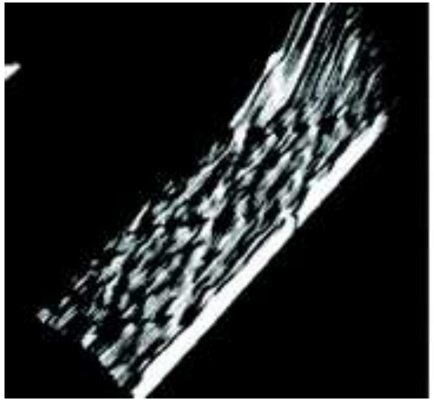
- Surface or volume technique ?
- Sensitivity ?
- Magnetization, stray field, other ?

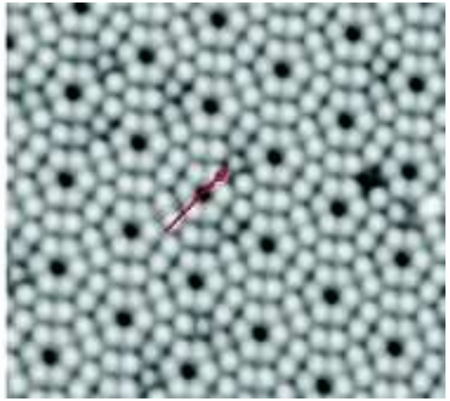
- No universal technique
- Many criteria to be balanced

Inventing the Scanning Tunneling Microscopy

1982 : inventing the scanning tunneling microscope

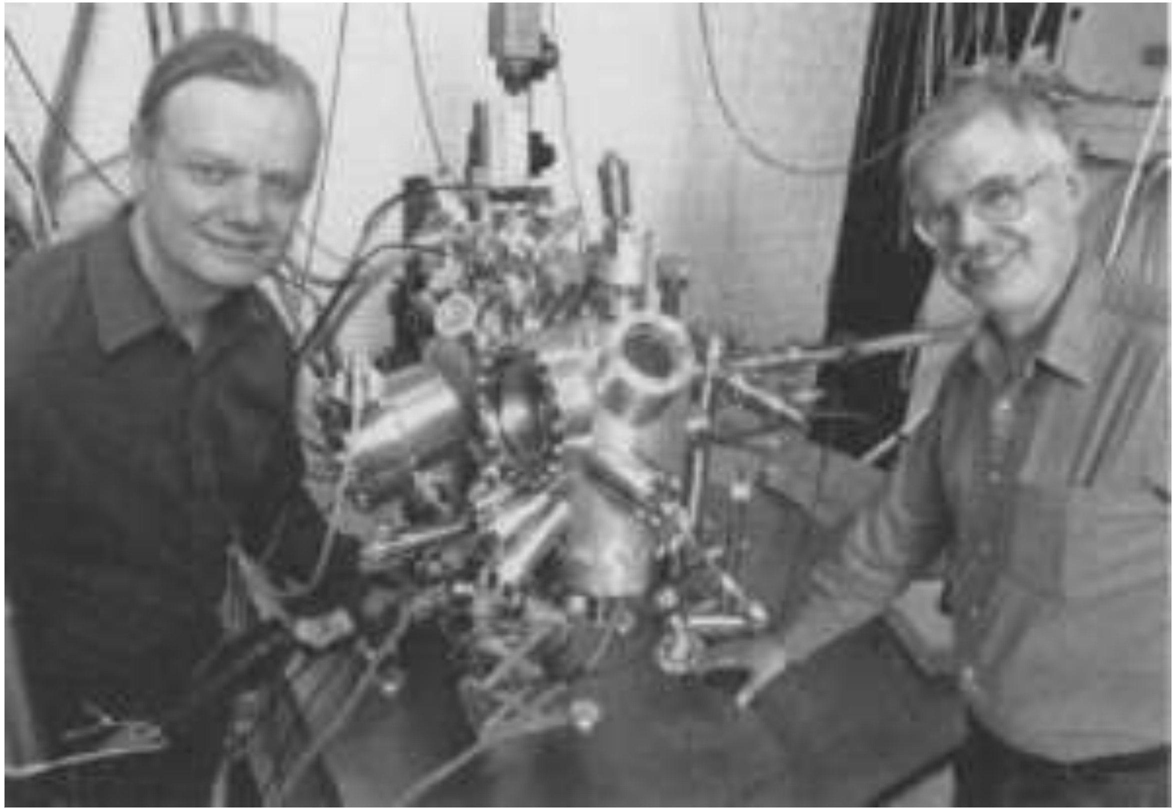






G. Binnig, H. Rohrer, C. Gerber & E. Weibel Tunneling through a controllable vacuum gap Appl. Phys. Lett. 40, 178 (1982)

1982 : inventing the scanning tunneling microscope



G. Binnig, H. Rohrer, C. Gerber & E. Weibel Tunneling through a controllable vacuum gap Appl. Phys. Lett. 40, 178 (1982)

Inventing the Scanning Tunneling Microscopy

The Nobel Prize in Physics 1986

Ernst Ruska
Prize share: 1/2

Gerd Binnig
Prize share: 1/4

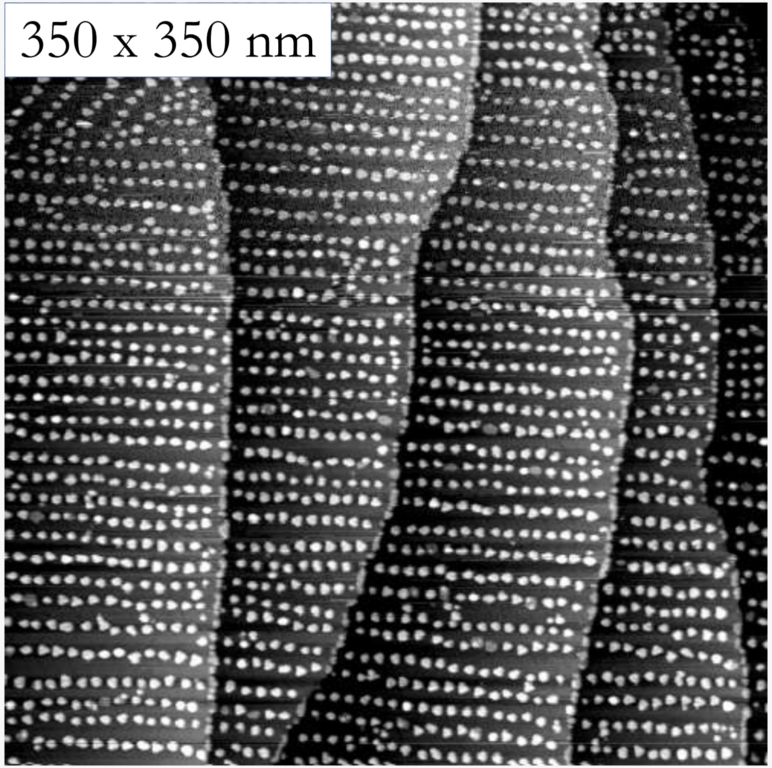
Heinrich Rohrer
Prize share: 1/4

The Nobel Prize in Physics 1986 was divided, one half awarded to Ernst Ruska *"for his fundamental work in electron optics, and for the design of the first electron microscope"*, the other half jointly to Gerd Binnig and Heinrich Rohrer *"for their design of the scanning tunneling microscope"*.

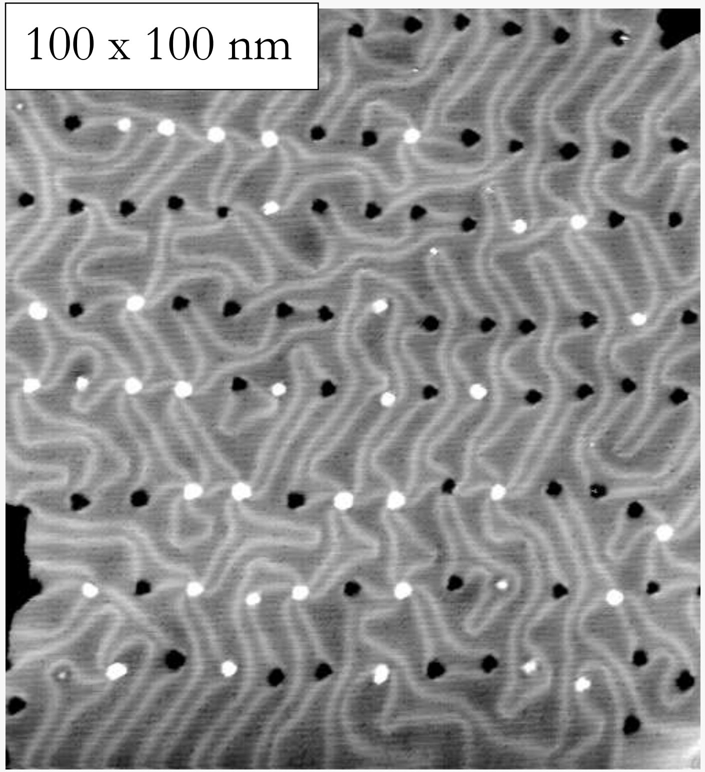
https://www.nobelprize.org

Topography – Large scale

Self-organized growth of magnetic dots (Co)



High resolution and sensitivity

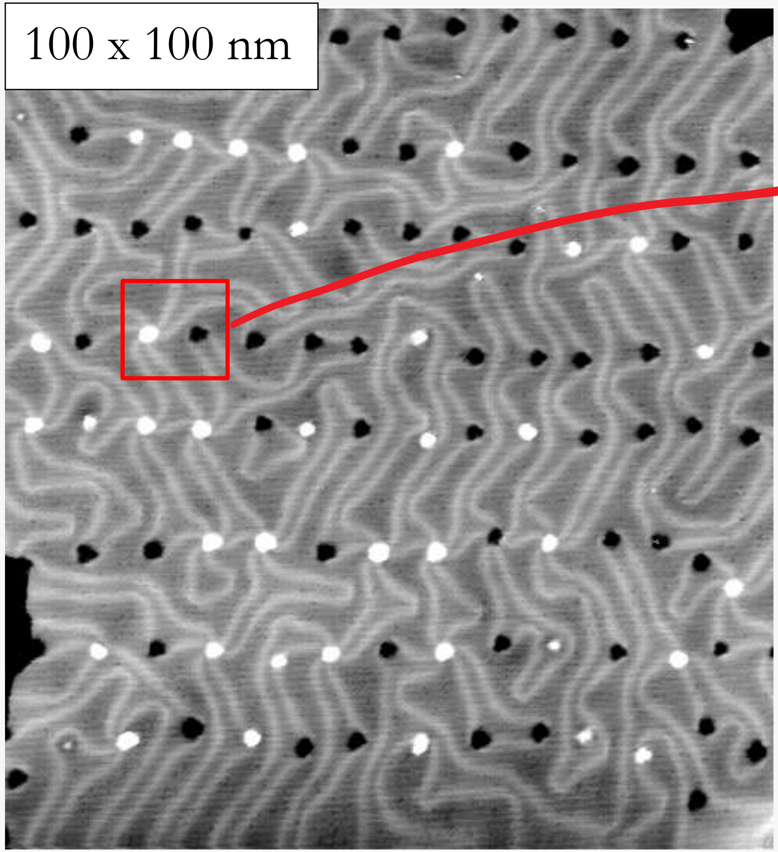


O. Fruchart et al., Phys. Rev. Lett. 23 (14), 2769 (1999)

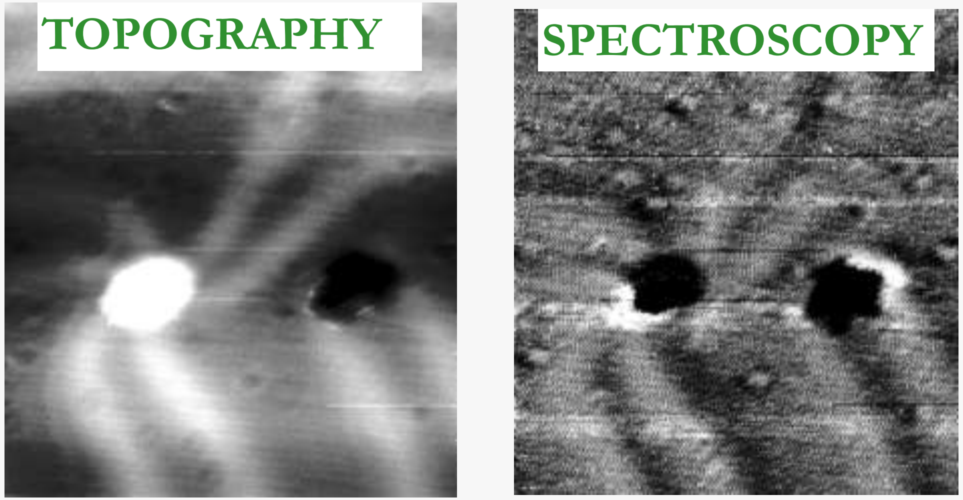
Scanning Tunneling Microscopy

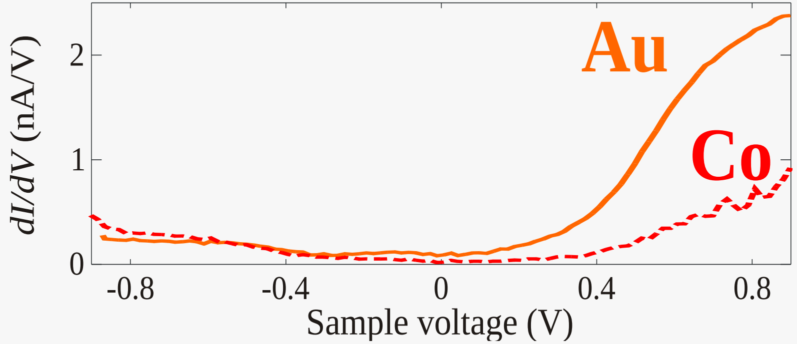
High resolution and sensitivity

Dots embedded in Au matrix



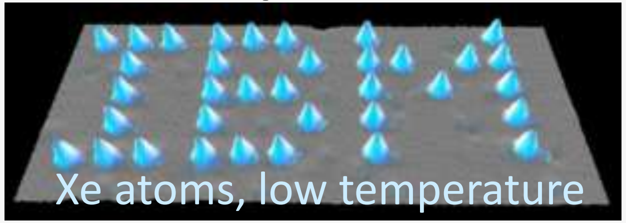
Spectroscopy → Elemental information



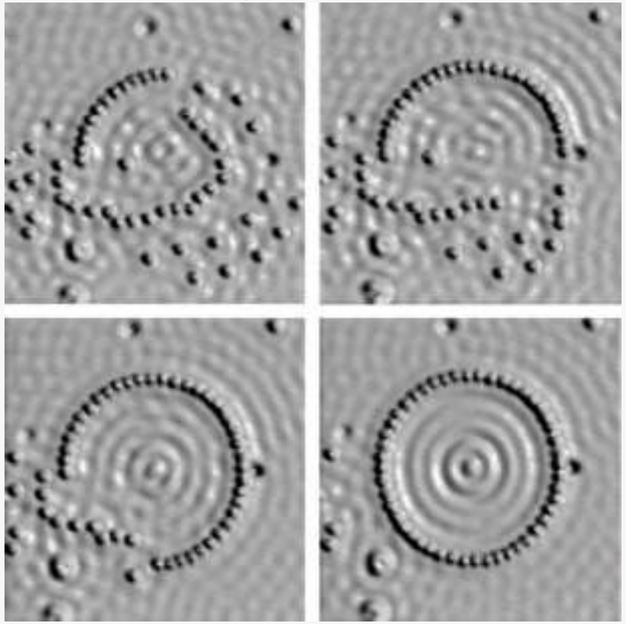


Scanning Tunneling Microscopy

Atom manipulation



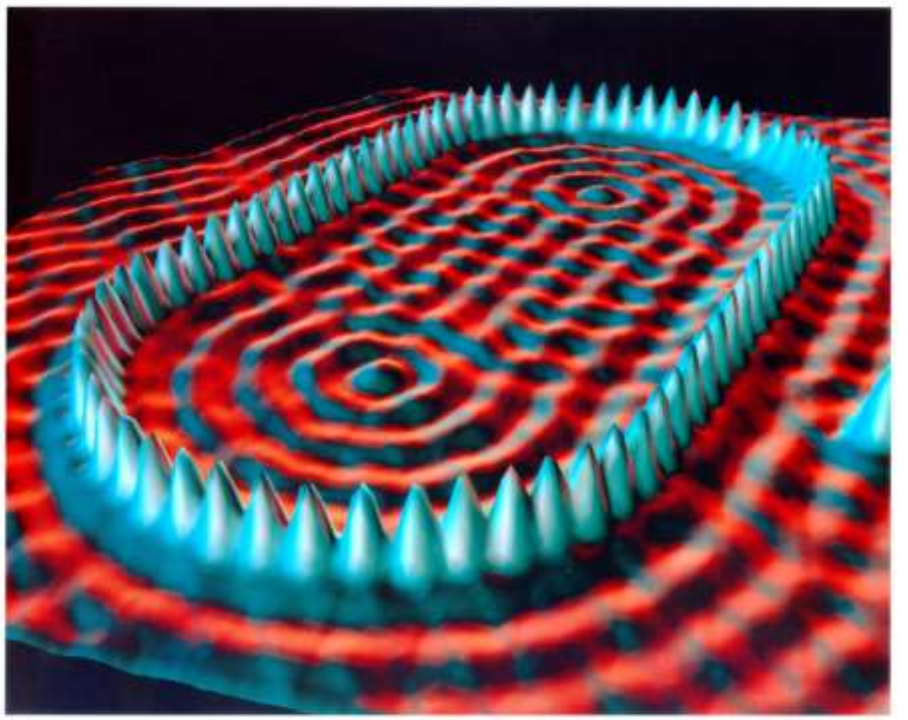
D. Eigler, Nature (1990)



http://research.physics.berkeley.edu/crommie

Mapping surface quantum well states

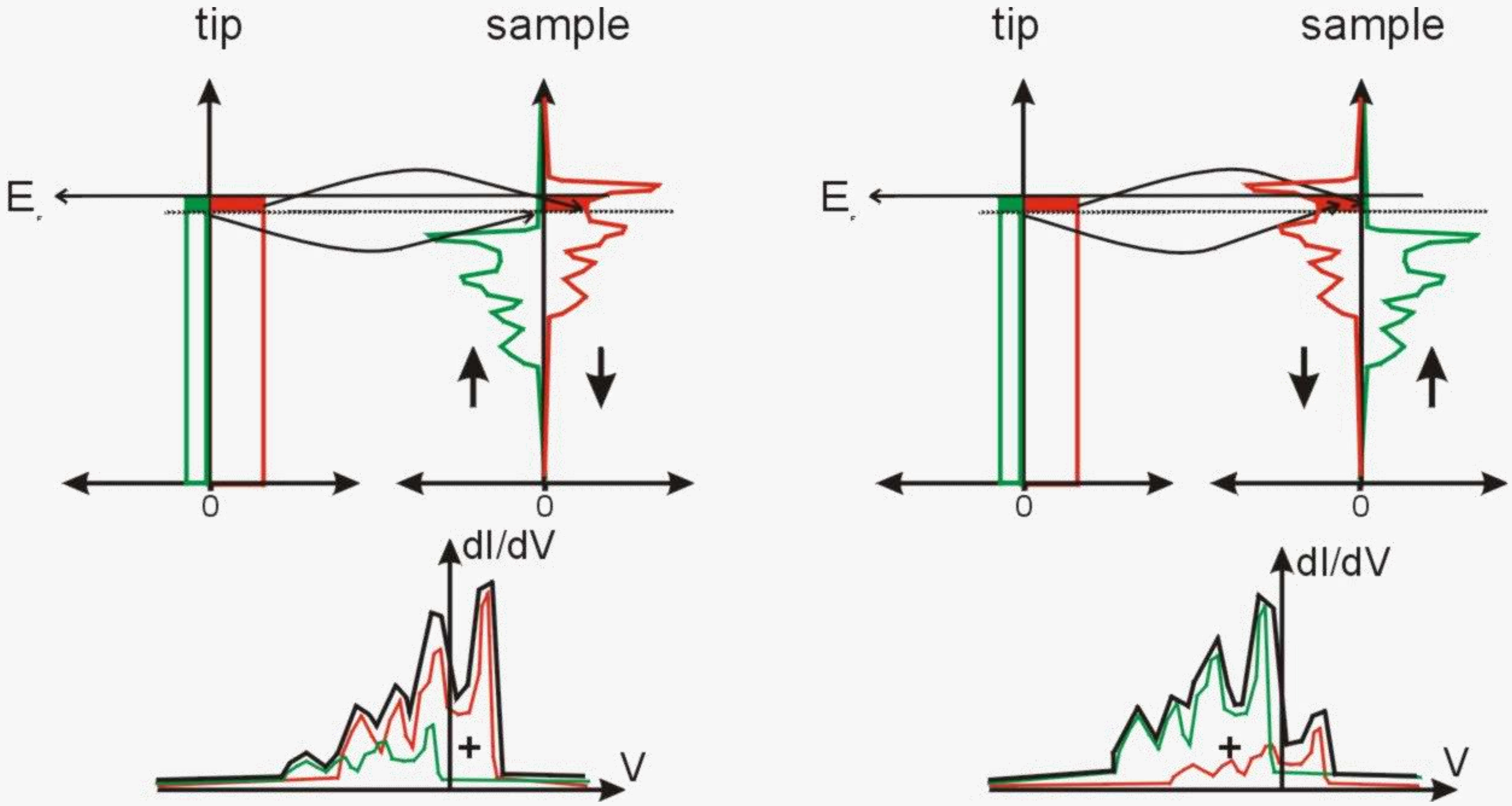
Fe atoms on Copper, low temperature



For magnetism: H. Oka et al., Spin-polarized quantum confinement in nanostructures: Scanning tunneling microscopy, Rev. Mod. Phys. 86, 1127-1168 (2014)

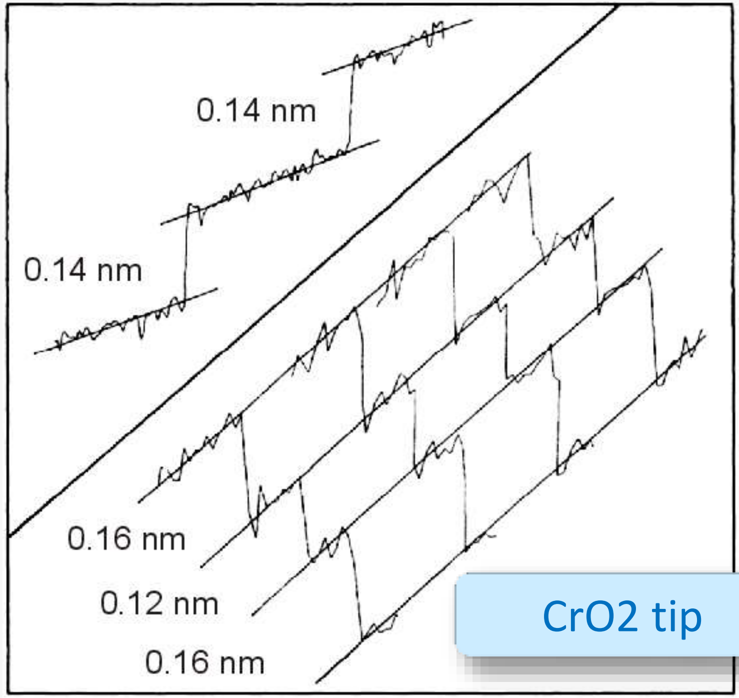
Spin-polarized Scanning Tunneling Microscopy

Spectroscopic principle Same principle as tunneling magnetoresistance (TMR) in the solid state



Courtesy: W. Wulfhekel

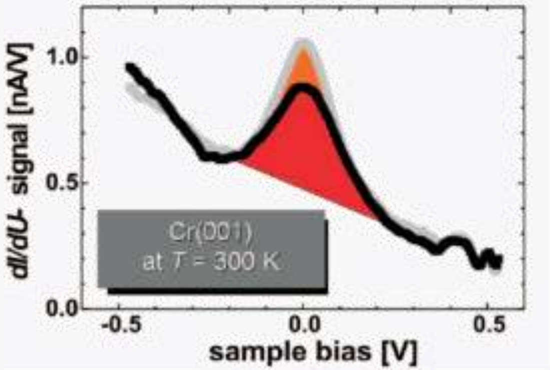
First hints: apparent height of AF atomic steps on Cr(001)

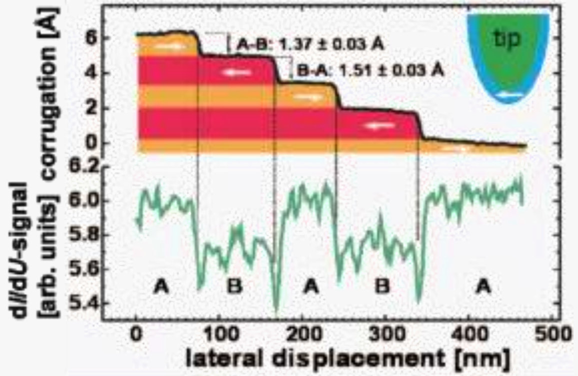


CrO2 tip

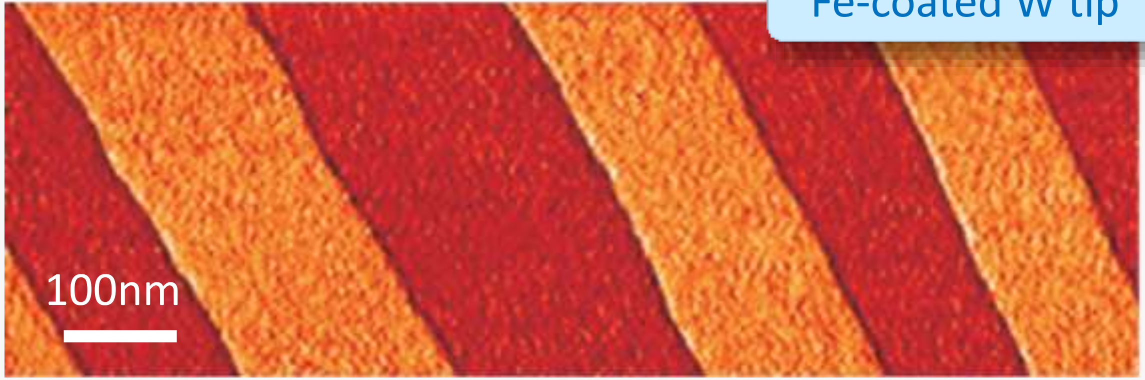
R. Wiesendanger et al.,
Phys. Rev. Lett. 65, 247 (1990)

Spectroscopy: the Cr(001) surface





Fe-coated W tip

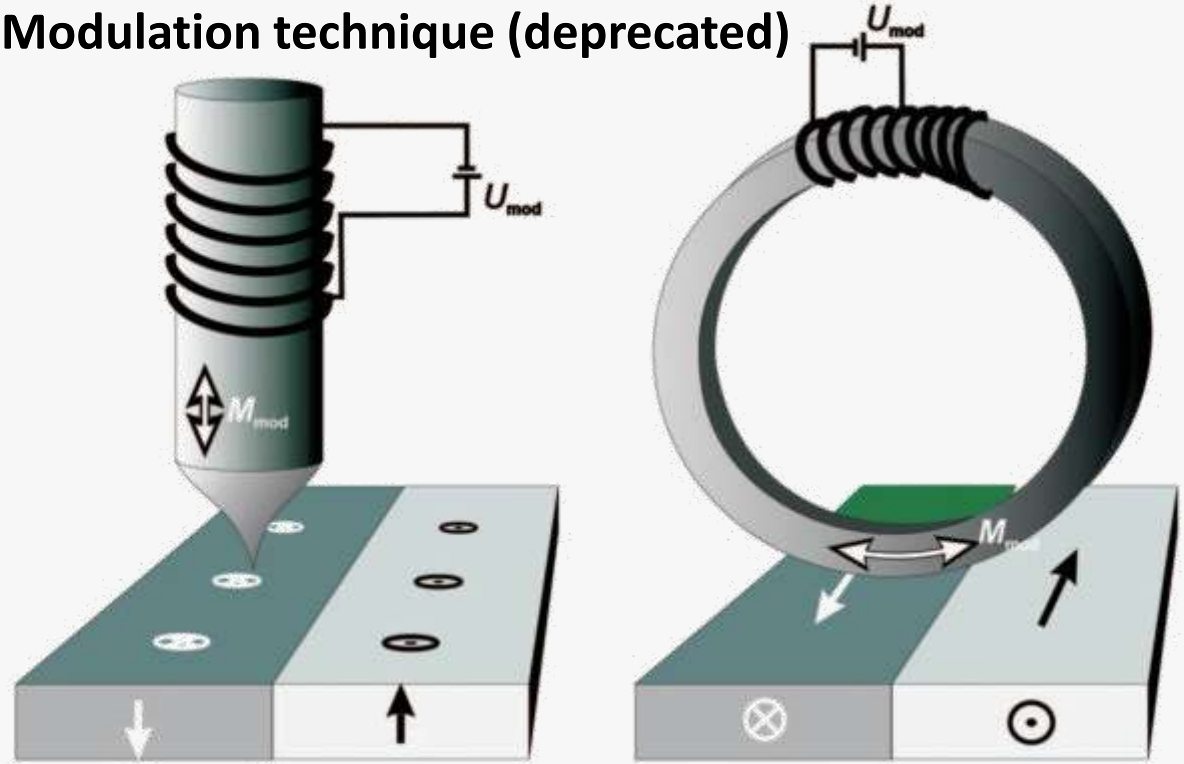


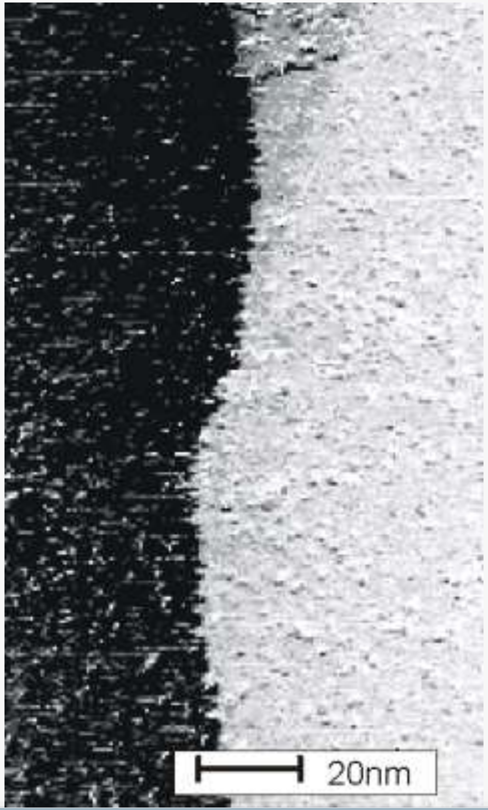
M. Kleibert et al., Phys. Rev. Lett. 85, 4606 (2000)

R. Wiesendanger et al., Rev. Mod. Phys. 81, 1495 (2009)

Spin-polarized Scanning Tunneling Microscopy

Modulation technique (deprecated)





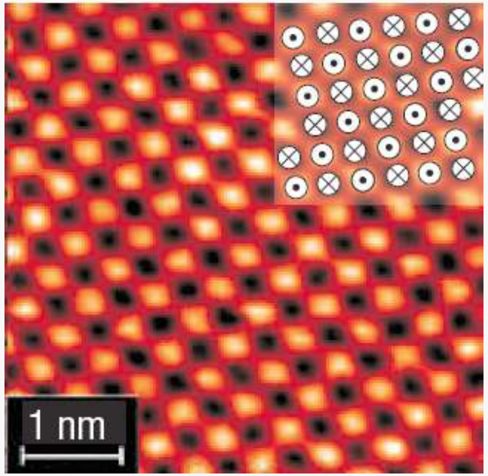
- ac modulation of magnetization of soft bulk tip
- Lock-in detection of tunneling current

Co(0001) – Micro-domain wall

H. Ding at al., Europhys. Lett. 57, 100 (2002)

Spin-polarized Scanning Tunneling Microscopy – Selected highlights

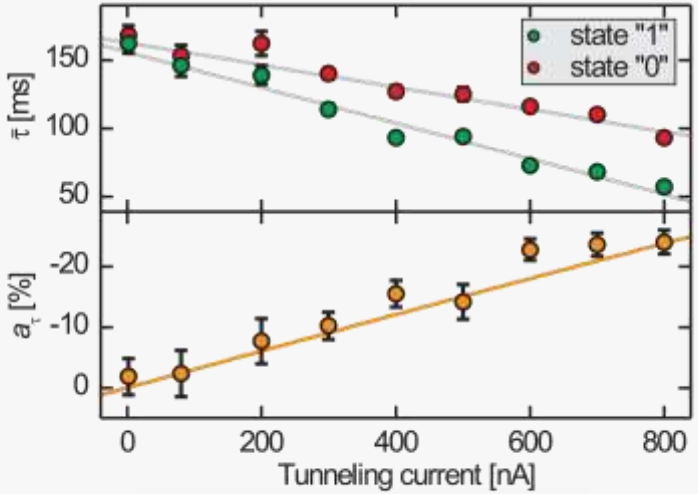
Antiferromagnetic Fe/W(001)



One monolayer Fe

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

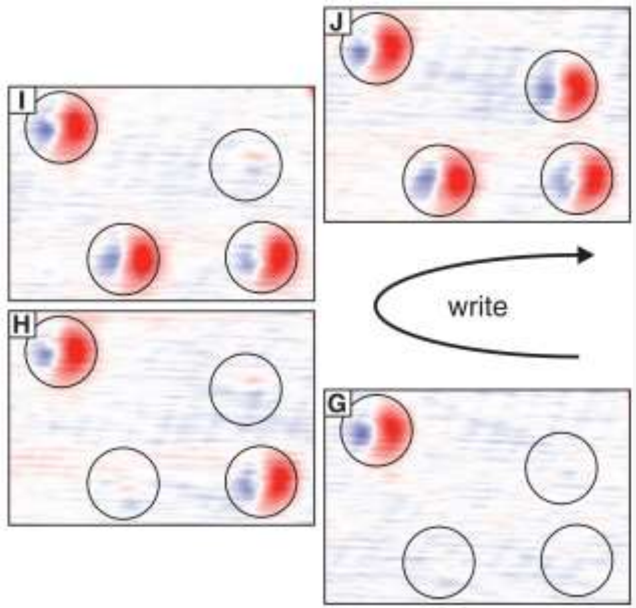
Current-assisted switching



1ML Fe(110)/W(110)

S. Krause et al., Science 317, 1537 (2007)

Skyrmions, write & delete

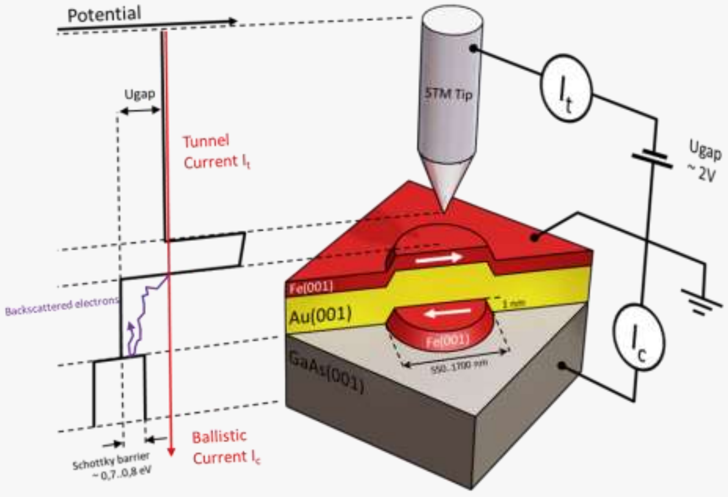


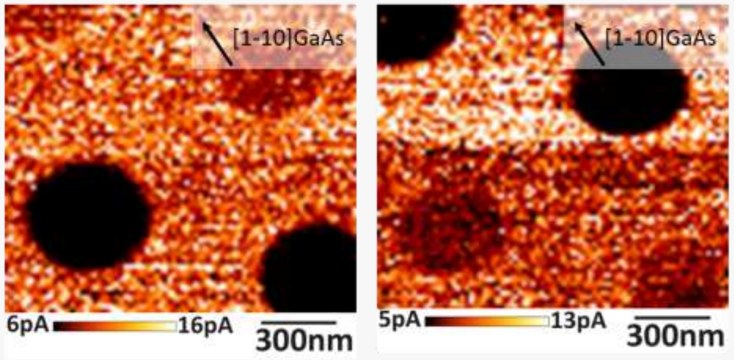
N. Romming et al., Science 341, 636 (2013)

R. Wiesendanger et al., Rev. Mod. Phys. 81, 1495 (2009)

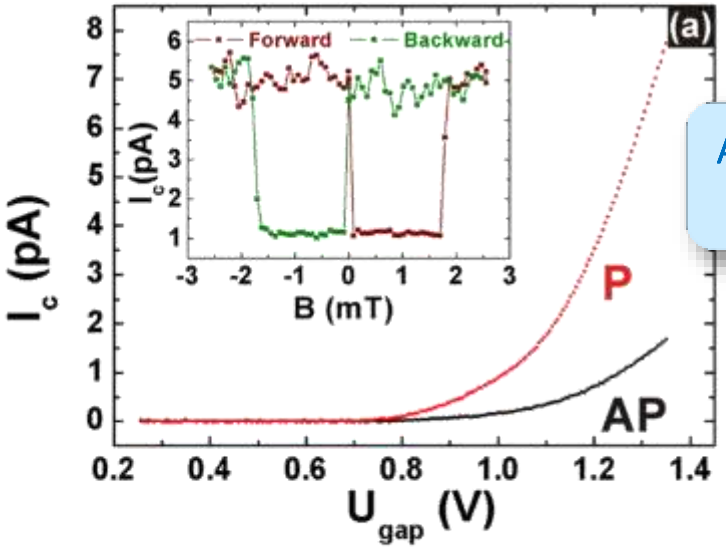
Ballistic-Electron Magnetic Microscopy (BEMM)

Principle





P. Turban, H. Marie, Rennes



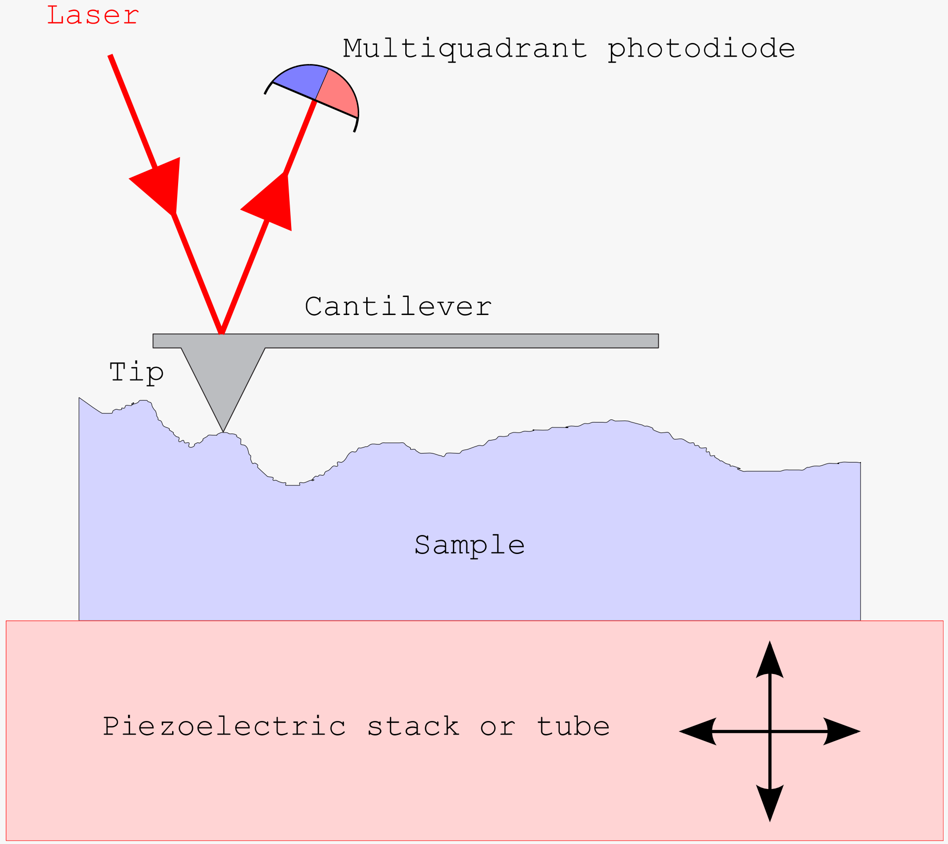
Au[2.2nm]/Fe[1]/Au[2.6]/Fe[1.6]/GaAs

Assets

- Sensitive to transport
- High contrast
- High spatial resolution (5-10 nm?)
- Not so versatile

Atomic force microscopy

Key elements of an Atomic Force Microscope (AFM)



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

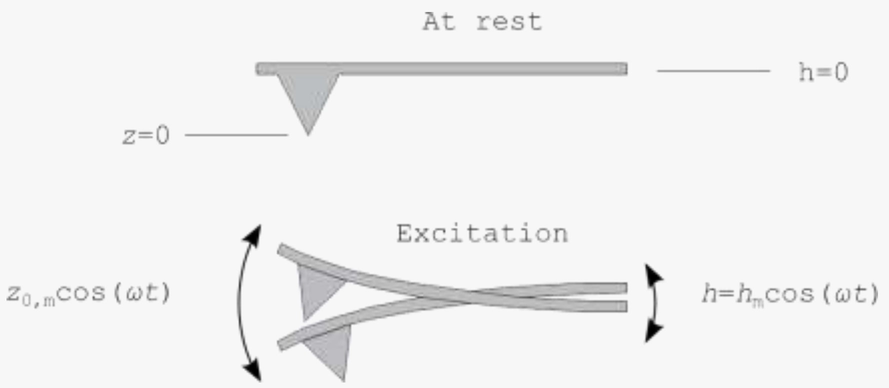
Probing

- Mechanical force -> Topography, tribology (adhesion etc.)
- Magnetic force -> magnetic domains
- Electric forces -> ferroelectric domains, semiconductor memory cells etc.

Detecting

- Laser deflection / interference
- Capacitance

Mechanical excitation of cantilevers



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

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

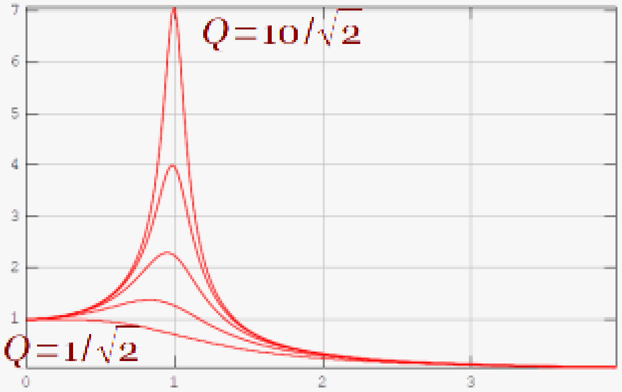
Notations

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

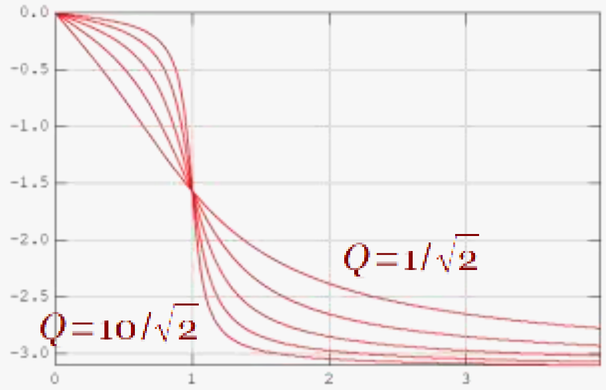
Reference angular velocity $\quad \omega_0=\sqrt{\frac{k}{m}}$

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

Amplitude



Dephasing



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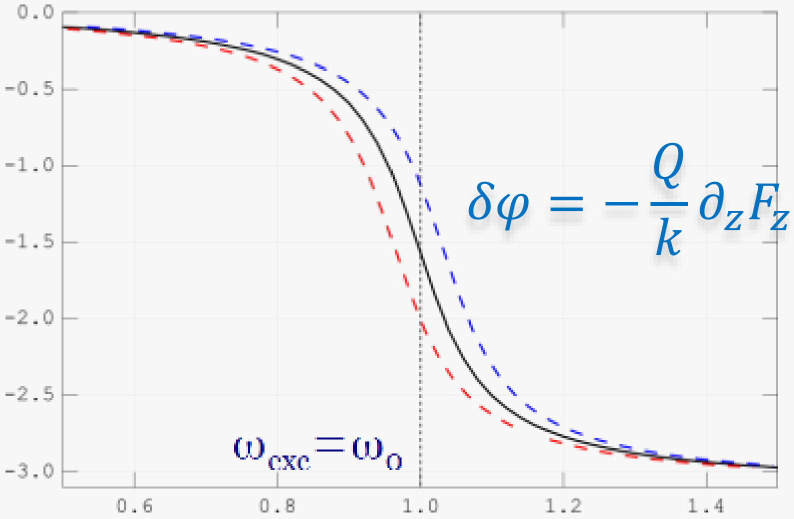
Tip-sample interaction treated as perturbation

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

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

Phase shift



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

Attractive force → Red shift

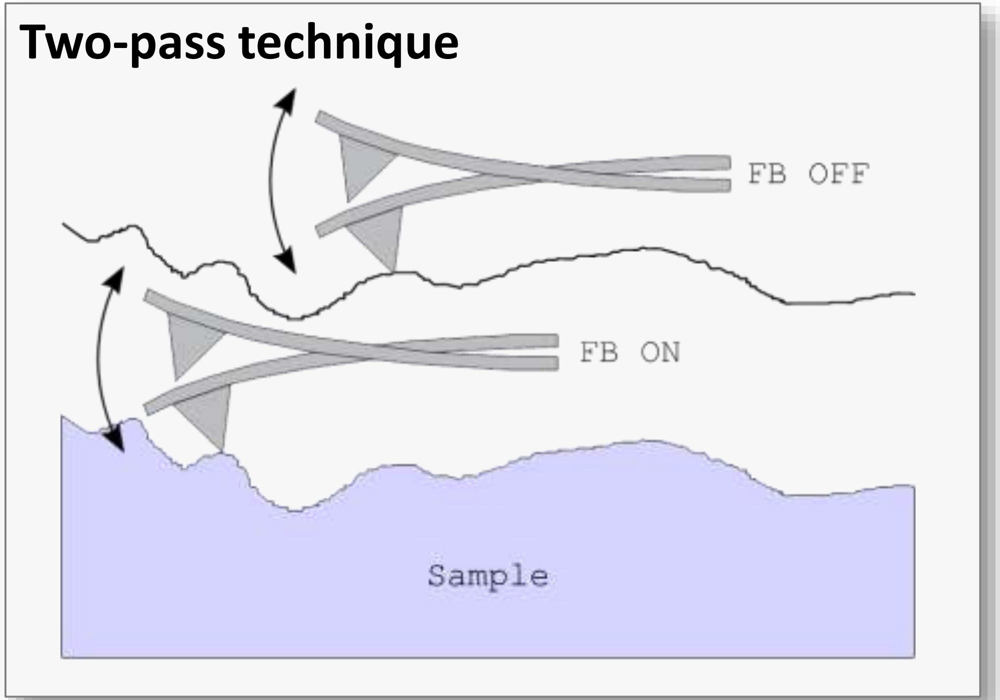
Repulsive force → Blue shift

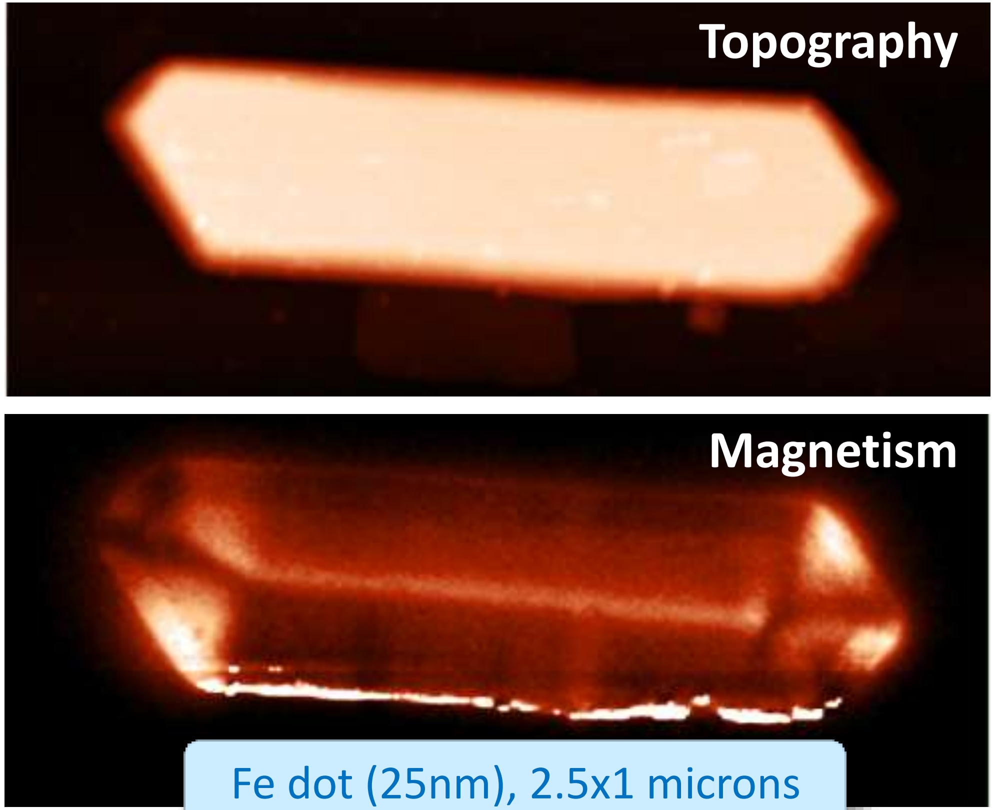
- Forces monitored through phase shift
- Notice my convention : decreasing phase

Magnetic force microscopy

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)

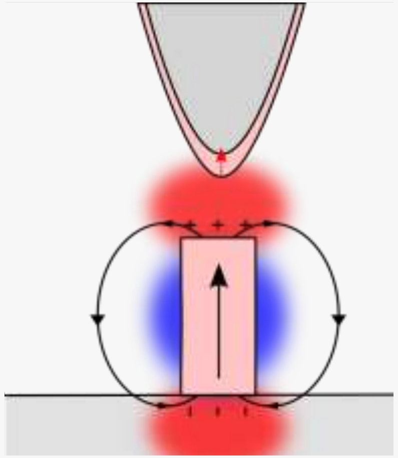




Fe dot (25nm), 2.5x1 microns

Magnetic force microscopy

Tip is a dipole

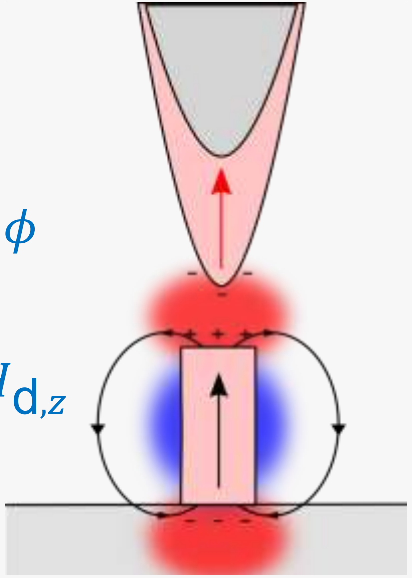


$$E_{1,2} = -\mu_0 \mu_2 . H_{\mathrm{d}}$$

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

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

Tip is a monopole



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

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

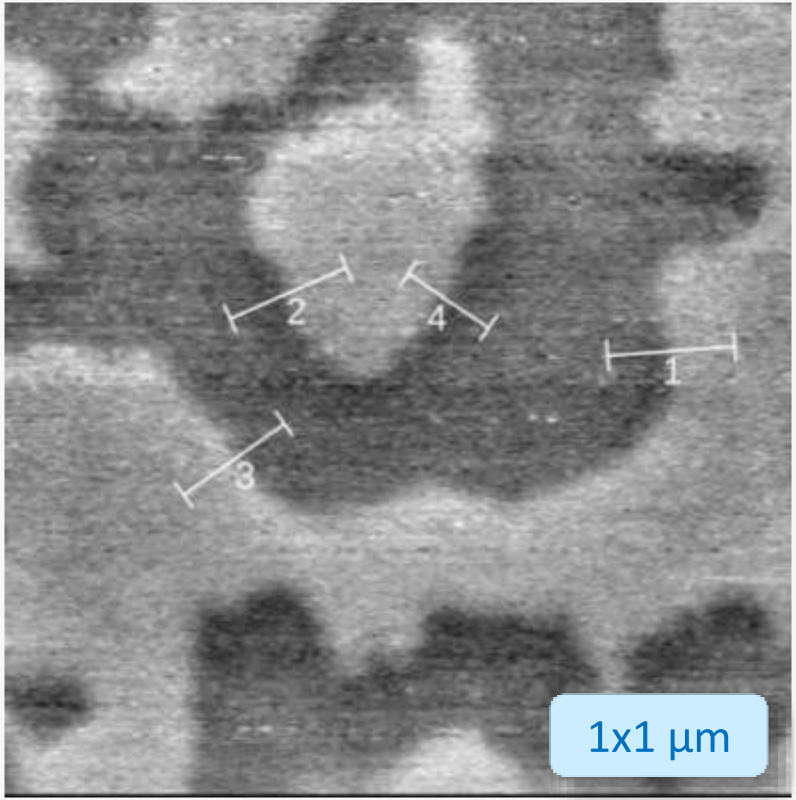
$$\Rightarrow \quad \delta\varphi = \frac{Q}{k} \mu_0 \sigma \partial_z H_{\mathrm{d},z}$$

- 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

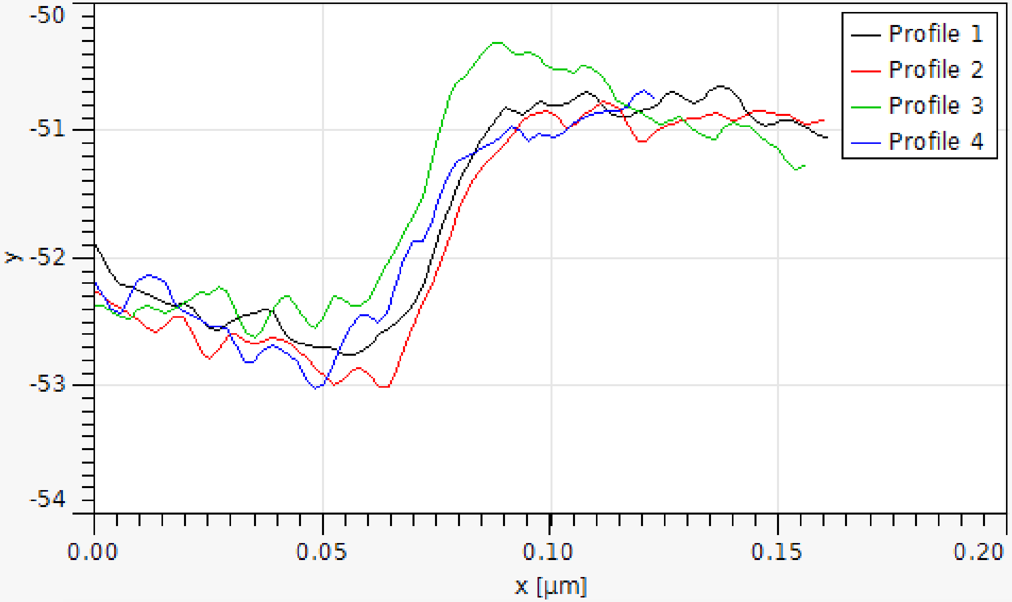
Quantitative analysis, see e.g.: H. Hug, J. Appl. Phys. 83, 5609 (1998) and followers

Magnetic force microscopy

Ultimate spatial resolution: 20nm ?

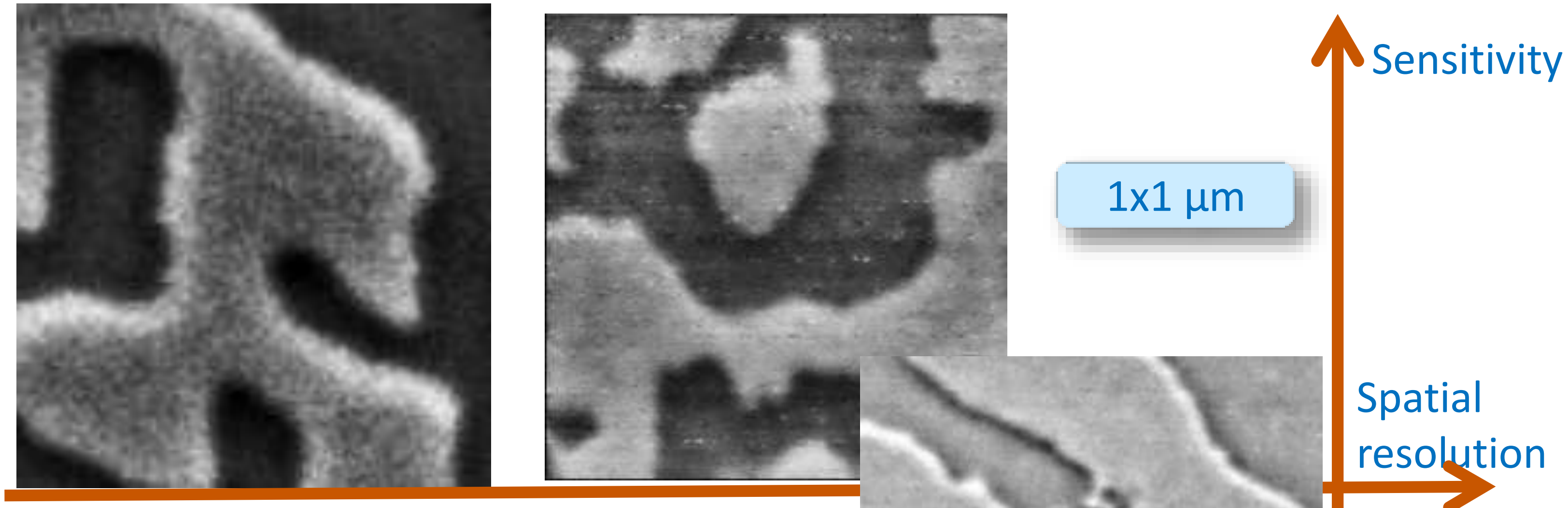


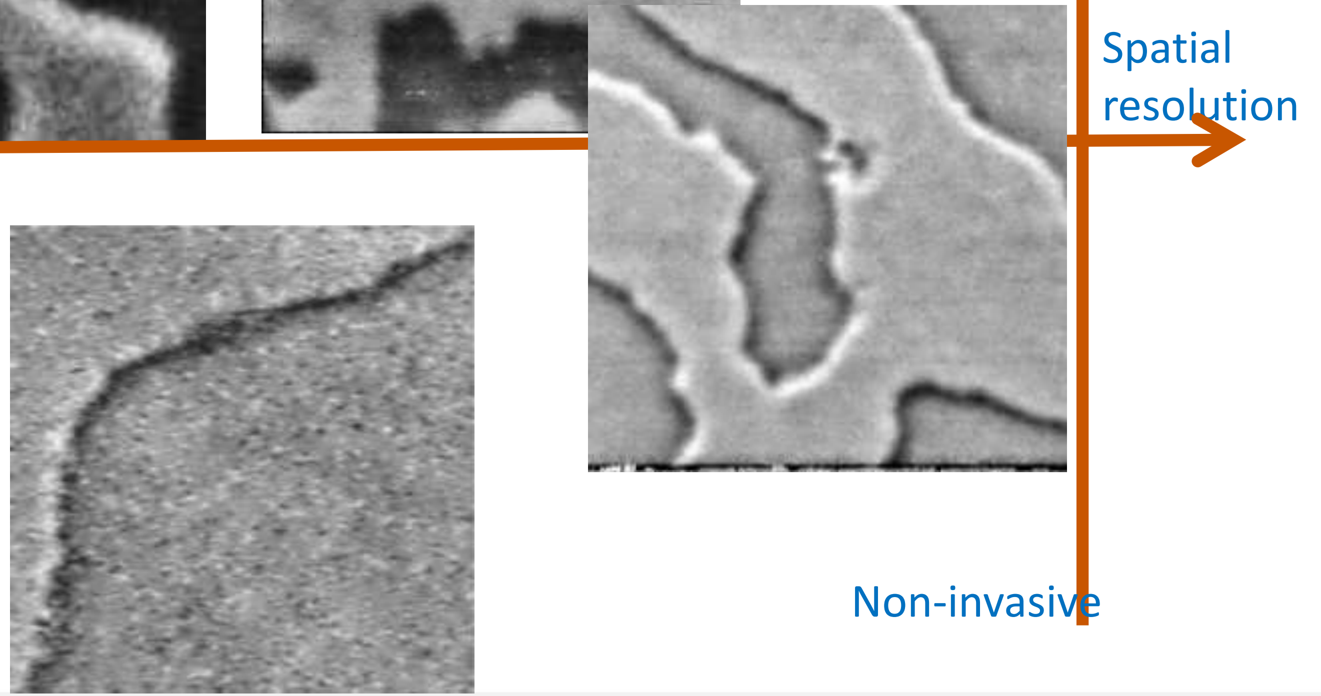
FePt, epitaxial (4nm)



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

Magnetic force microscopy





- Tricks lie in tips
- All matters: sensitivity, resolution, invasivity, coercivity…

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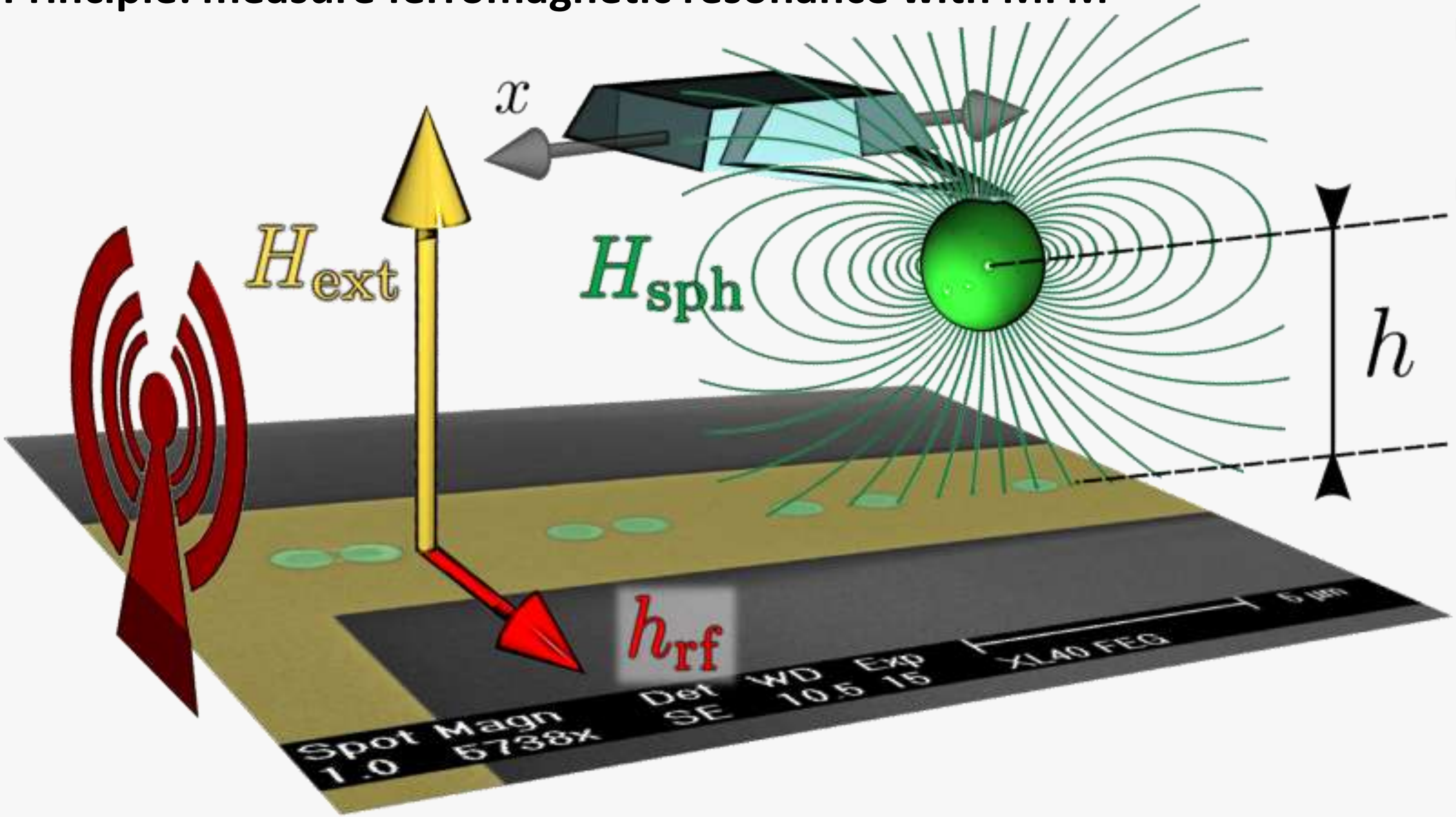
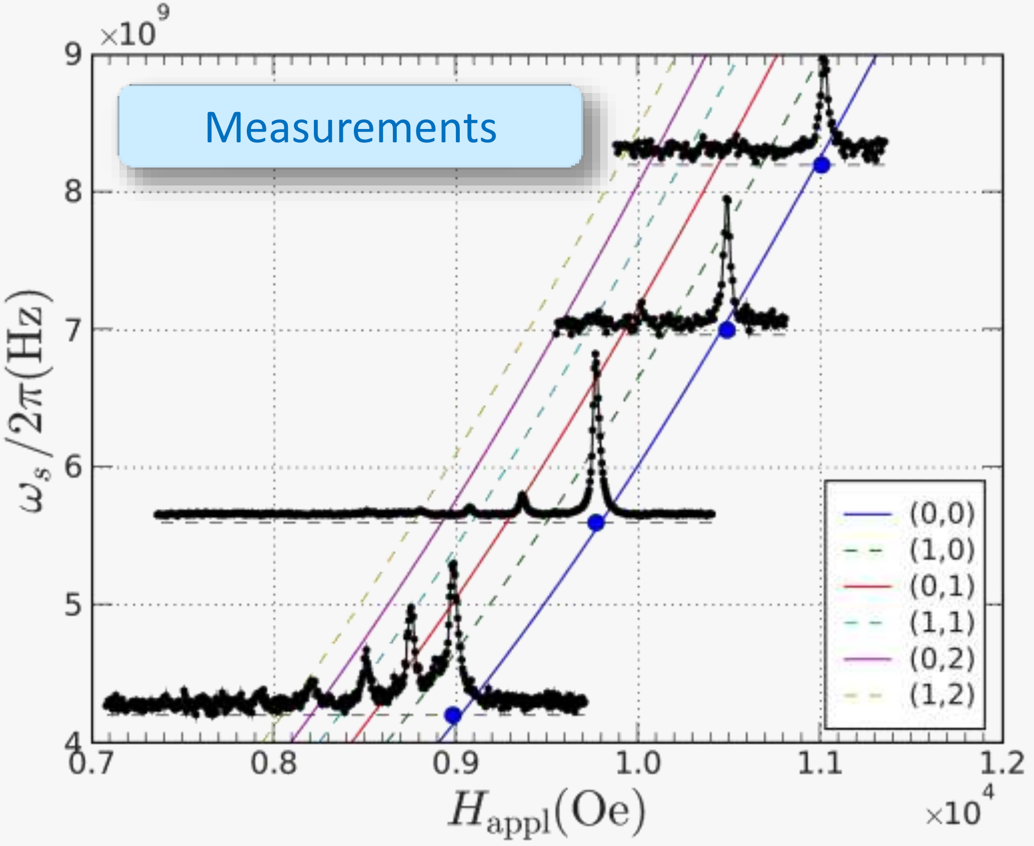
Principle: measure ferromagnetic resonance with MFM

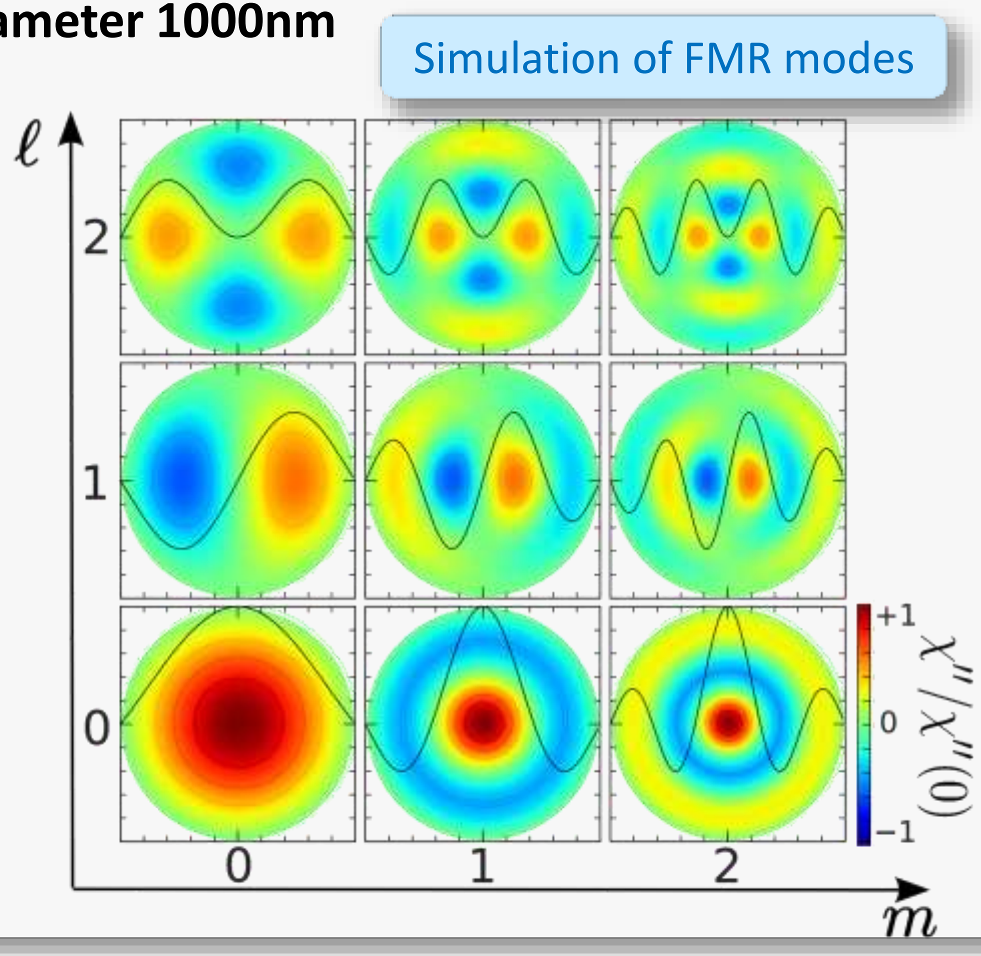


- Measures the longitudinal (static) moment
- Magnetic biasing of the sample with the stray field of tip allows some kind of imaging

Courtesy: O. Klein, Grenoble

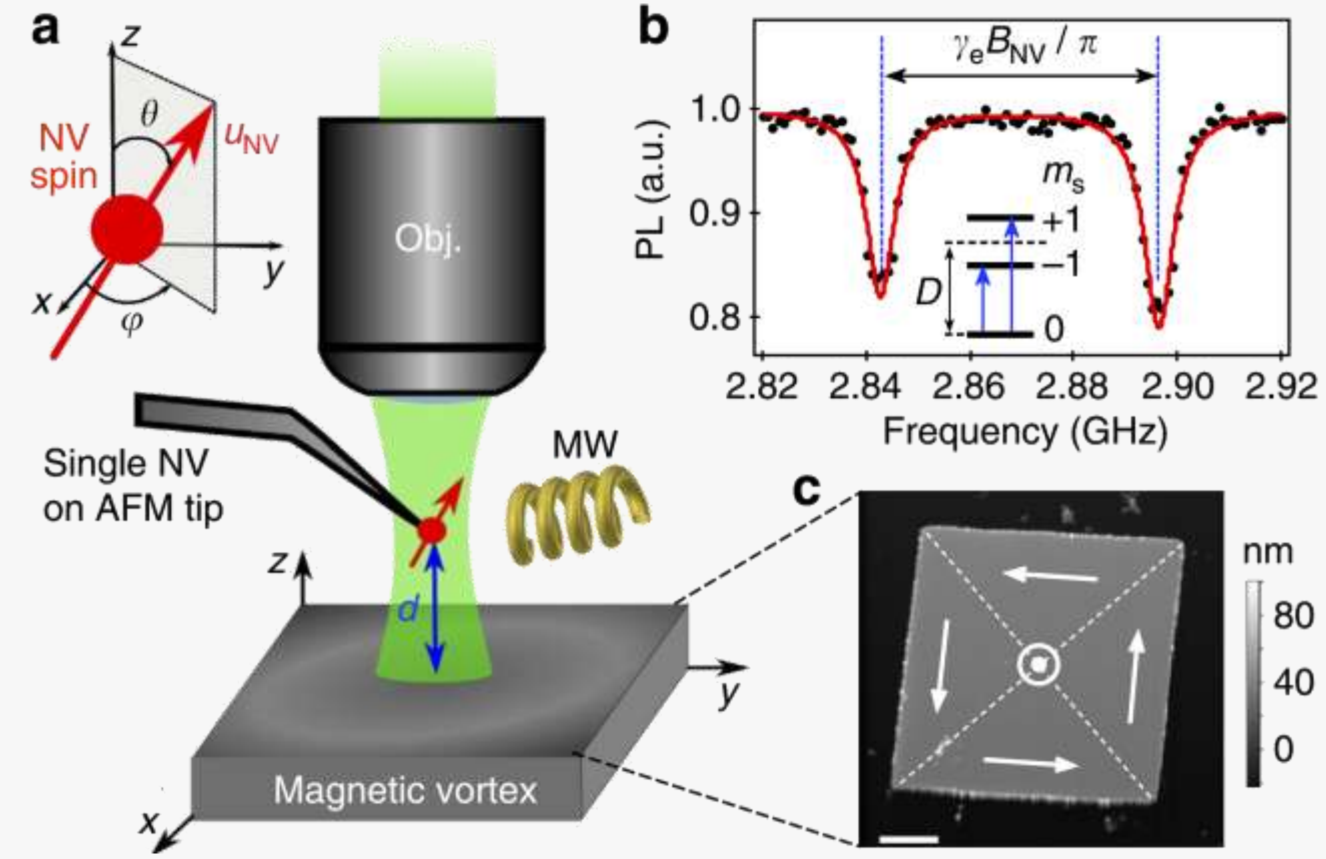
Example: FMR spectra of a permalloy disk with diameter 1000nm





O. Klein et al., Phys. Rev. B 78, 144410 (2008)

Principle: spectroscopy of a Nitrogen-Vacancy center in a diamond nanocrystal

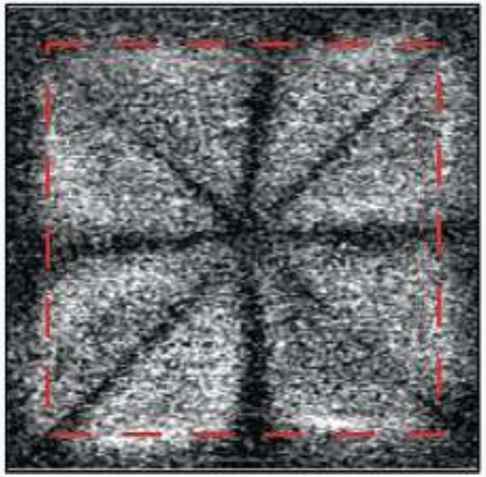


L. Rondin et al., Nat. Comm. 4, 2279 (2013)

NV center microscopy

Micromagnetics

Square Fe20Ni80 dot

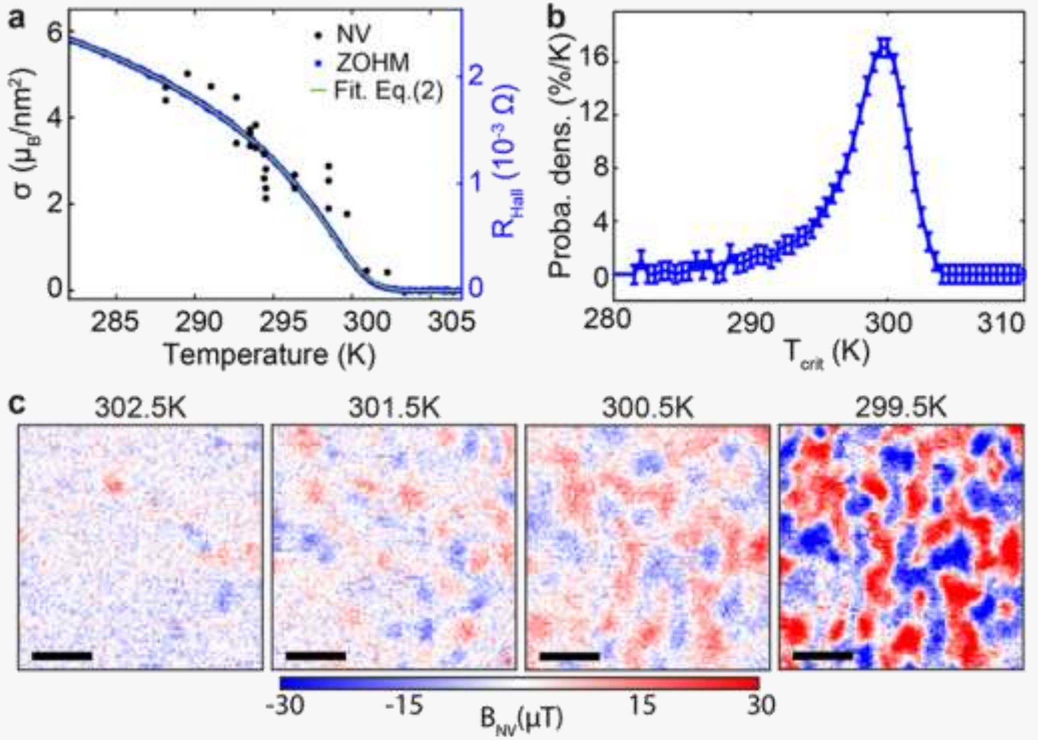


5 µm

Signature of flux-closure

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

Sensitivity: image antiferromagnetic domains



Cr_2O_3 200nm thin film

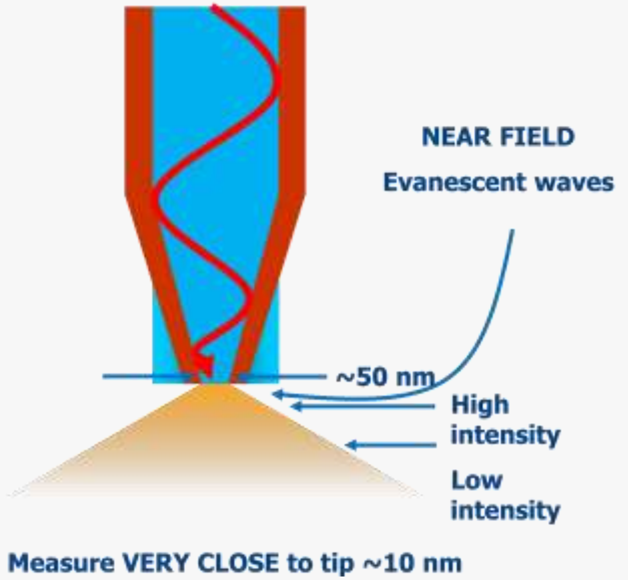
P. Appel et al., Nano Lett. 19, 1682 (2019)

Assets

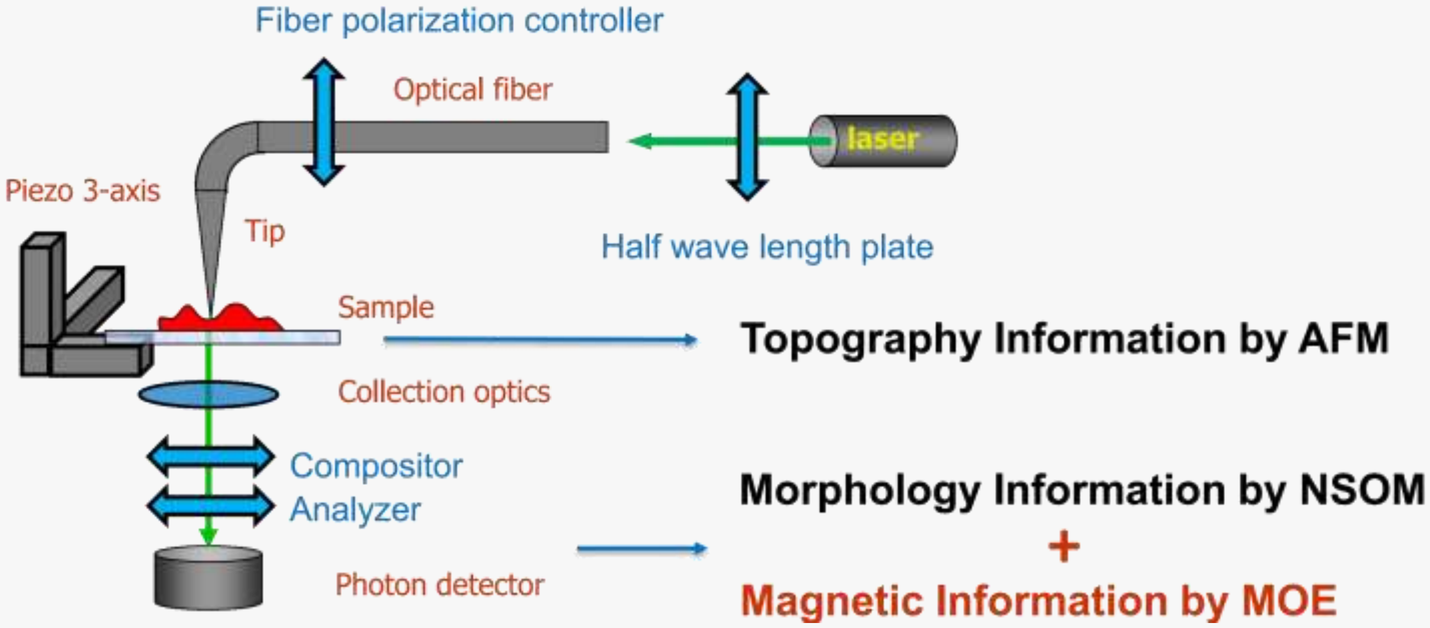
- High sensitivity
- Possibly quantitative in field
- Quantitative reconstruction of magnetization pattern not straightforward
- Imaging under high magnetic field not possible

SNOM – Scanning near-field optical microscopy

Near-field optics



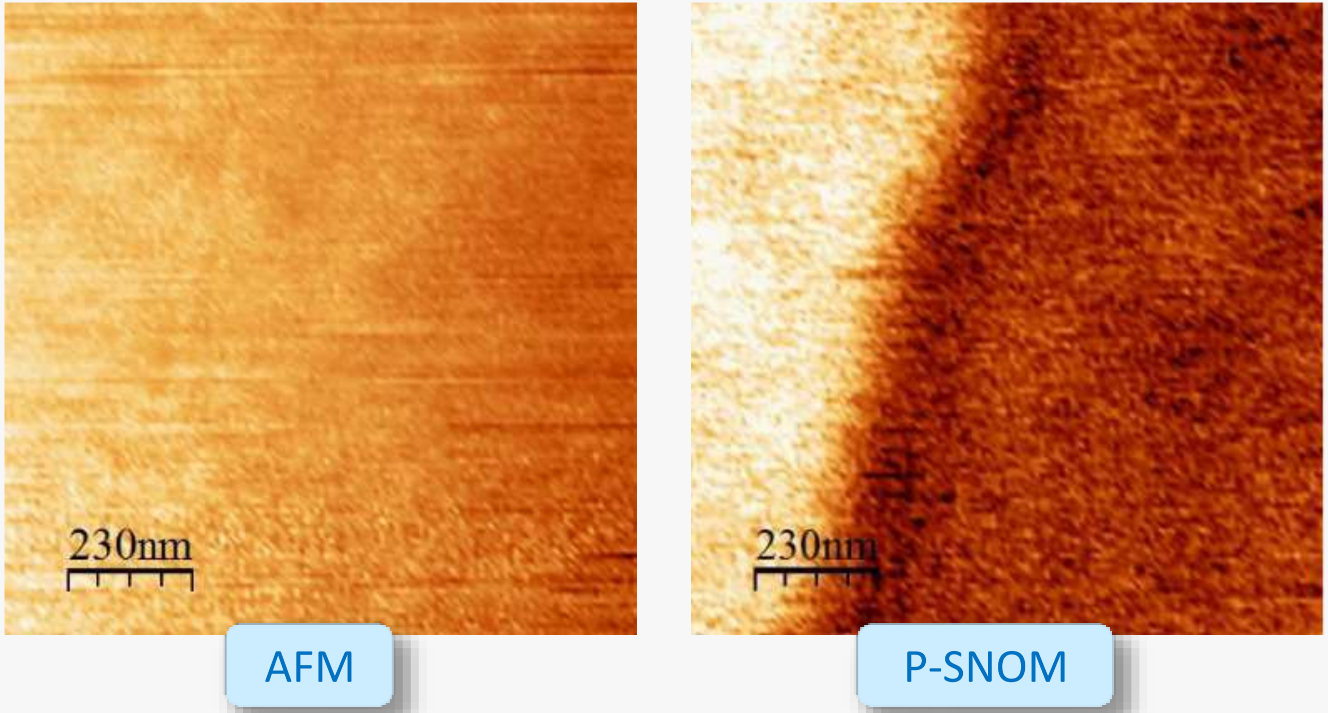
Implementation for magnetic microscopy



Courtesy: M. Miron, Grenoble

SNOM – Scanning near-field optical microscopy

Out-of-plane magnetization Ultrathin Pt/Co/Pt film



Assets

- Reasonable spatial resolution
- Compatible with time resolution
- Hardly quantitative

Courtesy: M. Miron, Grenoble

Overview of pros and cons (personal feelings)

	Sp-STM	MFM	NV	BEMM	SEMPA	SPLEEM	TEM	XMCD -PEEM	XMCD-microscopy (Fresnel ZP)	SNOM
Resolution	<1nm	15nm	5-10 nm	1-5nm	10nm	10nm	1-2nm	25nm → 10nm	15nm	50-100nm?
Sensitivity	High	Med	High	Med	Med	High	Low	High	High	Med
In-field	YES	Limited	Limited	YES	local	No?	Limited	No?	YES	YES
Versatile*	No	YES	Yes	No	Limited	UHV	Limited	Yes	Limited	Limited
Dynamics	Part	Part	No	No	No	No	Part	Yes	Yes	Yes
Element-sensitive	Limited	No	No	No	Limited	Limited	Limited	Yes	Yes	No
	m_i	$\mathrm{H_d}$	$\mathrm{H_d}$	m_i	m	m	$m_{x,y}$	m_k	m_k	unsure

More extensive slides on: http://magnetism.eu/esm/repository-topics.html#techniques

Lecture notes from undergraduate lectures, plus various slides on microscopy (MFM etc.):
http://fruchart.eu/olivier/slides/

[1] Handbook of magnetism and advanced magnetic materials, H. Kronmüller and S. S. P. Parkin Eds., Wiley (2007). VOLUME 3: Novel Techniques for Characterizing and Preparing Samples

[2] Magnetic microscopy of nanostructures, Oepen Ed., Springer (2005)

[3] Modern techniques for characterizing magnetic materials, Y. Zhu Ed., Springer (2005)

[4] Magnetic domains, A. Hubert, R. Schäfer, Springer (1999, reed. 2001

I wish you a nice second week in ESM !

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