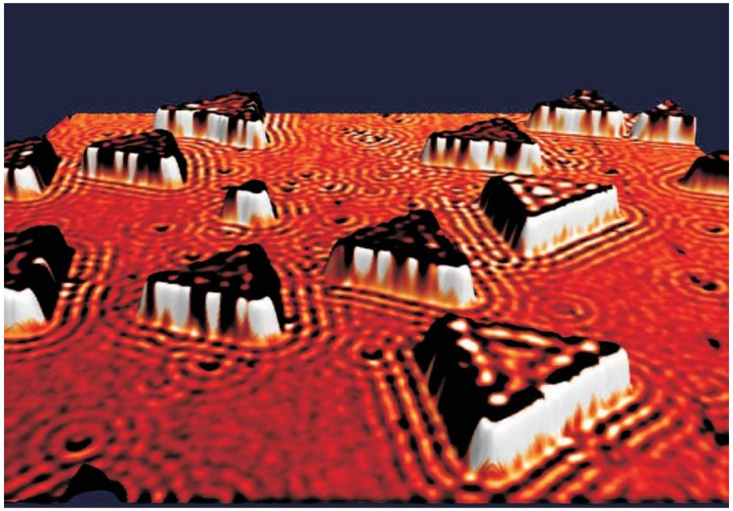
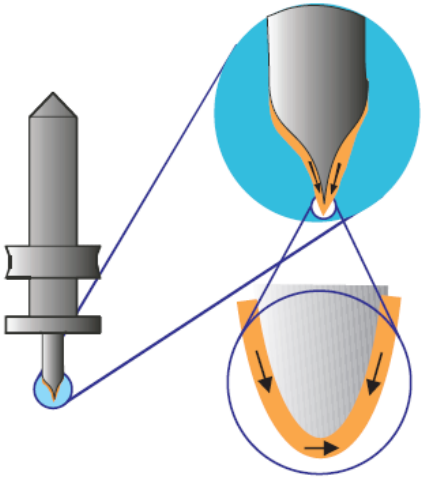
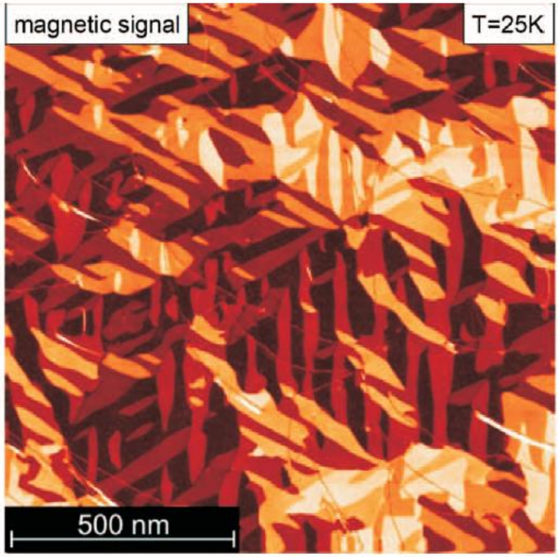
Spin mapping at the nanoscale and atomic scale

Roland Wiesendanger







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Magyarkuti András
Nanophysics Seminar
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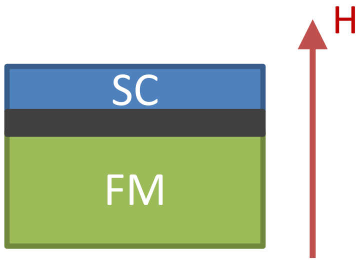
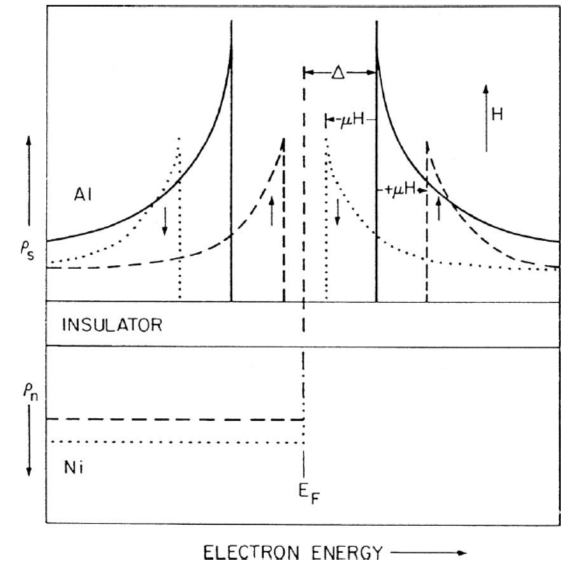
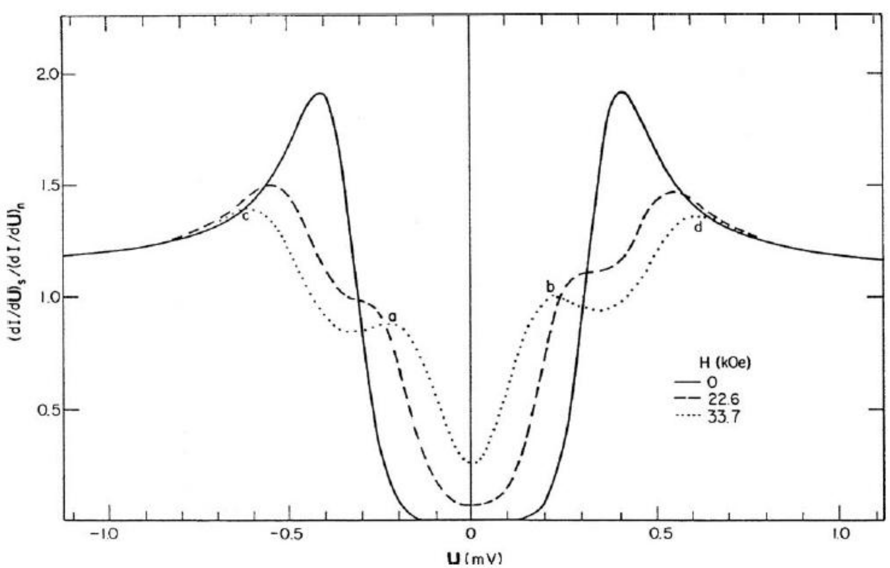
Tunneling between ferromagnet and superconductor



- Zeeman splitting: $\pm\mu H$
- Thin SC layer -> no spin scattering
- Spin polarization: $P \equiv \dfrac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}$,



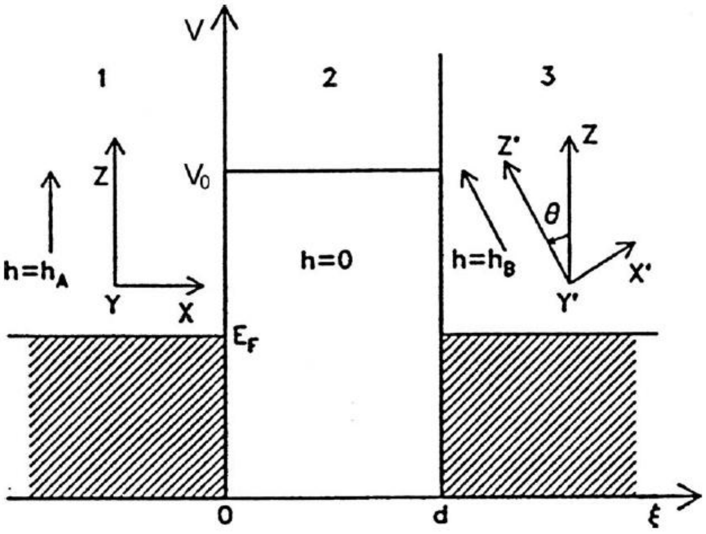
Assymetric conductance-voltage curve:



$$P = \frac{(G_d - G_a) - (G_c - G_b)}{(G_d - G_a) + (G_c - G_b)}$$

[Tedrow and Mersevey, 1971]

Tunneling between two ferromagnets



- Identical ferromagnets:

$$G = G_{\mathrm{fbf}}(1 + P_{\mathrm{fb}}^2 \cos\theta), \quad |P_{\mathrm{fb}}| \leqslant 1$$

P_{fb} effective spin polarization

G_{fbf} non magnetic tunneling conductance

θ angle of internal magnetic fields

- Different ferromagnets:

$$G = G_{\mathrm{fbf'}}(1 + P_{\mathrm{fb}} P_{\mathrm{f'b}} \cos\theta)$$

$$G_{\uparrow\uparrow} = G_{\mathrm{fbf'}}(1 + P_{\mathrm{fb}} P_{\mathrm{f'b}})$$

$$G_{\uparrow\downarrow} = G_{\mathrm{fbf'}}(1 - P_{\mathrm{fb}} P_{\mathrm{f'b}})$$

$$\frac{G_{\uparrow\uparrow} - G_{\uparrow\downarrow}}{G_{\uparrow\uparrow} + G_{\uparrow\downarrow}} = P_{\mathrm{fb}} P_{\mathrm{f'b}} =: P_{\mathrm{fbf'}}$$

Tersoff-Hamann theory of STM

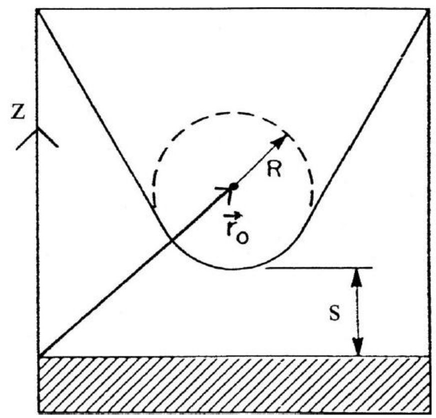
- First-order time-dependent perturbation: $$I = \frac{2\pi e}{\hbar}\sum_{\mu,\nu}\{f(E_\mu)[1-f(E_\nu+eU)] - f(E_\nu+eU)[1-f(E_\mu)]\}|M_{\mu\nu}|^2\delta(E_\nu - E_\mu)$$

Unperturbed electronic states of tip: Ψ_μ and sample: Ψ_ν

- Tunneling matrix element: $$M_{\mu\nu} = \frac{-\hbar^2}{2m}\int dS(\Psi_\mu^* \nabla \Psi_\nu - \Psi_\nu \nabla \Psi_\mu^*)$$

- Model tip wavefunction: s-type

$$\Psi_\mu = \frac{1}{R}e^{-\kappa R}$$



Low T, small U bias voltage

$$I \propto U n_t(E_F)\exp(2\kappa R)\sum_\nu |\Psi_\nu(\vec{r}_0)|^2\delta(E_\nu - E_F)$$

DOS of the tip

LDOS at the sample's surface: $n_S(E_F,\vec{r}_0) = \sum_\nu |\Psi_\nu(\vec{r}_0)|^2\delta(E_\nu - E_F)$

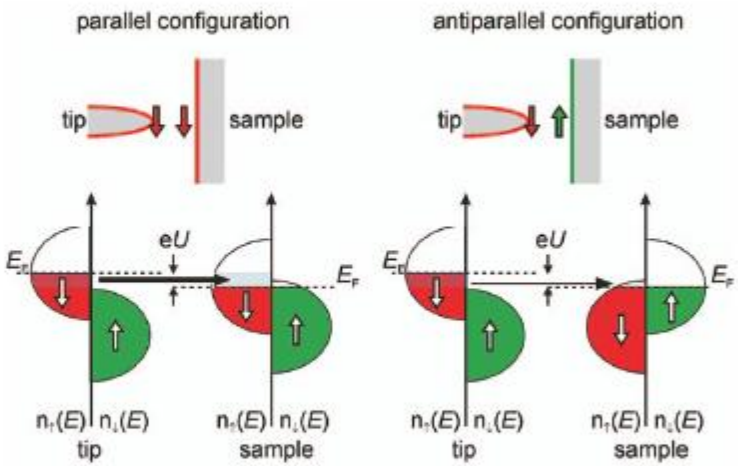
$$|\Psi_\nu(\vec{r}_0)|^2 \propto \exp[-2\kappa(s+R)] \Longrightarrow I \propto \exp(-2\kappa s)$$

Spin resolved STM

- Magnetic tip -> spin dependent tunneling current

Spinor transformation between the spin coordinate system of tip and sample:

$$G = 2\pi^2 G_0 (n_t^{\uparrow} n_s^{\uparrow} |M_{\uparrow\uparrow}|^2 + n_t^{\uparrow} n_s^{\downarrow} |M_{\uparrow\downarrow}|^2 + n_t^{\downarrow} n_s^{\uparrow} |M_{\downarrow\uparrow}|^2 + n_t^{\downarrow} n_s^{\downarrow} |M_{\downarrow\downarrow}|^2).$$



$$n_t = n_t^{\uparrow} + n_t^{\downarrow}, \quad n_s = n_s^{\uparrow} + n_s^{\downarrow}$$

$$m_t = n_t^{\uparrow} - n_t^{\downarrow}, \quad m_s = n_s^{\uparrow} - n_s^{\downarrow},$$

$$G = 2\pi^2 G_0 |M_0|^2 (n_t n_s + m_t m_s \cos\theta)$$

$$P_t = m_t / n_t, \quad P_s = m_s / n_s,$$

$$G = 2\pi^2 G_0 |M_0|^2 n_t n_s (1 + P_t P_s \cos\theta)$$

$$I_{SP}(U_0) \propto I_0 \cdot [1 + P_{tip} \cdot P_{sample} \cdot \cos(\vec{m}_{tip}, \vec{m}_{sample})]$$

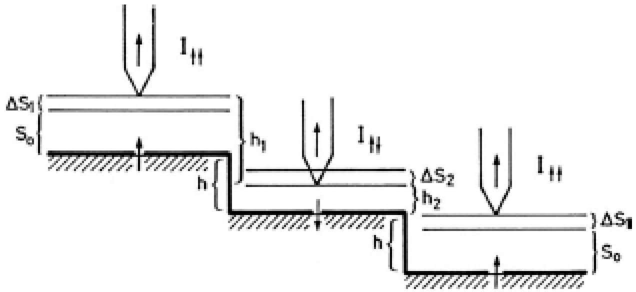
- Spin resolved LDOS at E_F for both sample and tip
- $\cos\theta$ angle between the magnetization direction of tip and sample

Finite bias:

$$I \propto \int^{eU} n_t(\pm eU \mp E) n_s(E) T(E, eU) dE$$

Spin resolved STM

First experiment with magnetic tip and sample



- CrO_2 tip with Cr (001) sample surface: alternately magnetized terraces separated by monatomic steps.
- At constant height, the current would change:

$$I_{\uparrow\uparrow} = I_0(1+P) \qquad I_{\uparrow\downarrow} = I_0(1-P) \qquad P = \frac{I_{\uparrow\uparrow} - I_{\uparrow\downarrow}}{I_{\uparrow\uparrow} + I_{\uparrow\downarrow}}$$

- At constant current mode, the height changes:

$$h_1 = h + \Delta s_1 + \Delta s_2 \qquad h_2 = h - \Delta s_1 - \Delta s_2$$

Low bias:

$$P = \frac{\exp(A\phi\Delta s) - 1}{\exp(A\phi\Delta s) + 1}$$

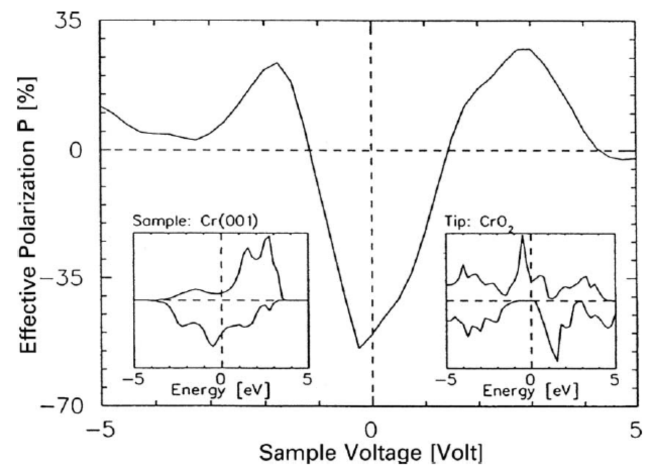
$$A = 1.025 \text{ eV}^{-1/2} \text{ Å}^{-1}$$

$$\Delta s = \Delta s_1 + \Delta s_2$$

ϕ barrier height

Finite bias: Spin and Energy dependent LDOS of tip and sample

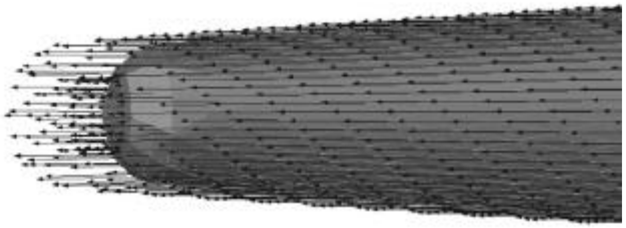
- Model calculation:
- P is strongly bias dependent, can change sign!
- Distance dependent behavior is expected, different decay rates for s, p, d states.



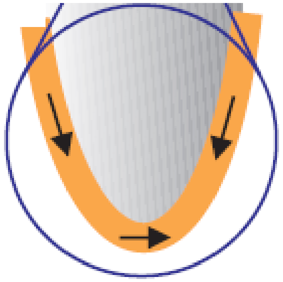
Tip fabrication

- High spatial resolution
- High spin polarization
- Nondestructive magnetic imaging process
- Control of the spin orientation: measuring in plane/out of plane component

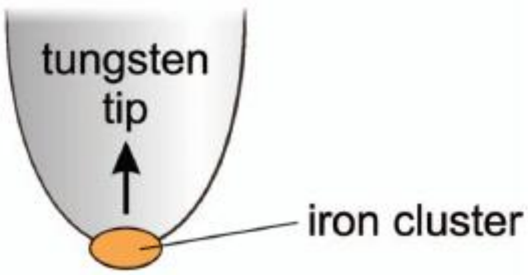
- Tips from bulk magnetic material:



- Non magnetic tip with ultrathin film of magnetic material:



- Non magnetic tip with a cluster of magnetic material:



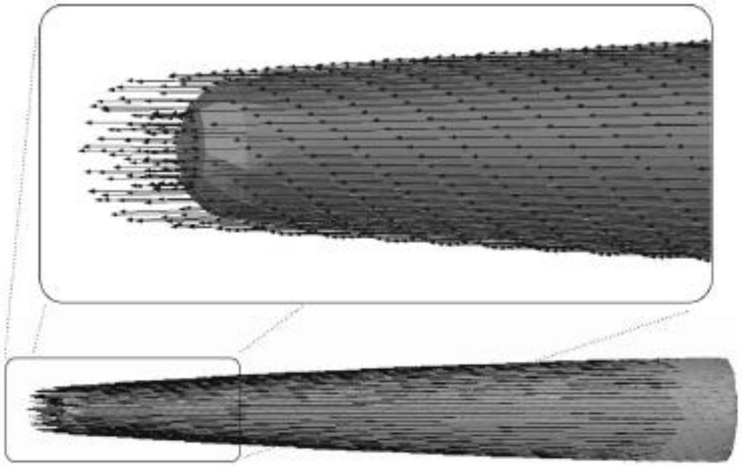
Tips from bulk magnetic material

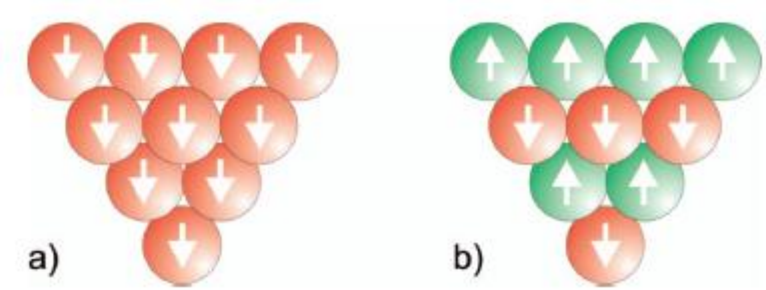
- Large magnetic stray fields

  Suitable for FM or AFM samples, not sensitive to external magnetic fields.

- Compensate stray fields with the use of antiferromagnetic materials
- Blunt AFM tip -> spin polarized tunneling current of the different sublattices cancel out

Energetically lowest magnetic configuration:





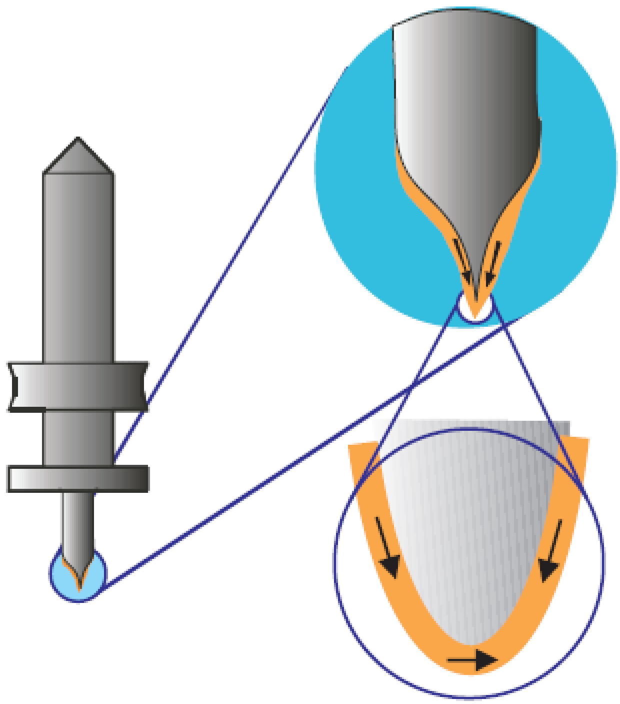
FM AFM

High spin contrast is needed -> high spin polarization

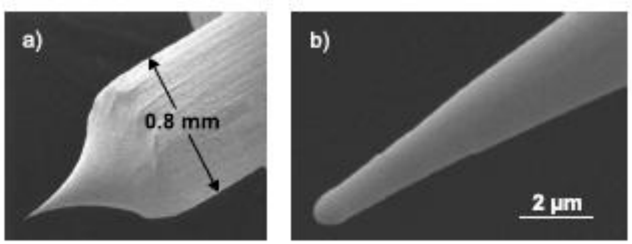
Optimal materials: half metallic magnets (CrO_2, Fe_3O_4) - metallic behavior for one spin direction, insulator for the other spin direction -> near 100% spin polarization.

Non magnetic tip with ultrathin magnetic coating

- Reducing the stray field: magnetic thin film tips



- Electrochemical etching
- UHV, in situ cleaning: electron beam, high T (2200K) flash up -> blunt tip ≈1µ



- Magnetization direction: material specific surface, interface anisotropies, depending on the layer thickness both in plane and out of plane magnetization can be achieved:

  W tip + 10 ML Au + < 8 ML Co -> out of plane

  + >8 ML Co -> in plane

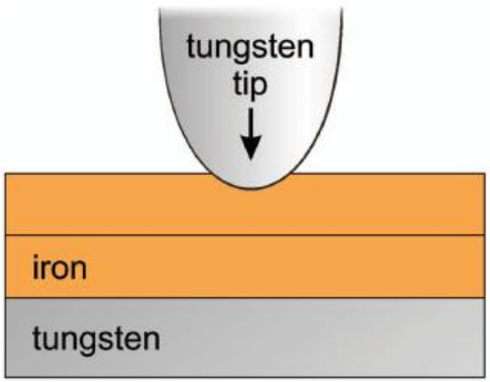
- External field can be used to force the magnetization from the easy to the hard direction

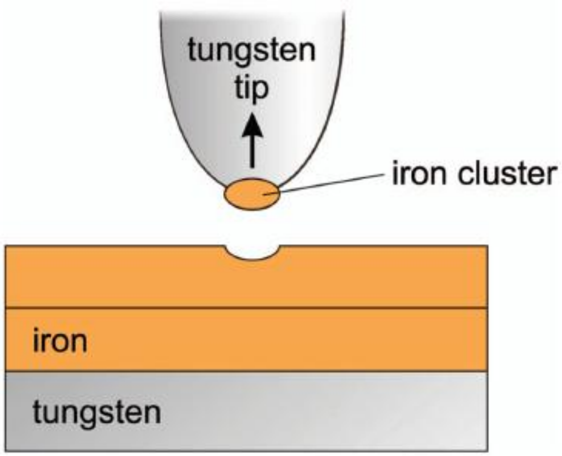
- Spin sensitivity direction can be tuned by the bias voltage.

[Intra-atomic non collinear magnetism at thin film probe tips, Bode et al., 2001]

Non magnetic tip with cluster of magnetic material

- Easiest method
- Voltage pulses between nonmagnetic STM tip and magnetic sample
- Nonmagnetic STM tip dipped into a magnetic sample:

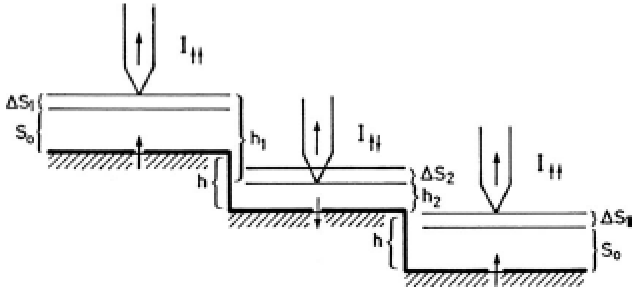




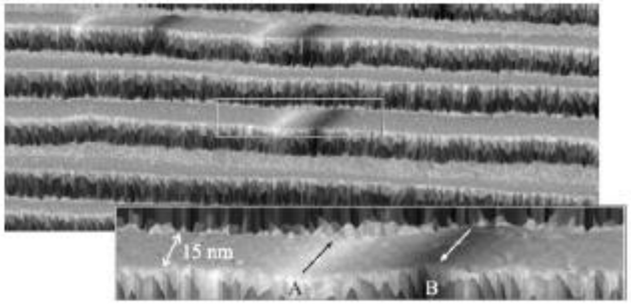
- Cannot control the direction of magnetization!

SP-STM modes of operation

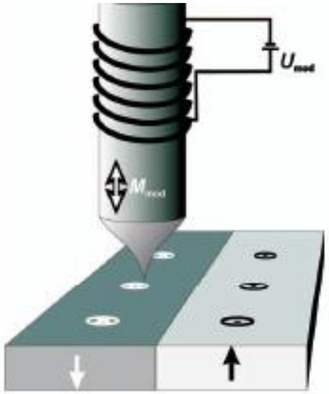
- Constant-current mode



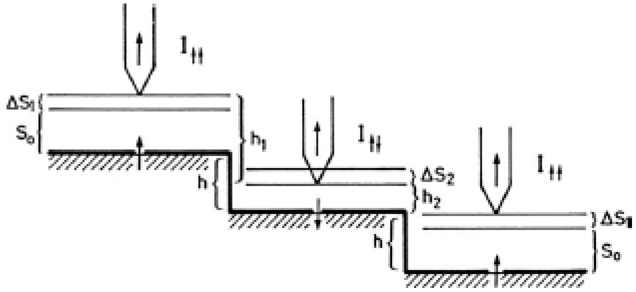
- Spin-resolved spectroscopic mode



- Modulated tip magnetization



Constant-current mode

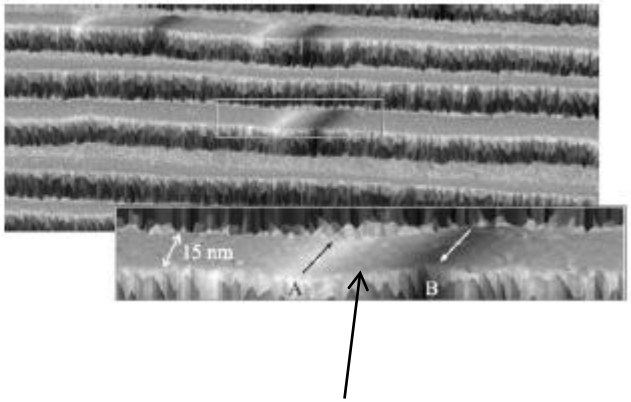


- Investigation of spin structures on the atomic scale
- Also can be applied for atomically flat surfaces of single crystals, nanowires, nanoscale islands
- Not applicable to rough surfaces -> topographic and magnetic structures interfering
- Spin polarized current is sensitive only to the energy integrated spin polarized LDOS, if a large bias voltage is used and the spin polarization changes sign -> spin polarized current is reduced.

Spin-resolved spectroscopic mode

- Measurement of the local differential conductance $dI/dU(U,x,y)$ as a function of bias voltage at each point of the sample.

- Should be performed at constant tip surface separation - z position stabilized at a bias: $I_{sp}(U_0)=0$



- Samples with inhomogeneous electronic structure – separation of electronic and magnetic structure information:

$$A = \frac{dI/dU_{\uparrow\uparrow} - dI/dU_{\uparrow\downarrow}}{dI/dU_{\uparrow\uparrow} + dI/dU_{\uparrow\downarrow}}$$

Two simultaneously recorded dI/dU images with zero (electronic contrast image) and maximum (magnetic contrast image) spin asymmetry.

Modulated tip magnetization

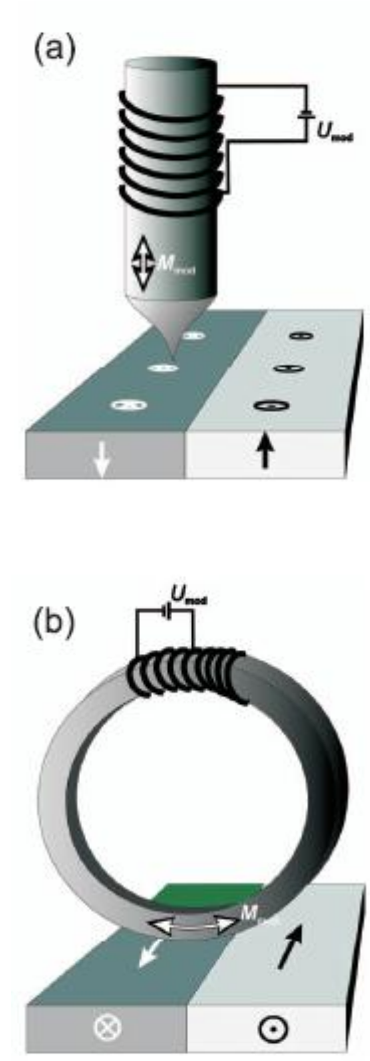
- Periodical switching of tip magnetization with a frequency higher than the cutoff frequency of the feedback loop:

$$\frac{dI}{d\vec{m}_t}(\vec{r}_0) \propto \vec{m}_s(U)$$

- Effectively separate electronic from magnetic contrast effects.

- The spin polarized current may vanish at a given U bias voltage even if local magnetization of the sample exists -> investigation of bias dependence needed!

- Ferromagnetic tip have to be used -> magnetic stray field can affect the local magnetization of the sample.



Applications of SP-STM

- Magnetic domain and domain-wall structure of single crystals
- Magnetic domain and domain-wall structure of nanostripes and nanowires
- Magnetic states of nanoislands and nanoparticles
- Atomic-resolution spin mapping

Magnetic domain structure of ferromagnetic metal film

Spectroscopic mode

In plane magnetization

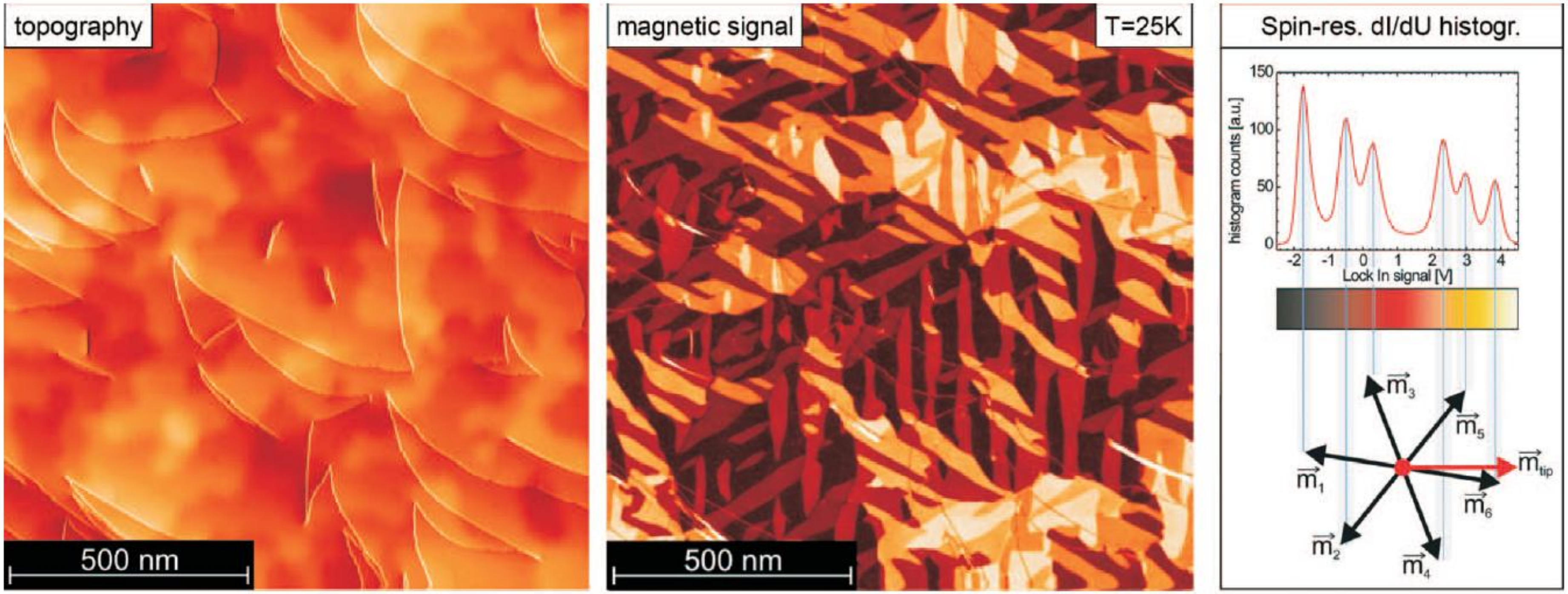
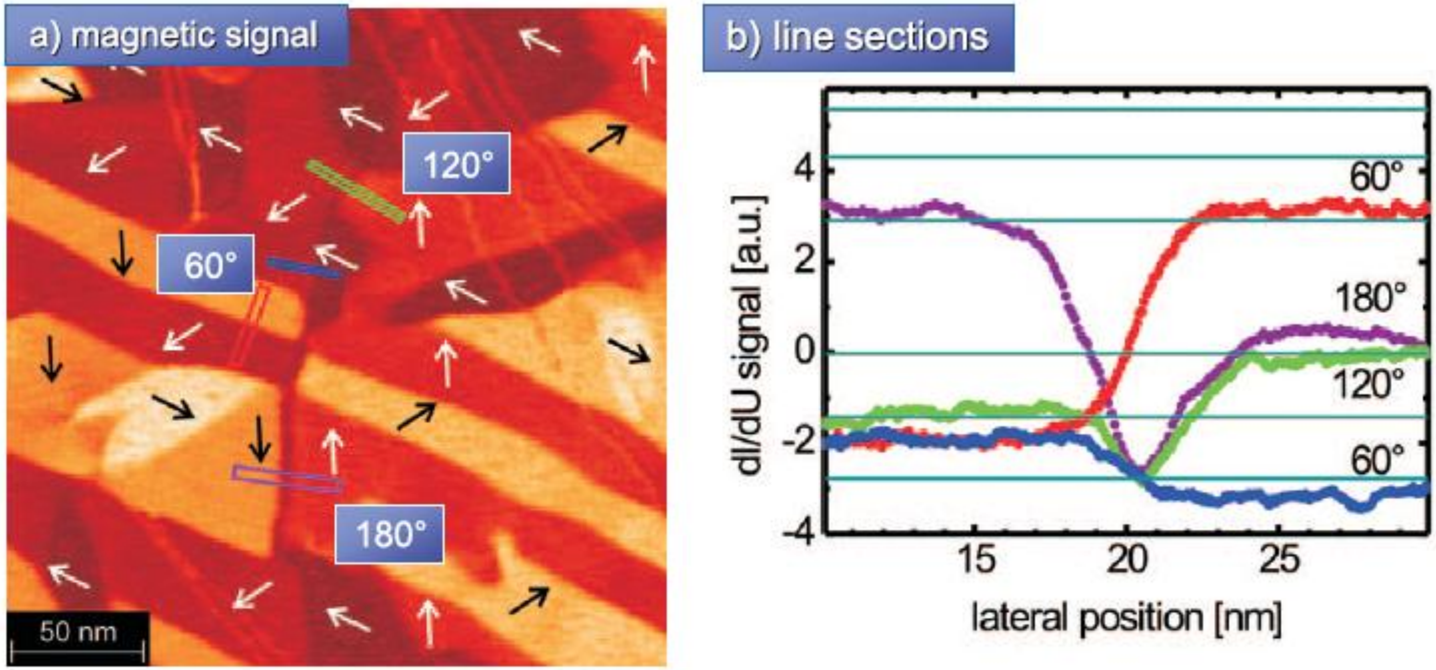


FIG. 17. (Color) Application of SP-STS for magnetic domain imaging with subnanoscale spatial resolution: a thin Dy(0001) film (90 ML) grown epitaxially on a W(110) substrate (a) exhibits a domain structure (b) with six different in-plane orientations of the local magnetization. (c) The six different contrast values in the SP-STM image result from the six different projections of the local sample magnetization onto the local magnetization direction (quantization axis) of the Dy probe tip. From Krause *et al.*, 2006.

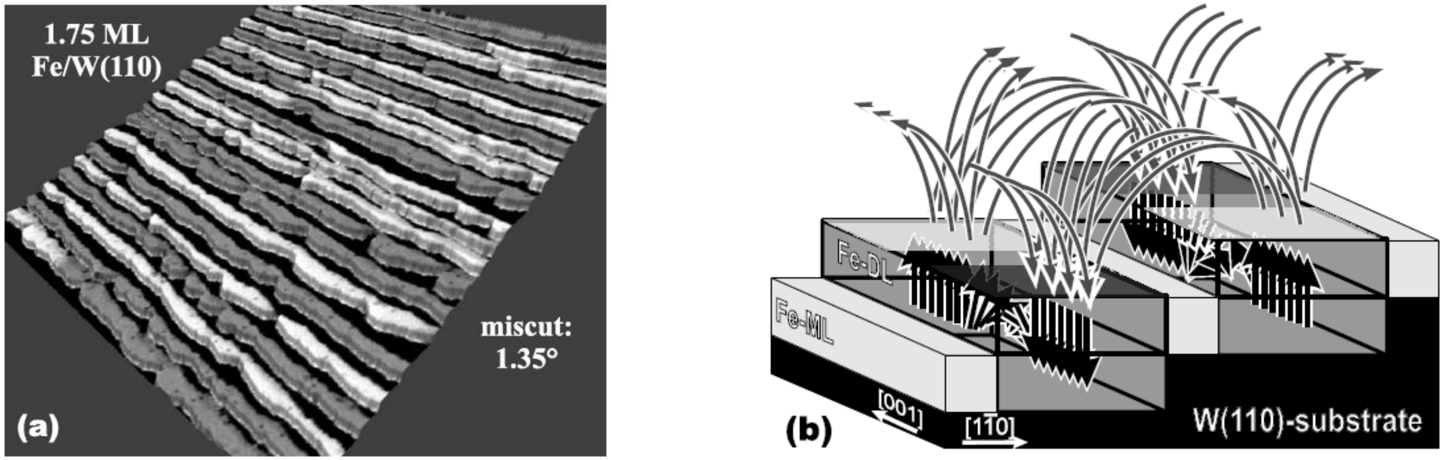
Magnetic domain structure of ferromagnetic metal film

Magnetic domain wall widths:



High magnetic anisotropy -> narrow domain walls ≈ 2-5 nm

Magnetic domain structure of nanostripes



- DL stripes are antiferromagnetically coupled
- DL stripes close to each other -> ferromagnetic coupling due to the exchange interaction

FIG. 25. Application of SP-STM to magnetic nanostripes. (a) Rendered perspective topographic STM image (200×200 nm^2) of narrow Fe nanostripes (~6–7 nm wide) prepared on a stepped W(110) substrate, grayscale coded with the spin-resolved spectroscopic dI/dU signal as measured with an out-of-plane-sensitive Gd-coated tip. A dipolar antiferromagnetic coupling between the Fe double-layer nanostripes leads to an alternating spin contrast. However, if two double-layer stripes are too close to each other, the exchange interaction leads to a ferromagnetic coupling. In some cases, narrow domain walls can be observed along the double-layer nanostripes. (b) Schematic of the perpendicularly magnetized double-layer Fe stripes exhibiting an antiparallel dipolar coupling in order to reduce the magnetic stray field of the array. Within the domain walls, the Fe double-layer nanostripes locally exhibit an in-plane magnetization. From Pietzsch *et al.*, 2000a; Bode, Kubetzka, *et al.*, 2001.

Magnetic domain structure of nanostripes

External magnetic field:

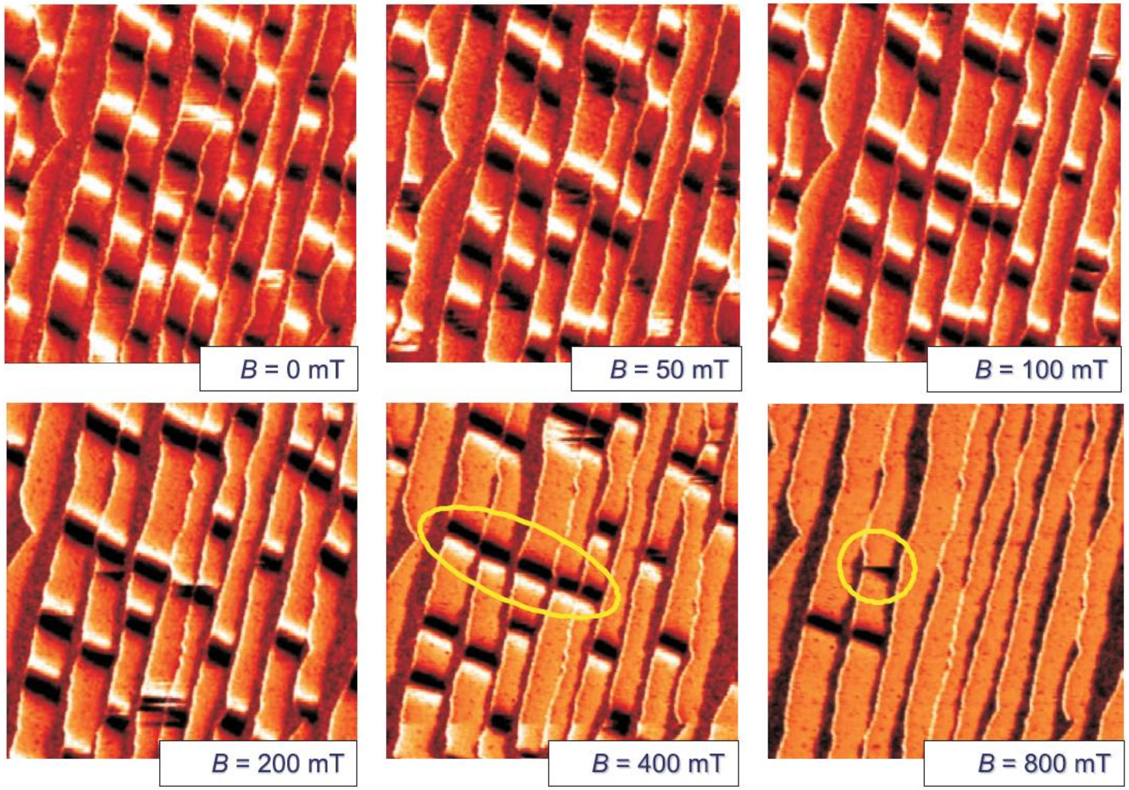


FIG. 27. (Color) Series of spin-resolved spectroscopic dI/dU maps (200×200 nm^2) of an array of multidomain Fe double-layer nanostripes obtained in an increasing perpendicular magnetic field. Pairs of 180° walls are gradually forced together, which is equivalent to the formation and compression of 360° walls. At a field of 800 mT, most of them have vanished, i.e., the Fe thin film is in magnetic saturation. From Kubetzka, Pietzsch, Bode, and Wiesendanger, 2003b.

Spin dependent quantum confinement states in nanoislands

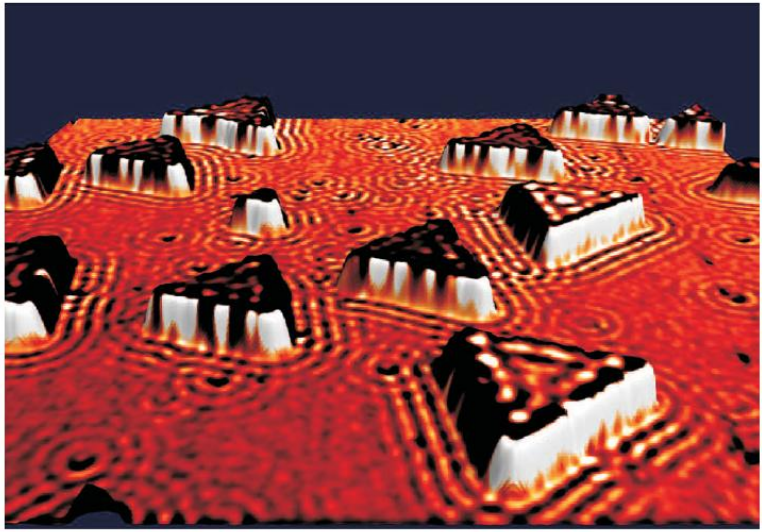


FIG. 43. (Color) Spin-averaged STS image ($60\times 60\ nm^2$) showing 2D electronic confinement states in double-layer Co nanoislands on Cu(111) as well as scattering states of the Cu(111) surface state electrons at single Co adatoms and Co/Cu interfaces.

Confinement -> energy-dependent oscillation of the LDOS on the islands surfaces

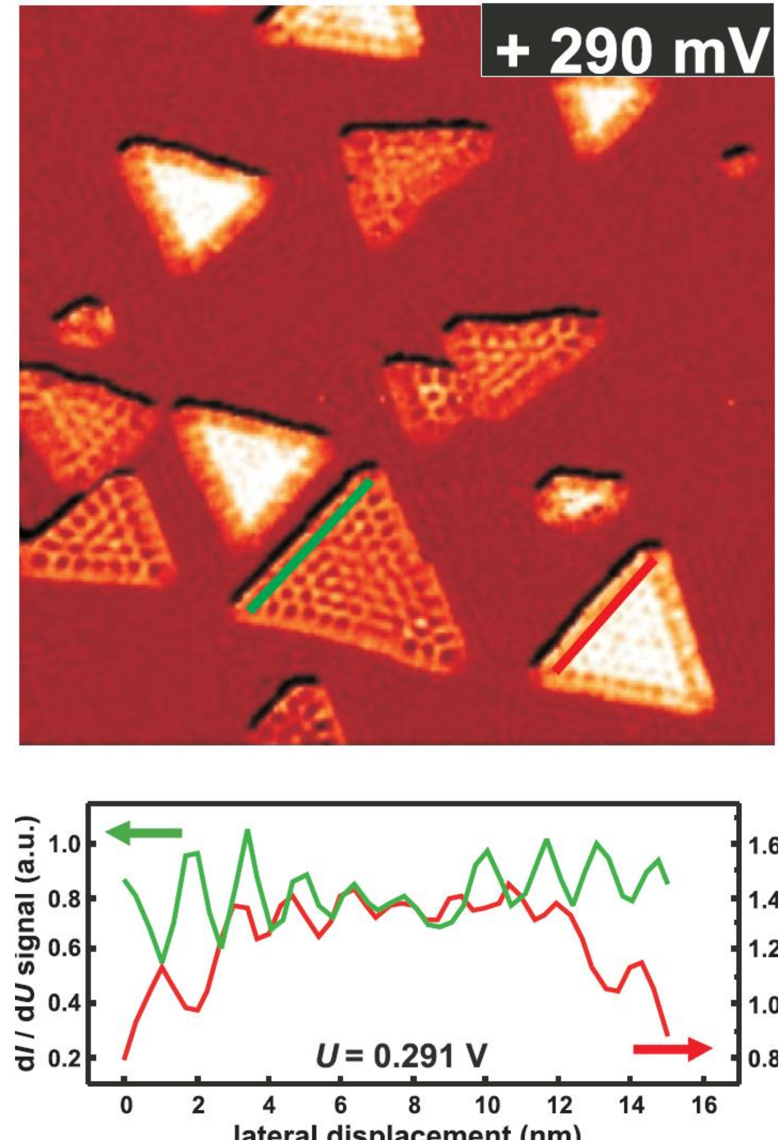
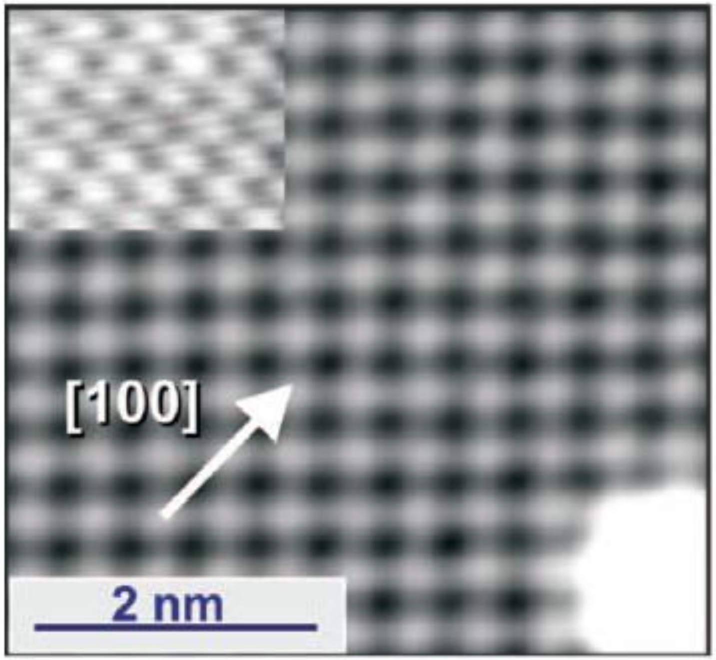


FIG. 44. (Color) SP-STS data ($60\times 60\ nm^2$) revealing the spin dependence of the 2D electronic confinement states in nanoscale Co islands which manifests itself by a spin-dependent oscillation amplitude of the confinement states for differently magnetized Co nanoislands. From Pietzsch *et al.*, 2006.

Atomic-resolution spin mapping

Fe monolayer on W(001)



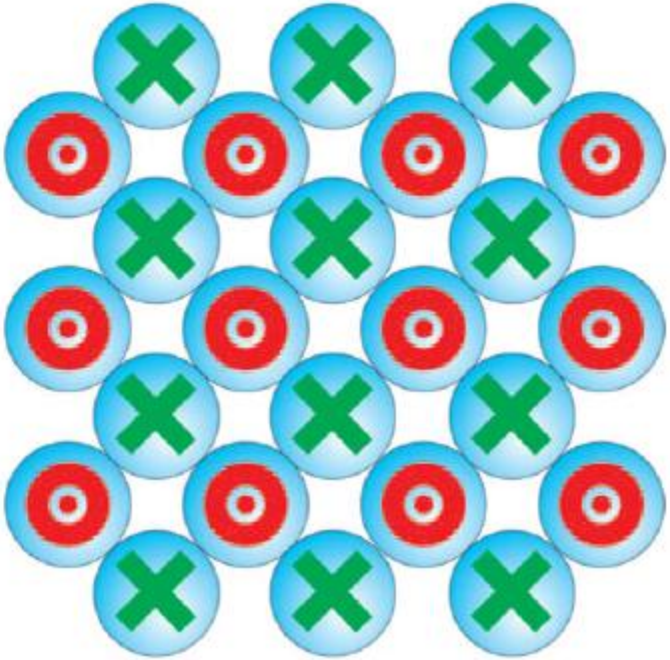


FIG. 46. (Color) Atomic-resolution spin mapping on an antiferromagnetic Fe monolayer. (a) SP-STM image showing the magnetic (2×2) superstructure of (b) an antiferromagnetic monolayer of Fe on a W(001) substrate. Since an out-of-plane magnetized Fe-coated W tip has been used, one concludes that the Fe monolayer on W(001) exhibits an out-of-plane magnetic anisotropy, which was subsequently confirmed by DFT calculations. The inset in (a) shows an atomically resolved (1×1) lattice as revealed either by a nonmagnetic or by an in-plane-sensitive probe tip. From Kubetzka *et al.*, 2005.

- (2x2) antiferromagnetic superlattice

Köszönöm a figyelmet!