Scanning Tunneling Microscopy (STM) and spin-polarized STM

Part I - STM

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- **Scanning Tunneling Microscopy**

  1. History and theory of STM

  2. STM as a tool to characterize magnetic nanostructures

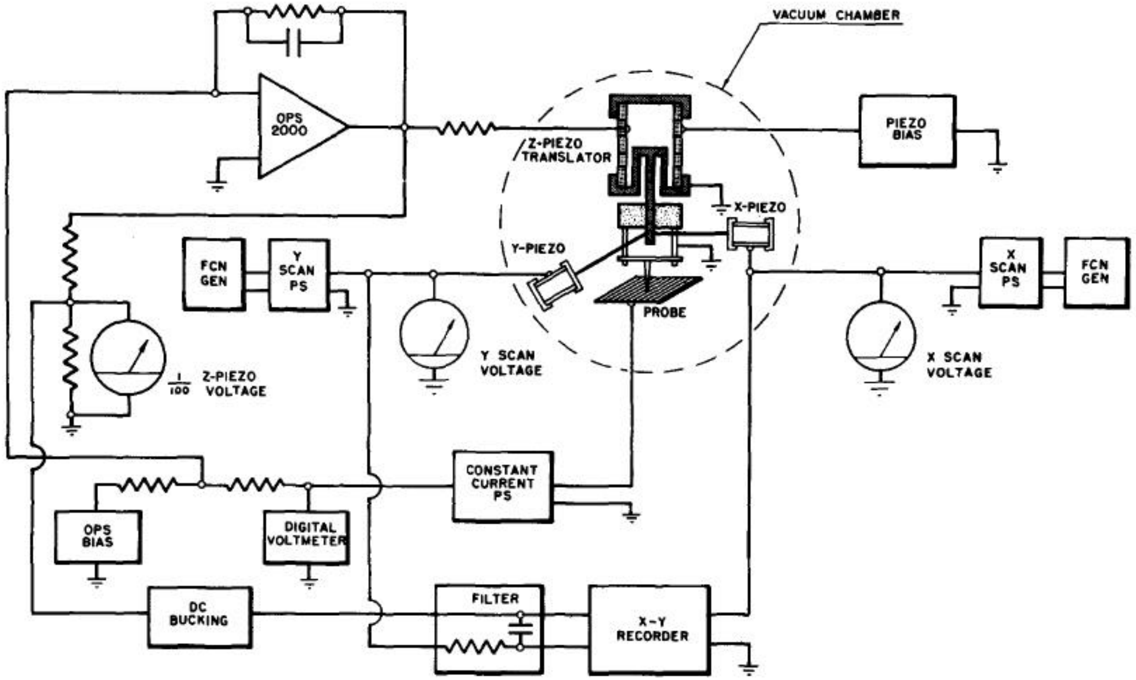
  3. STM as a tool to characterize growth of magnetic films

  4. STM to fabricate nanostructures

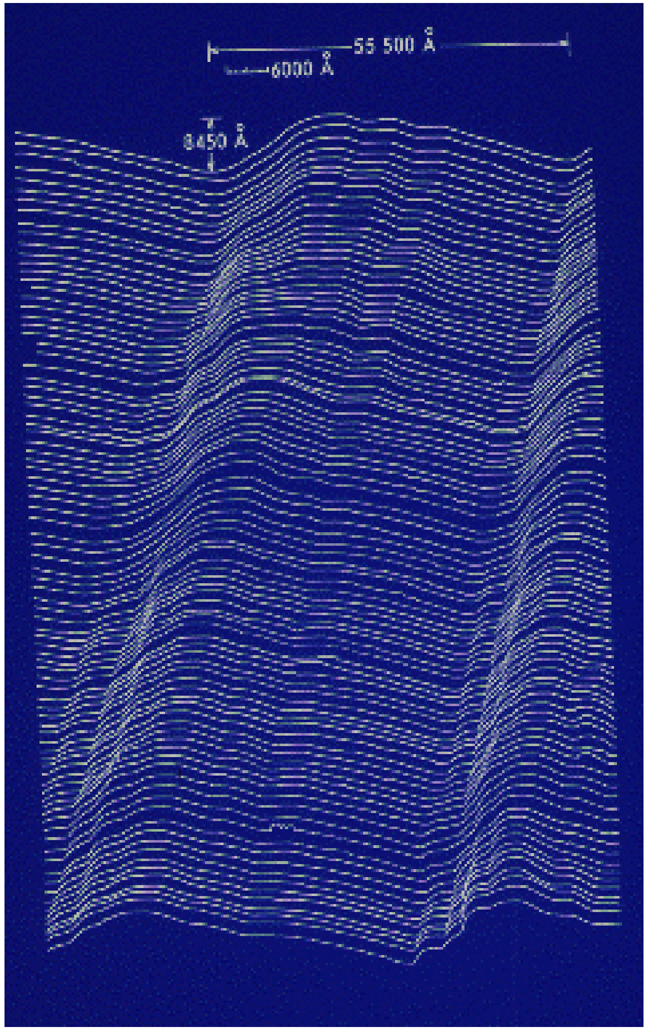
Simple picture of Scanning Tunneling Microscopy

The Topografiner: An Instrument for Measuring Surface Microtopography

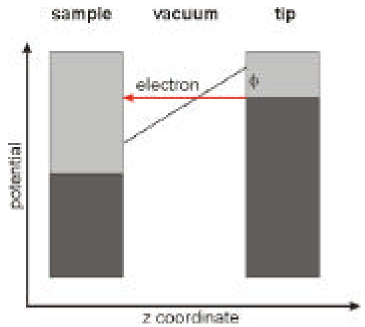
Russell Young, John Ward, and Fredric Scire

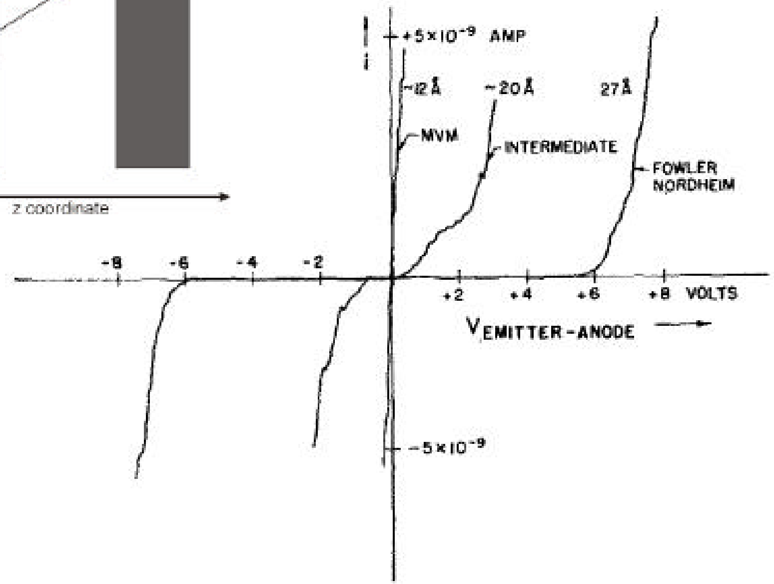


Review of Scientific Instruments 43, 999 (1972)



- feedback via field emission current
- sample bias in the range of 6-60 V
- lateral resolution up to 20 nm
- z-resolution of 3 nm



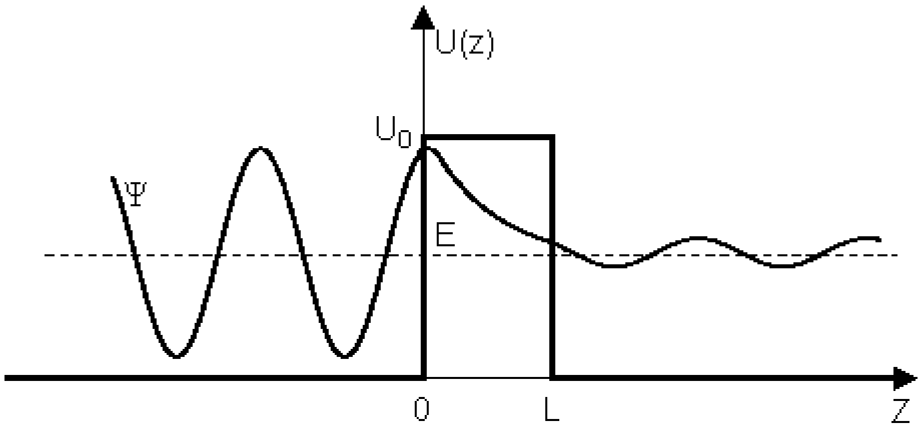


- Young et al. also demonstrated tunneling

Quantum Mechanics of Tunneling

Schrödinger equation for free particle of mass m in Potential landscape U(z) :

$$\frac{-\hbar^2}{2m}\frac{d^2\Psi(z)}{dz^2}+U(z)\Psi(z)=E\Psi(z)$$



General solution:

$$\Psi(z)=Ae^{ikz}+Be^{-ikz}, k=\frac{\sqrt{2m(E-U)}}{\hbar}$$

- E>U : plane wave
- E<U : exponential decay

Matching of wave functions and their derivatives yields:

Transmission :

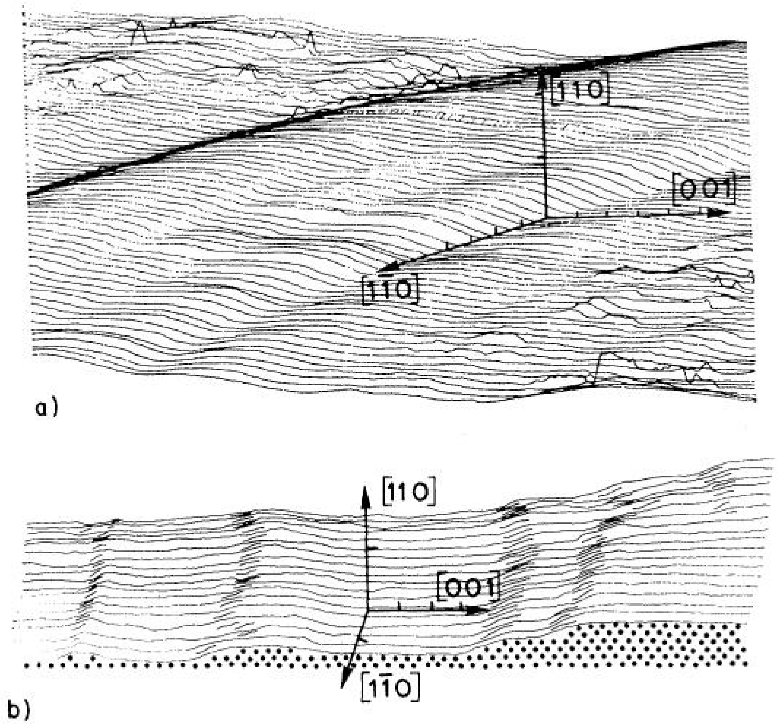
$$T\approx T_0 e^{\frac{2ikL}{\hbar}}, |ikL|>>1$$

The invention of Scanning Tunneling Microscopy
Nobel Prize in Physics in in 1986

Heinrich Rohrer and Gerd Binnig

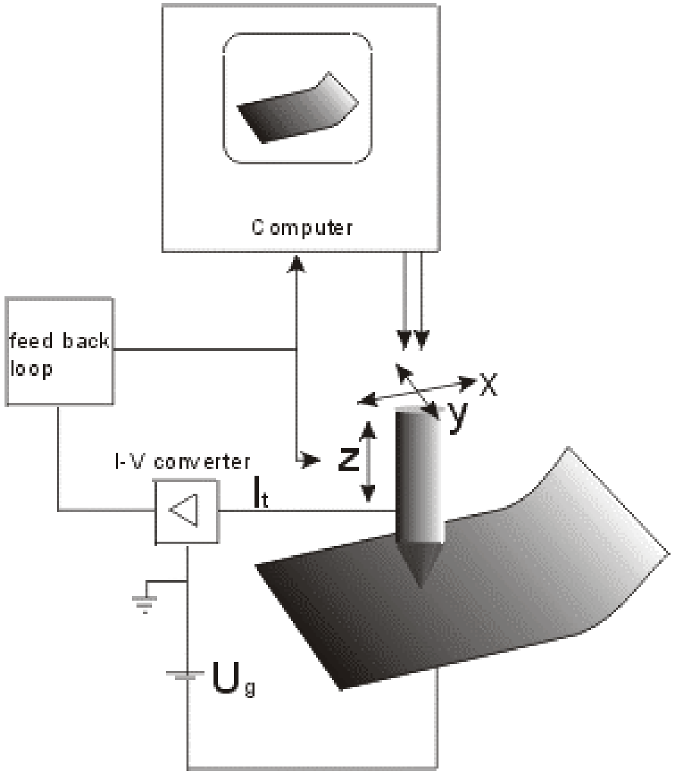
- atomic resolution in z-direction
- later also lateral atomic resolution

Atomic steps on Au(110)



Binnig, Rohrer, Gerber, Weibel, APL 40, 178 (1982), ibid. PRL 49, 57 (1982)

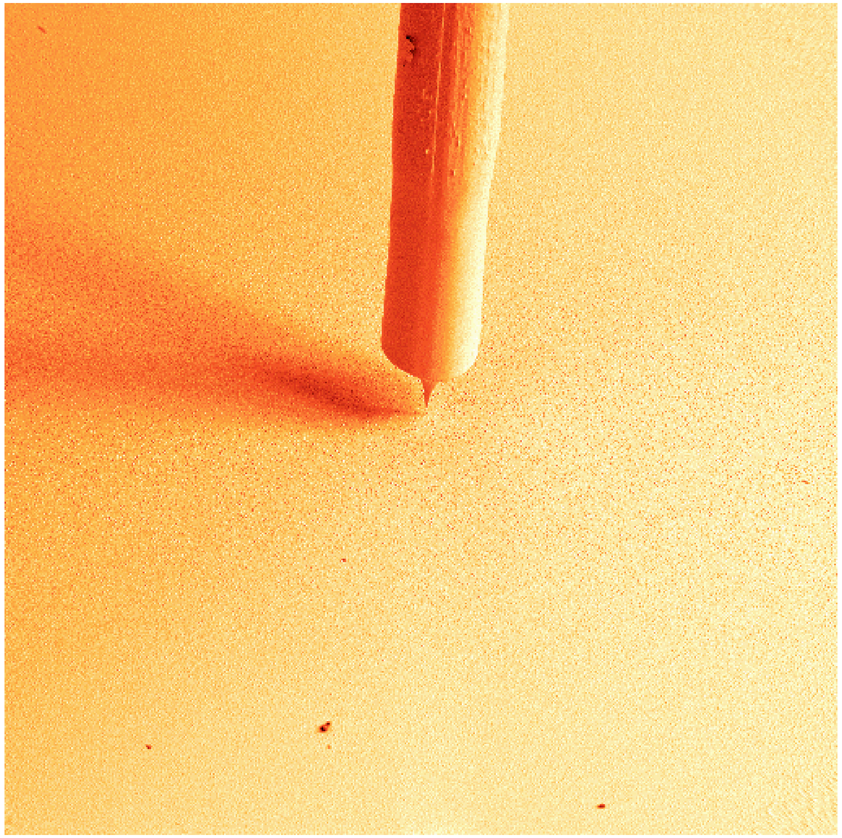
Imaging in the constant current mode



- x and y coordinates are scanned like a TV image
- tunneling current between tip and sample is detected with I-V converter
- feed back loop adjusts z coordinate such that the tunneling current is equal to the set point
- computer records z(x,y) and displays the image
- image corresponds to the “topography”

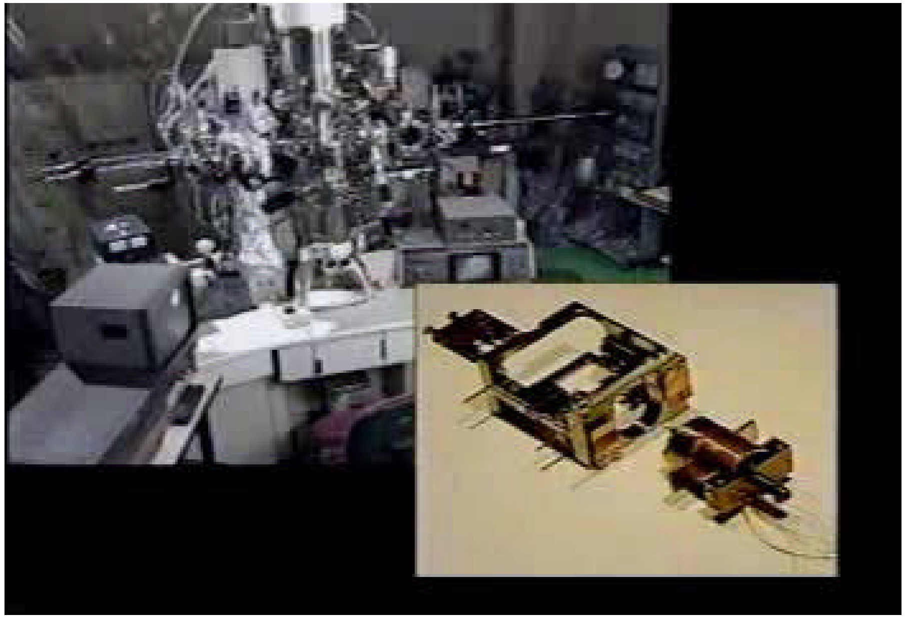
STM in operation

Scanning Electron Microscope



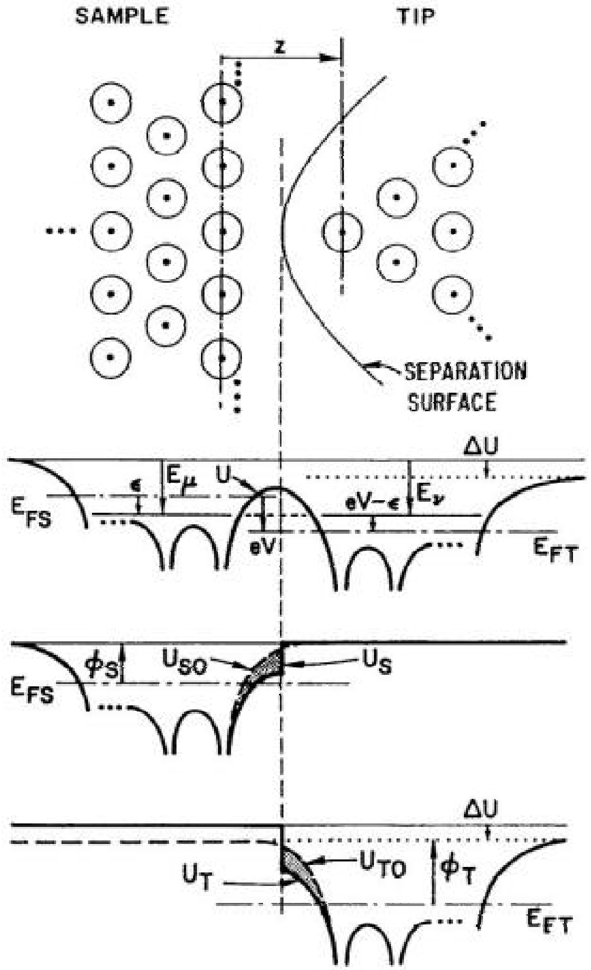
Prof. Bonzel, Forschungszentrum Jülich

Transmission Electron Microscope



Prof. Takayanagi, Tokyo Institute of Technology

How to estimate the tunneling current?



- tip and sample Schrödinger equations are solved seperately
- tip-sample interactions are therefore neglected
- current is calculated in first order perturbation approximation

$$I = \frac{4pe}{\hbar} \int \left[f(E_F^T - eV + e) - f(E_F^S + e) \right] \times$$

$$r^T (E_F^T - eV + e) r^S (E_F^S + e) \times \left| M(E_F^S + e, E_F^T - eV + e) \right|^2 de$$

$$M_{mn} = -\frac{\hbar^2}{2m} \int_{\Sigma} (\Psi_n^{T*} \nabla \Psi_m^S - \Psi_m^S \nabla \Psi_n^{T*}) dS$$

- tunneling matrix is described by an interface integral of the sample and tip wave functions

S-wave tunneling

- Tersoff-Hamann solved the Bardeen model for a tip with an s-wave wave function of the tip and for a constant tip density of states.

- At 0K, the tunneling current is proportional to the local density of states of the sample at the tip position r, integrated over the bias voltage.

- Under these approximations, constant current images reflect surfaces of constant sample density of electrons.

$$I(r,V) = \frac{16p^3 C^2 \hbar^3 e}{k^2 m^2} r^T \int_0^{eV} r^S(r, E_F^S + e)\, de$$

Relation of morphology and magnetism

- The shape and size of magnetic nanostructures influence their magnetic properties (magnetic stray fields)

- The dimension of a magnetic nanostructure influences their critical behaviour

- The relevant length scale for magnetism is given by the exchange length

$$l = \sqrt{\frac{A}{K}}$$

- λ for Fe, Co and Ni are in the range of few nm (shape anisotropy) or few 10 nm (magnetocrystalline anisotropy)

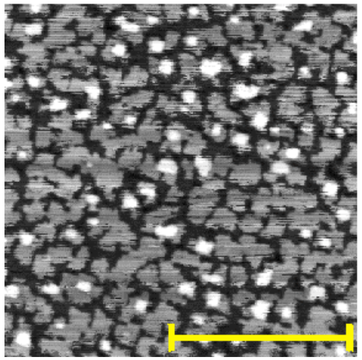
- STM offers the necessary lateral resolution to monitor the nanostructures

As a model system Fe/W(100) is used, as the 10% misfit induces a large variety of different self organized structures

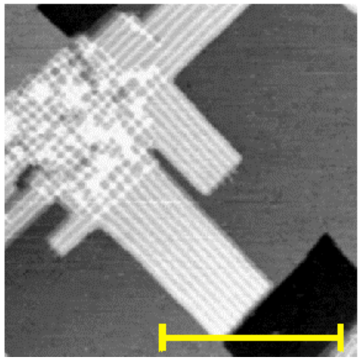
Growth temperature

300 K | 400 K | 500 K | 800 K

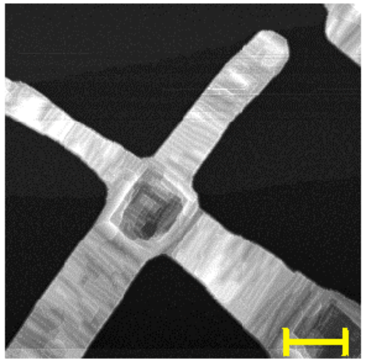
2D growth
unordered
low diffusion



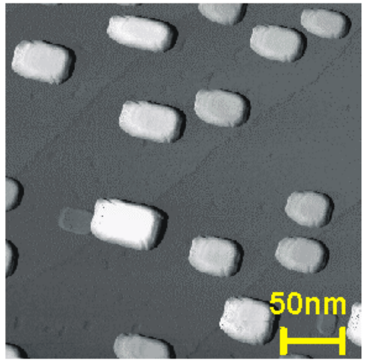
2D growth
ordered
dislocations



3D growth
Ostwald-ripening
dislocations



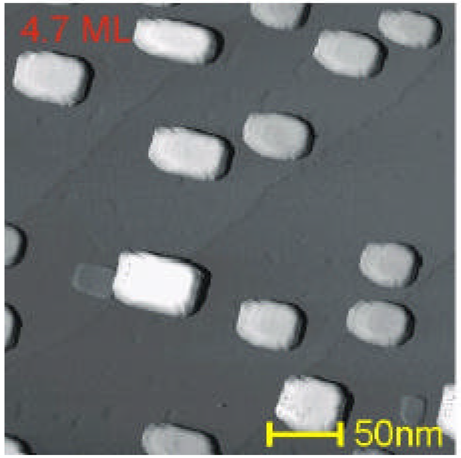
3D growth
Fe crystallites



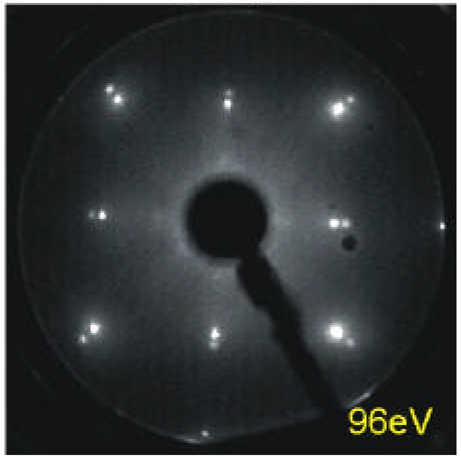
W. Wulfhekel et al., EPL 49, 651 ´00 und ibid. PRB 68, 144416 ´03

3D-Nanostructures : Fe/W(100) at 800K

STM

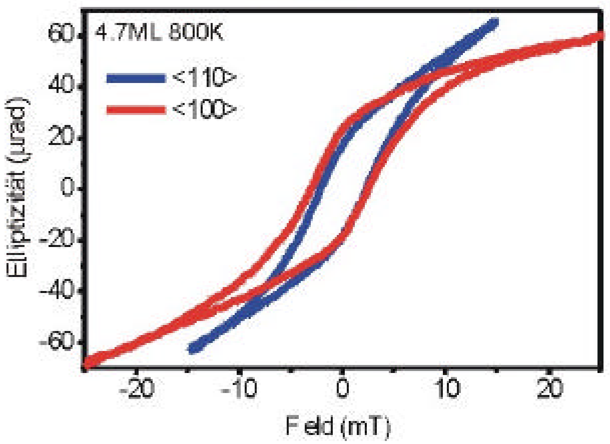


LEED

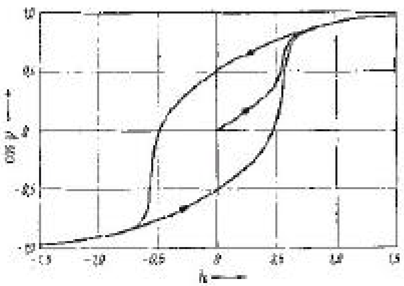


- during growth or annealing to 800K, fully relaxed Fe crystallites are formed
- thermodynamic ground state
- LEED shows bulk Fe lattice constant
- crystallites are 6-10 nm thick

MOKE



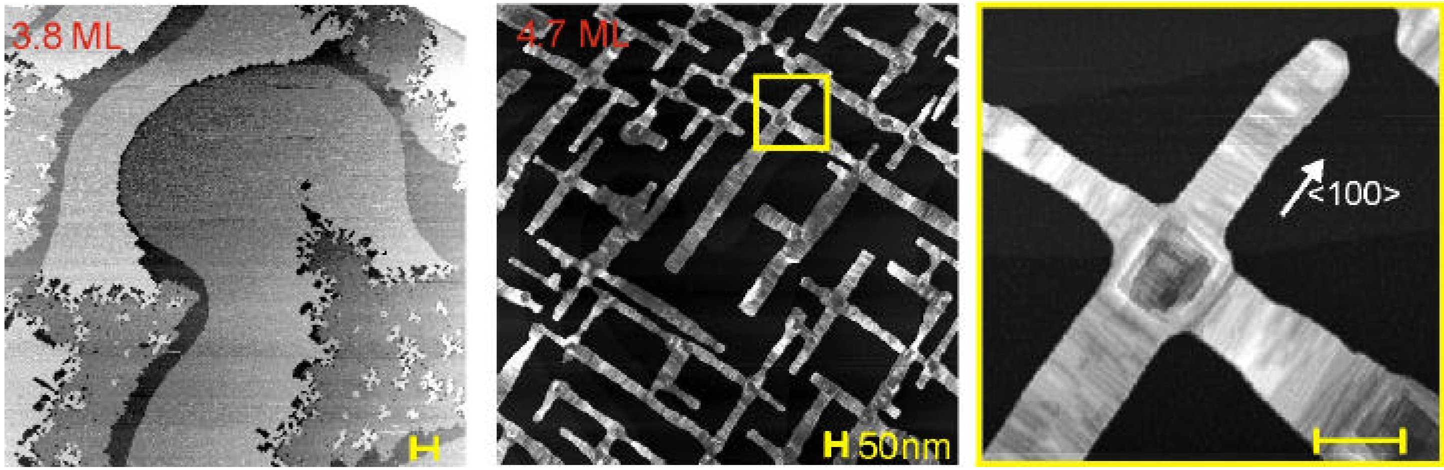
Stoner-Wohlfarth



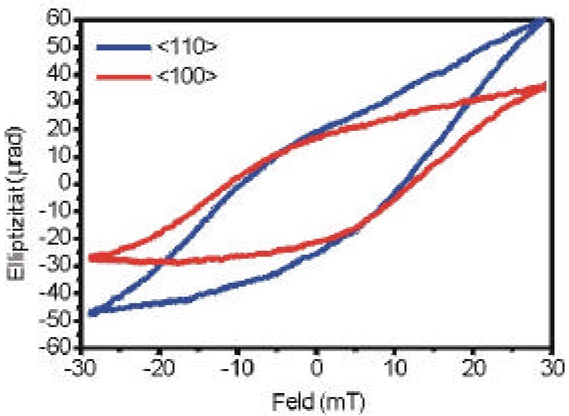
- s-shaped loop similar to loop of small particles with random easy axis
- particles are not coupled

3D-Nanostructures : Fe/W(100) at 400K

STM

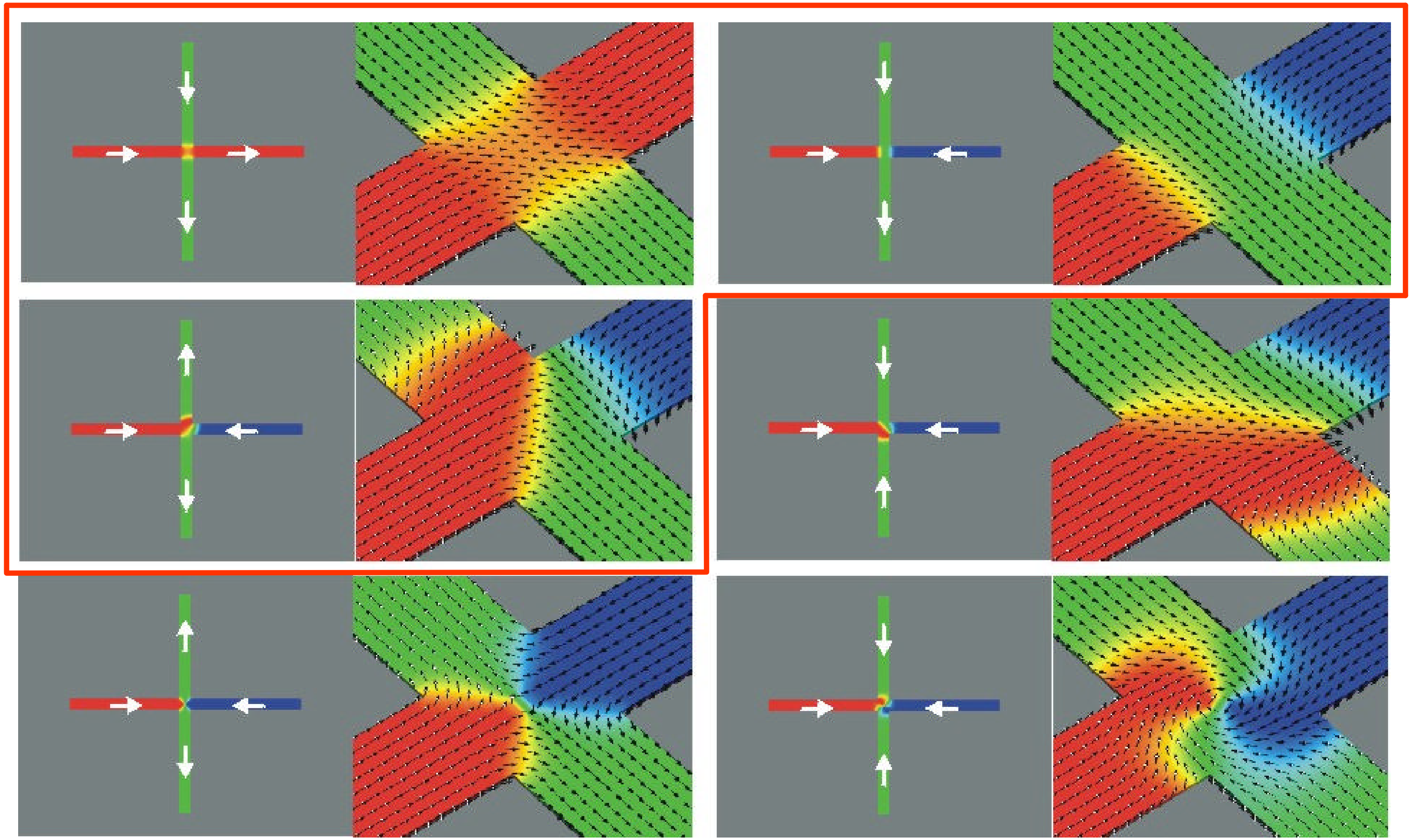


MOKE



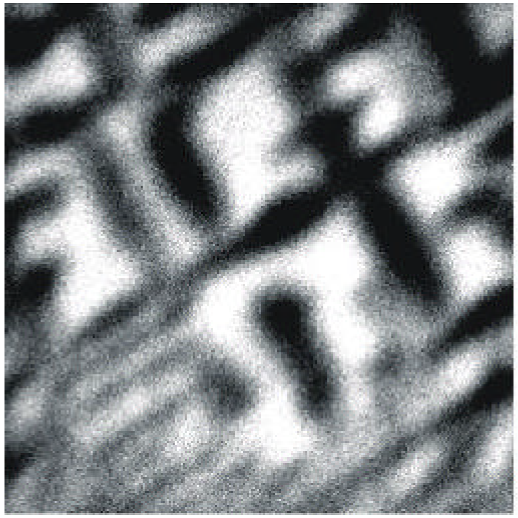
- under 4ML: pseudomorphic but fractal films caused by relaxation of strain at step edges
- above 5ML: formation of dislocation and fracturing of film
- relaxed, complex islands (1-2nm thick) on 2ML pseudomorphic Fe-carpet
- MOKE suggests multi domain state

Micromagnetic calculation of the possible states in crosses

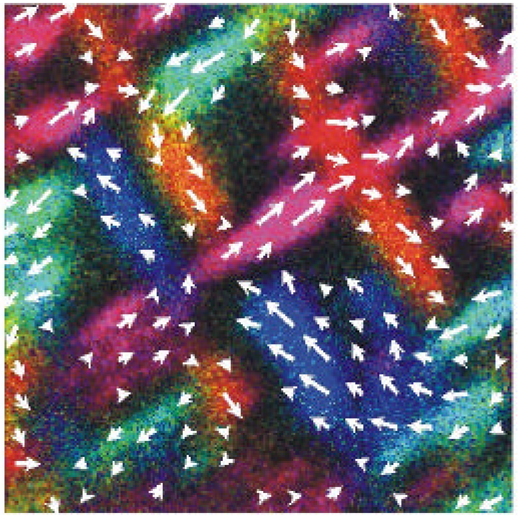


Magnetic crosses

SEM



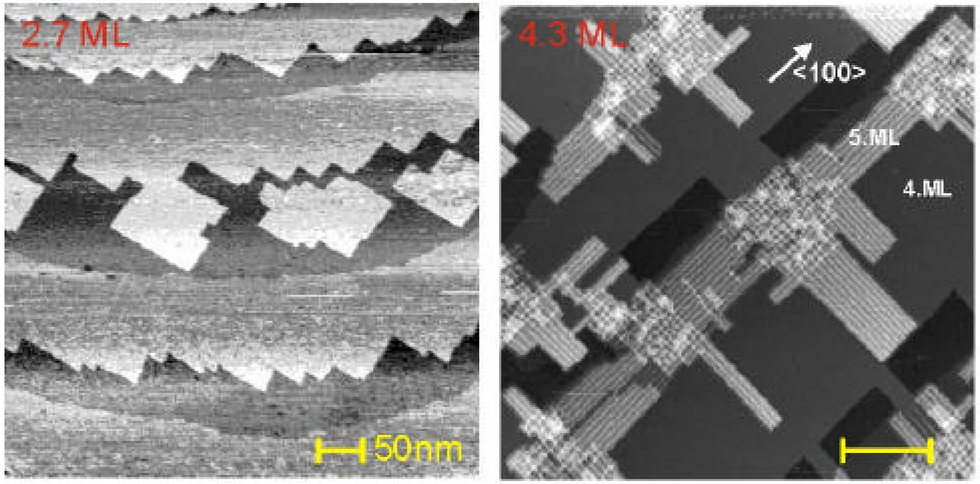
SEMPA



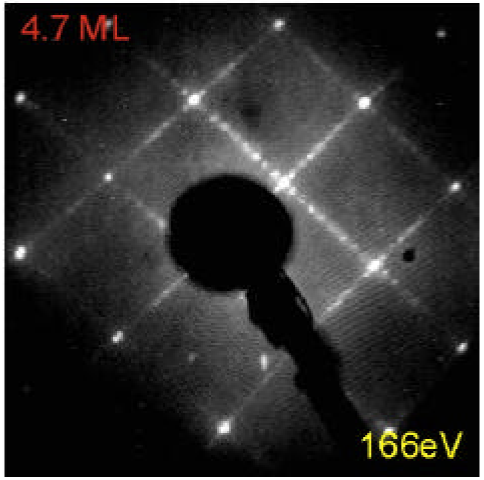
- Scanning Electron Microscopy with Spin Analysis (SEMPA) shows that crosses split up into domains
- Magnetization follows shape anisotropy of the arms
- 2ML film in between islands is not magnetic
- only 3 lowest energy states of calculations are found in experiment

2D-Nanostructures

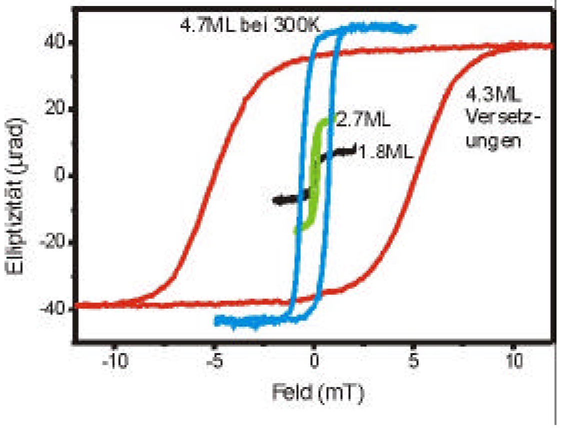
STM



LEED



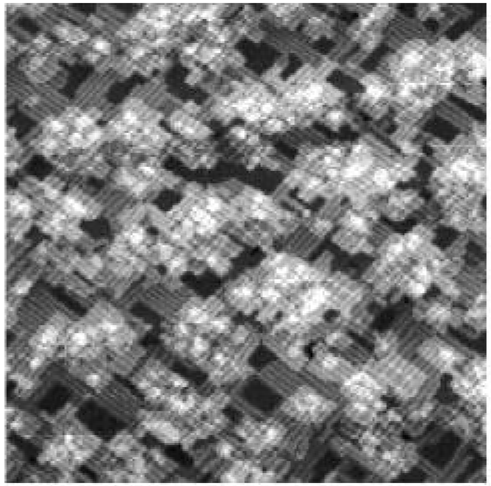
MOKE

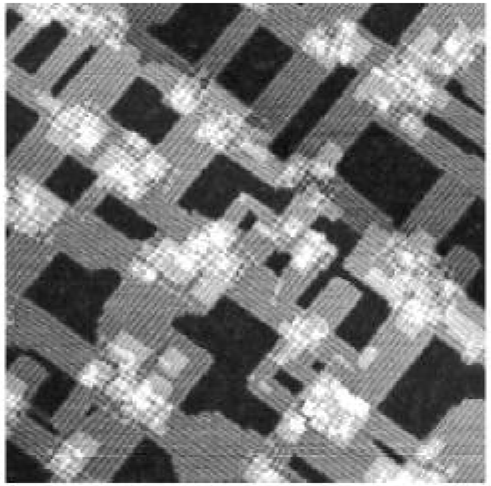


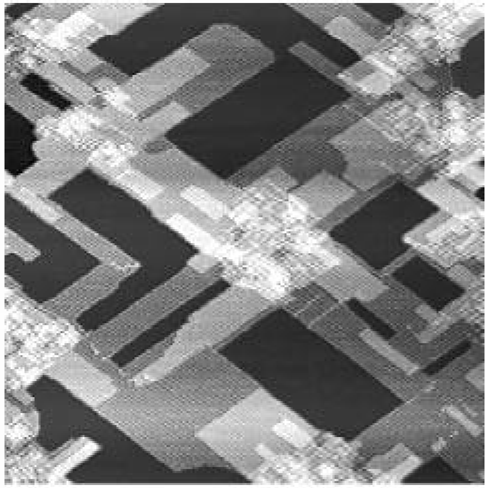
- 2D growth due to active interlayer mass transport
- psuedomorphic films up to 4ML
- start of dislocation formation in the 5th ML
- coercivity drastically increases with dislocation formation

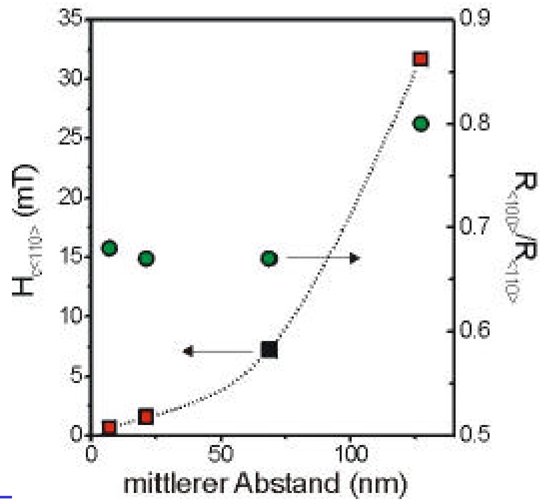
2D-dislocation bundles

STM



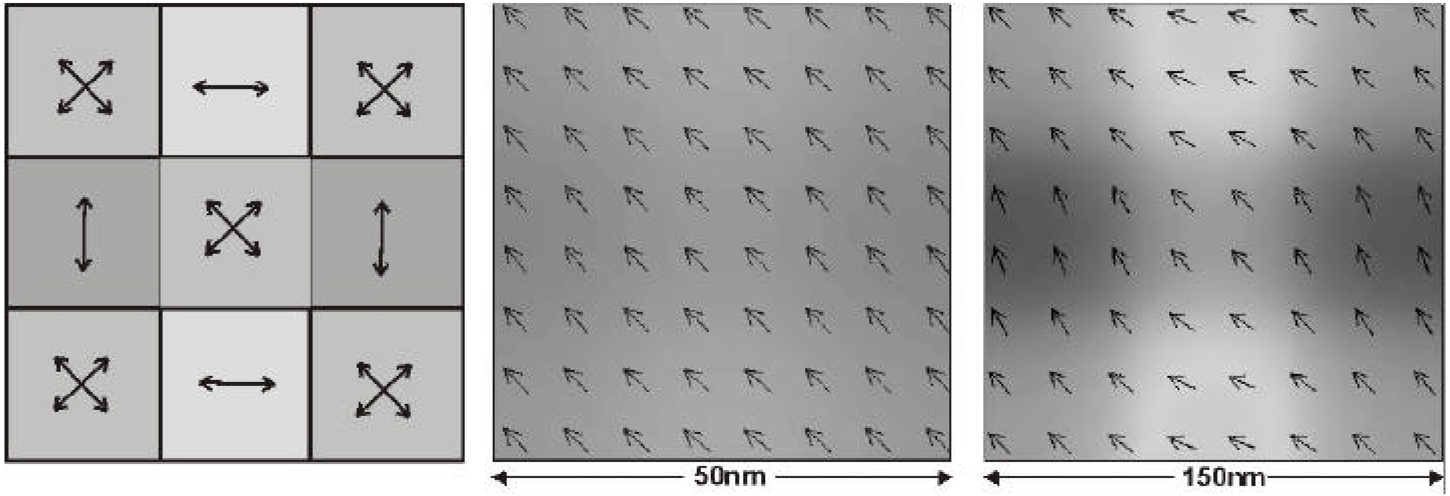






- coercivity varies with average bundle distance
- domain wall movement is impeded not by individual dislocations but by bundles
- ratio of remanences deviates from value for single domain state in largest structures
- domains expected

Micromagnetic model of dislocation bundles

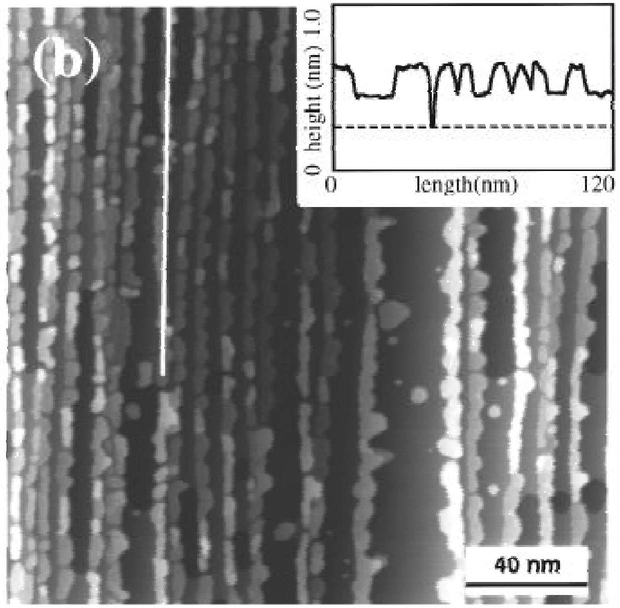


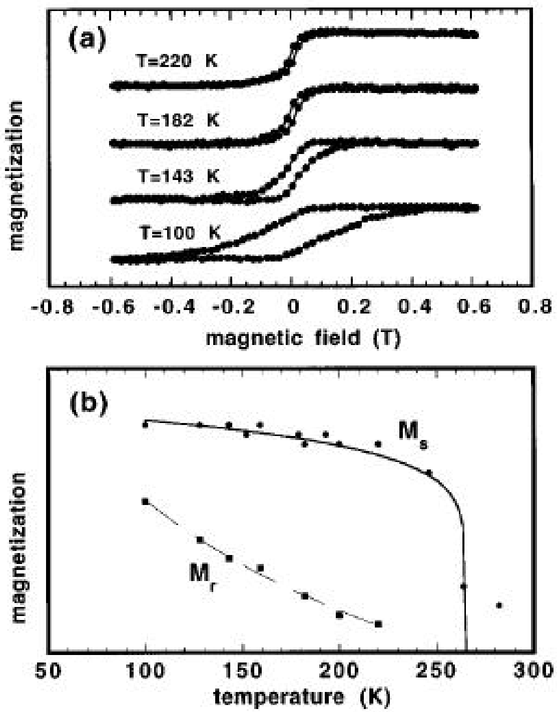
- fourfold anisotropy of K_4=-44kJ/m^3 from MOKE loops of 4ML Fe/W(100)
- 10% uniaxial strain creates via magnetoelastic effects of second order a uniaxial anisotropy of at least K_u=100kJ/m^3
- minimization of total energy gives single domain state for small and multidomain state for large dislocation bundles

W. Wulfhekel et al., EPL 49, 651 ´00

1D-Nanostructures

0.8 ML Fe/Cu(111)



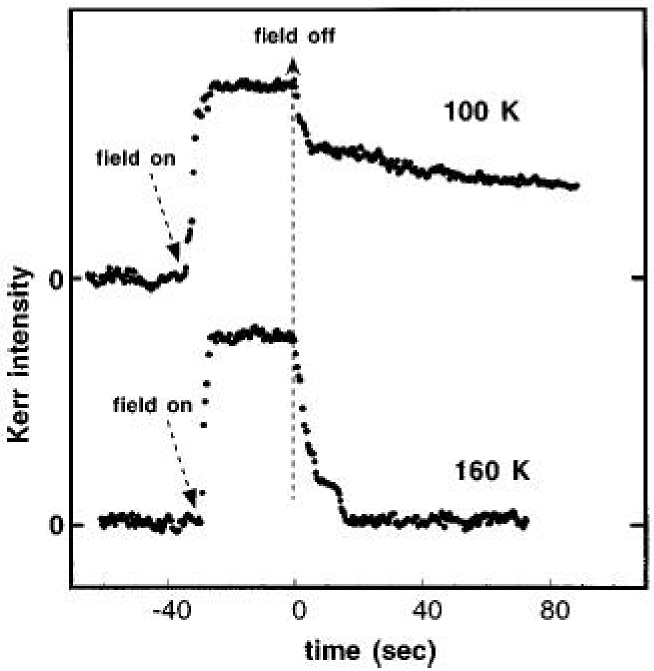


- decoration of Cu step edges with narrow, 1D Fe stripes
- magnetization of thin continuous Fe films on Cu(111) is normal to surface
- MOKE loops are observed up to 220 K
- remanence and saturation magnetization vanish only above 250 K

1D-Nanostructures

• Ising model: 1D chain of exchange coupled spins of infinite uniaxial anisotropy shows no magnetic ordering above 0K

Was Ising wrong or are the Fe stripes not one-dimensional ?



• magnetization of stripes is not stable with time

• after filed is turned off, the magnetization decays on the time scale of seconds to minutes

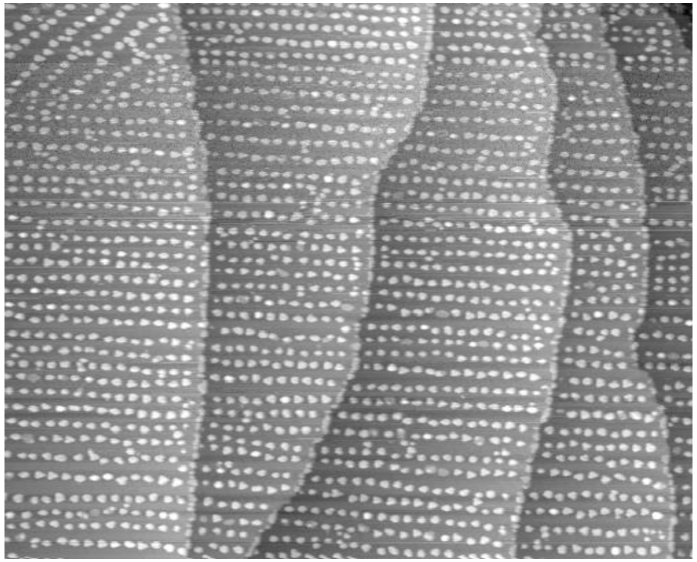
• the loops observed are not in thermal equilibrium but represent the slow dynamics of the 1D system

E. Ising, Z. Phys. 31, 253 (1929)
J. Shen et al., PRB 56, R2340 (1997)

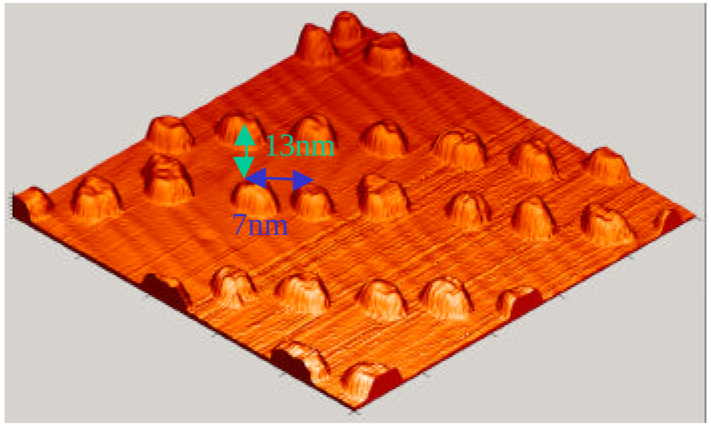
0D-Nanostructures

- magnetic particle that is smaller than λ in all dimensions and thus behaves as a macro-spin

Co/Au(111)



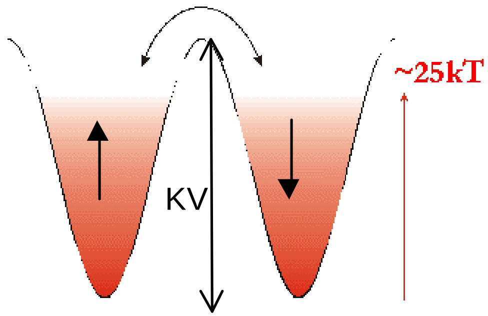
300x300nm



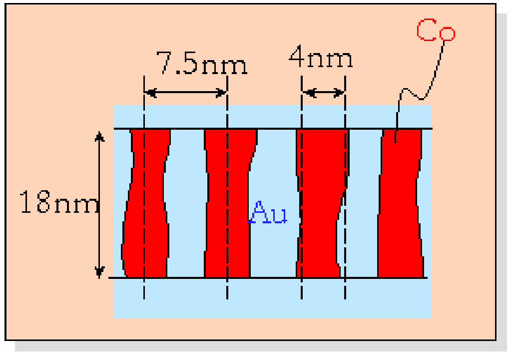
The heringbone reconstruction of Au(111) is used as template to nucleate magnetic Co nano-dots

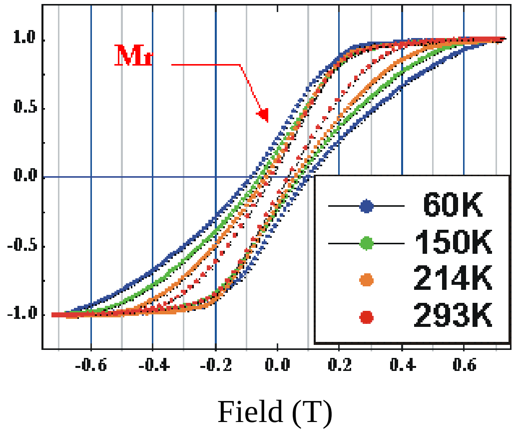
Fruchart et al. PRL83, 2769 (1999)

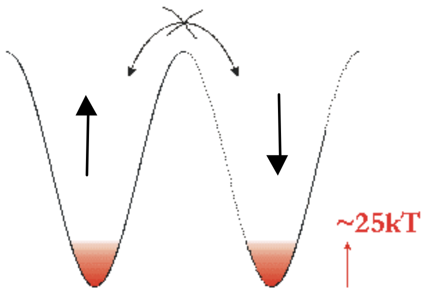
Problem : the particles are superparamagnetic at 300 K



Solution : increase magnetic volume and by this the barrier

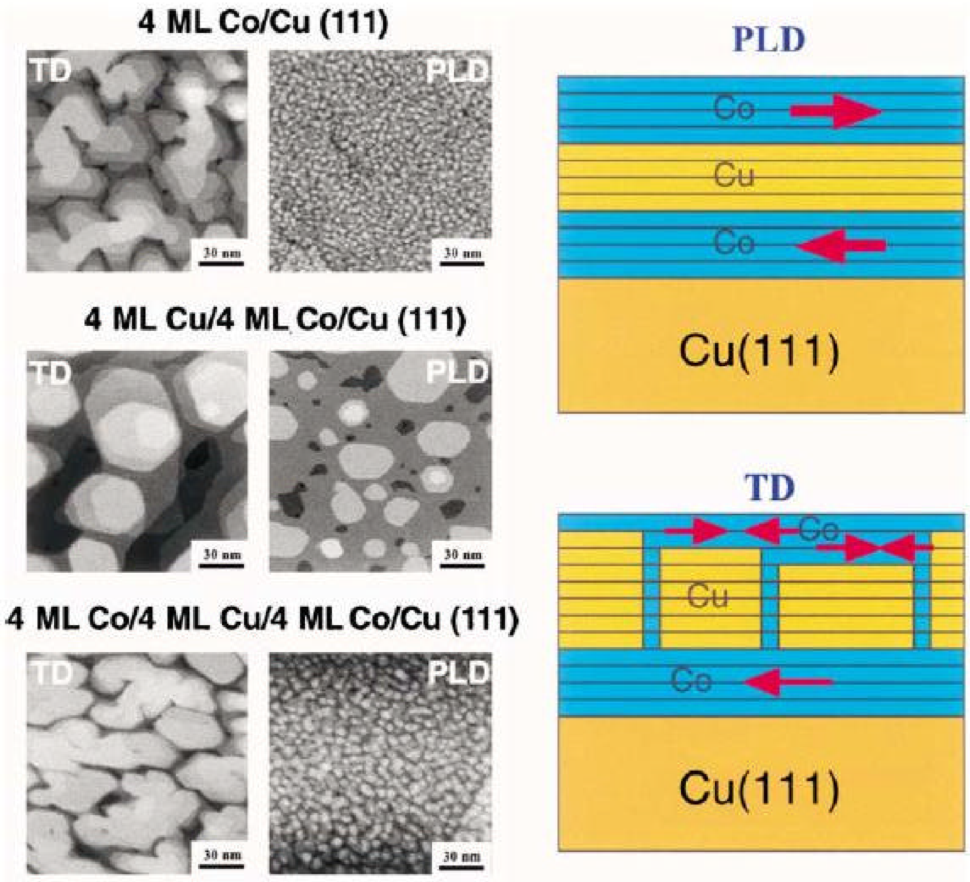






Fruchart et al. PRL83, 2769 (1999)

Growth mode of magnetic films

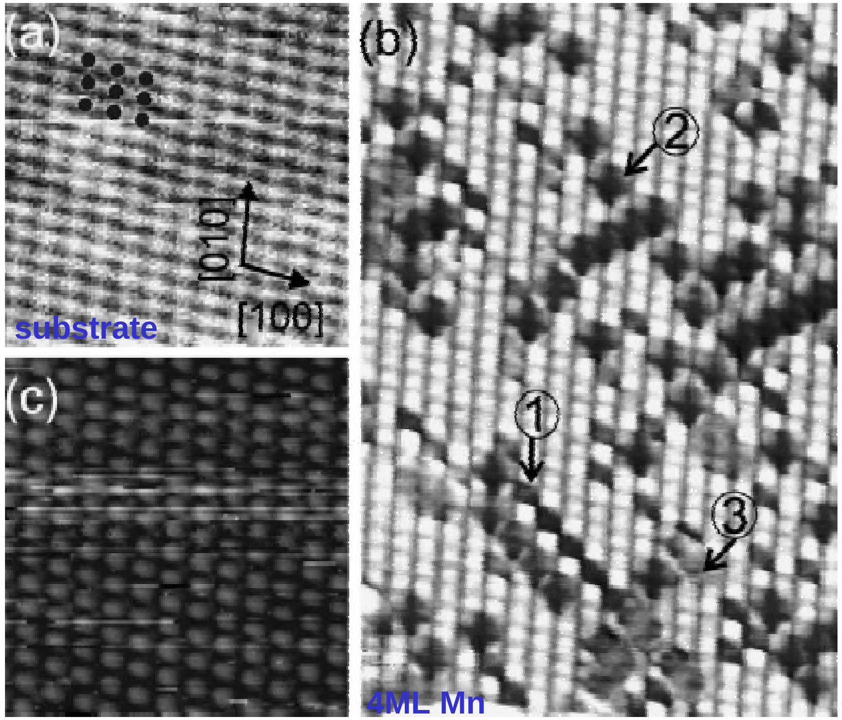


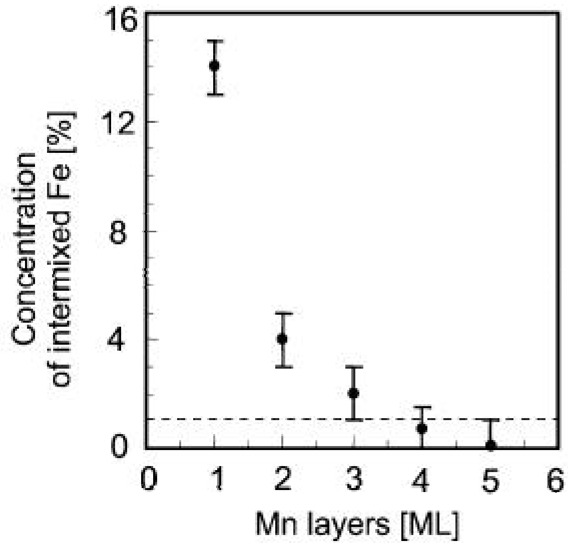
- STM can be used as tool to monitor film and multi layer growth
- Co/Cu multi layers on Cu(111) grow 3 dimensionally when thermally deposited (TD)
- pulsed laser deposited (PLD) multi layers are much smoother
- for application in GMR sensors TD is not suitable but PLD is

Shen and Kirschner, Surface Science 500, 300 (2002)

Detection of Intermixing

Mn/Fe(100) at 370K



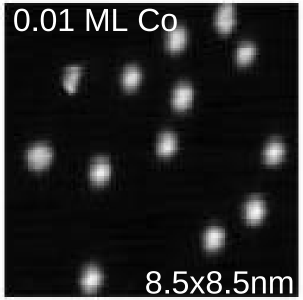


Yamada et al. Surf.Sci. 516, 179 (2002)

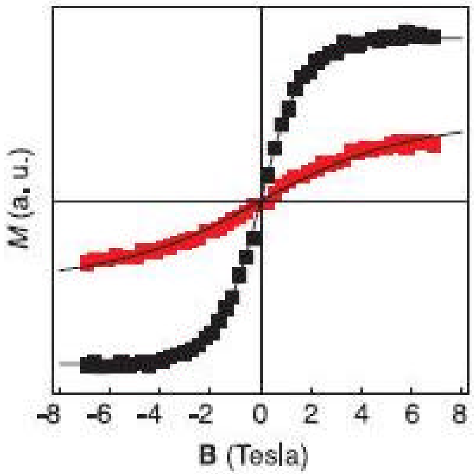
- Fe and Mn atoms have slightly different density of states
- difference causes a chemical contrast in topographic images
- intermixing can be observed on the atomic level and can be quantified

Nucleation of atomic clusters: Co/Pt(111)

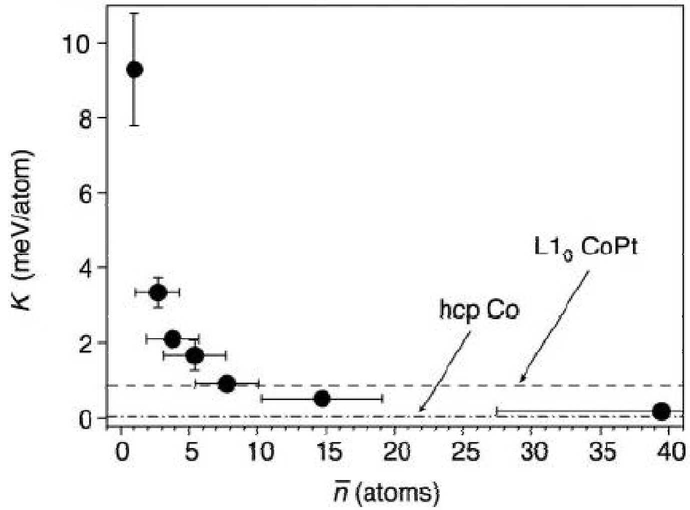
STM



XMCD

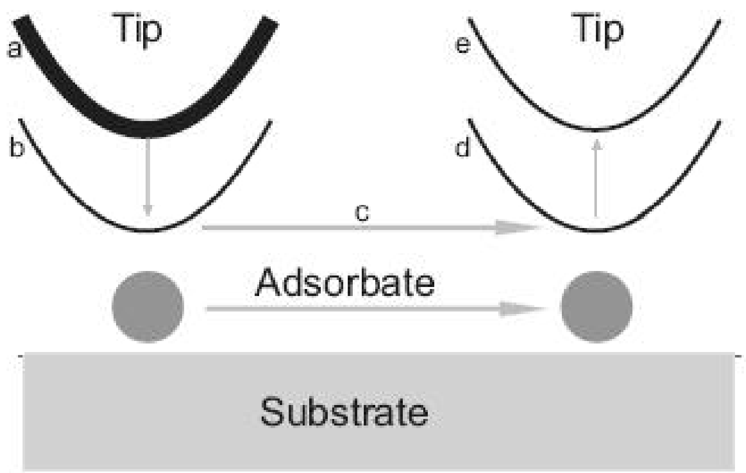


- low temperature STM is used to obtain average cluster size from total Co coverage and number of clusters
- XMCD is used to get integrated magnetic signal from clusters
- magnetic anisotropy of clusters as function of size can be obtained



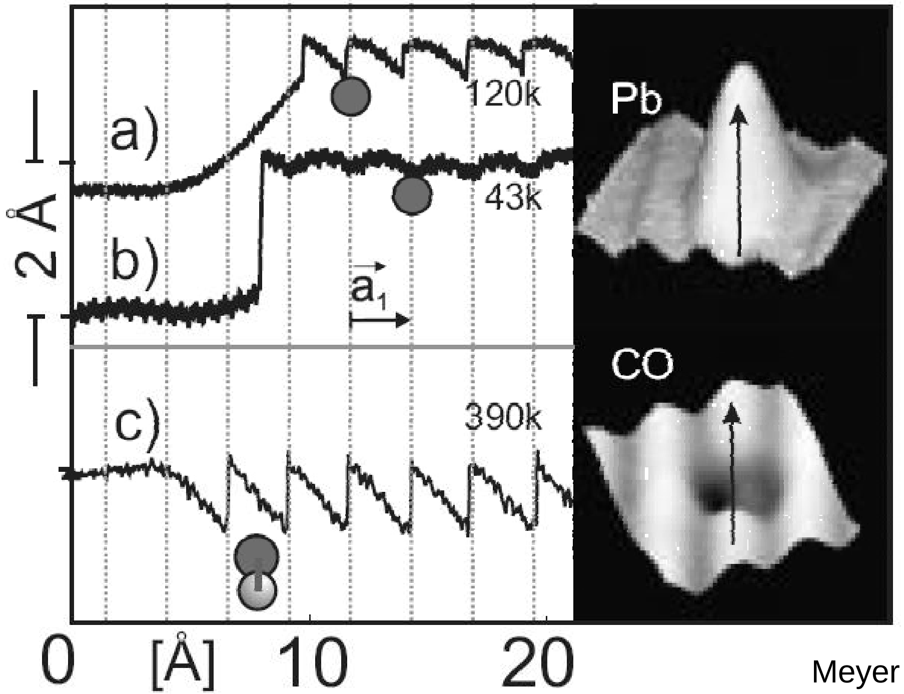
Gambardella et al., Science 300, 1130 (2003)

Moving atoms with the tip



- tip is approached from imaging distance (a) to a smaller distance (b) by increasing the feed-back current
- tip-sample interaction cannot be neglected anymore
- tip-adsorbate interaction may be attractive or repulsive
- tip pushes or pulls the adsorbate over the surface (c) to the desired position (d)
- tip is retracted to imaging distance (e) and interaction becomes small again

Pulling, sliding and pushing of atoms

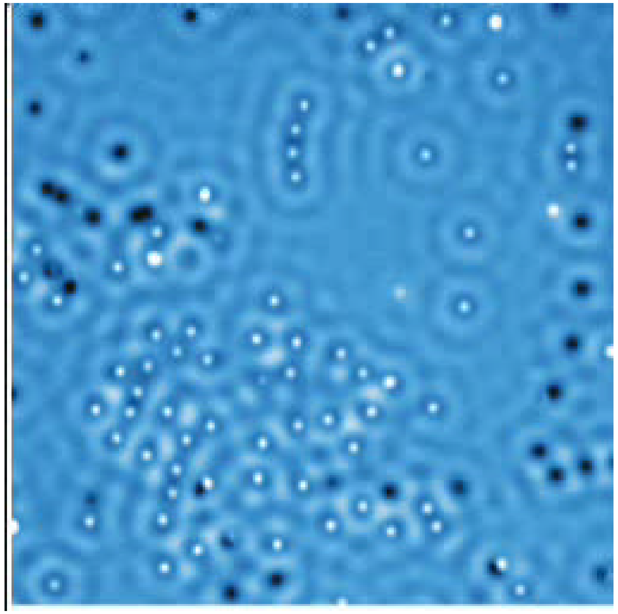


Meyer at al. Appl. Phys. A 68, 125 (1999)

- if interaction is attractive, adsorbates are pulled from lattice position to lattice position along with the tip (a)
- if lateral tip-adsorbate interaction is stronger than adsorbate-substrate interaction, the adsorbate slides with the tip (b)
- if interaction is repulsive, adsorbates are pushed from lattice position to next (c)

Building a nano structure atom by atom

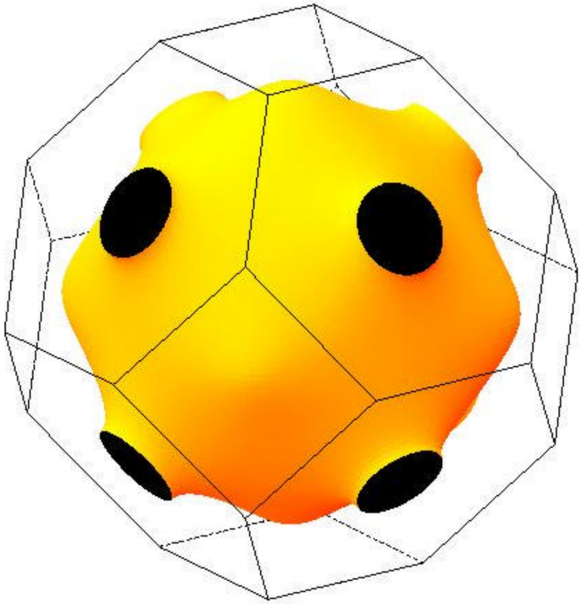
Ag/Ag(111)



- complex nano structure can be build up atom by atom with STM
- the structures can immediately also be studied with STM

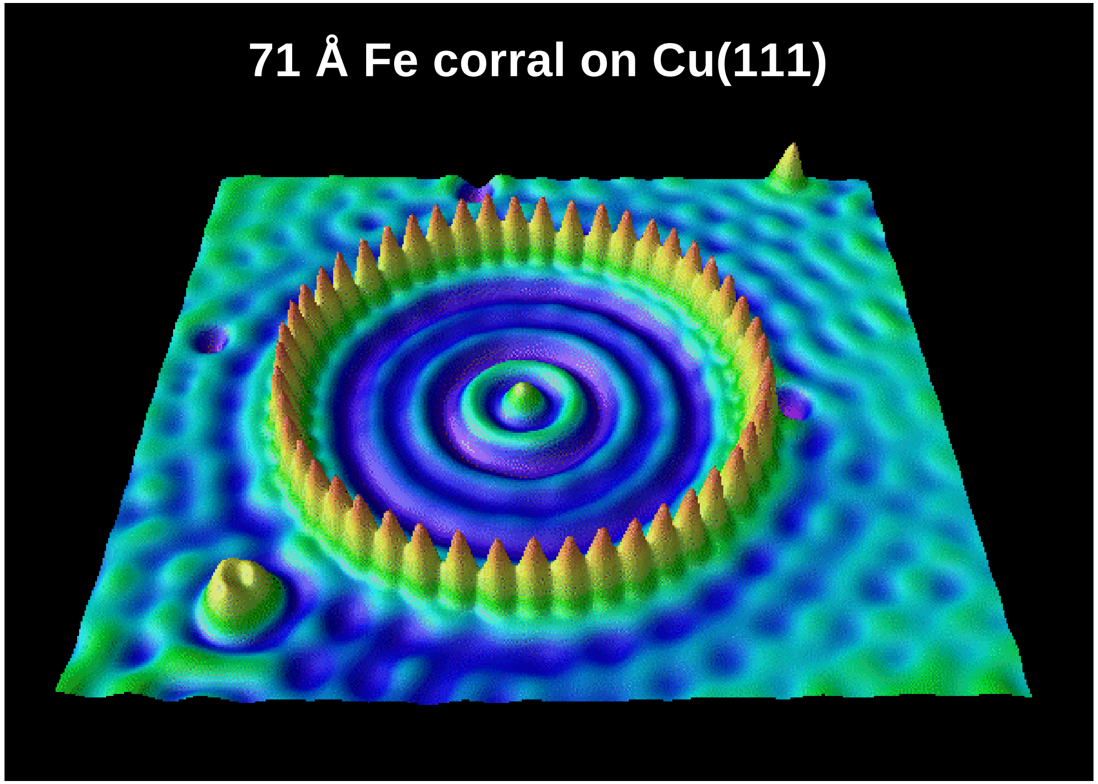
Rieder et al., FU Berlin

The surface state on noble metal (111) surfaces



- the Fermi surface of Cu, Ag and Au have a gap in the states along the (111) direction
- electrons at the surface can neither enter the bulk nor can they leave to the vacuum (work function)
- a 2D surface state is the result

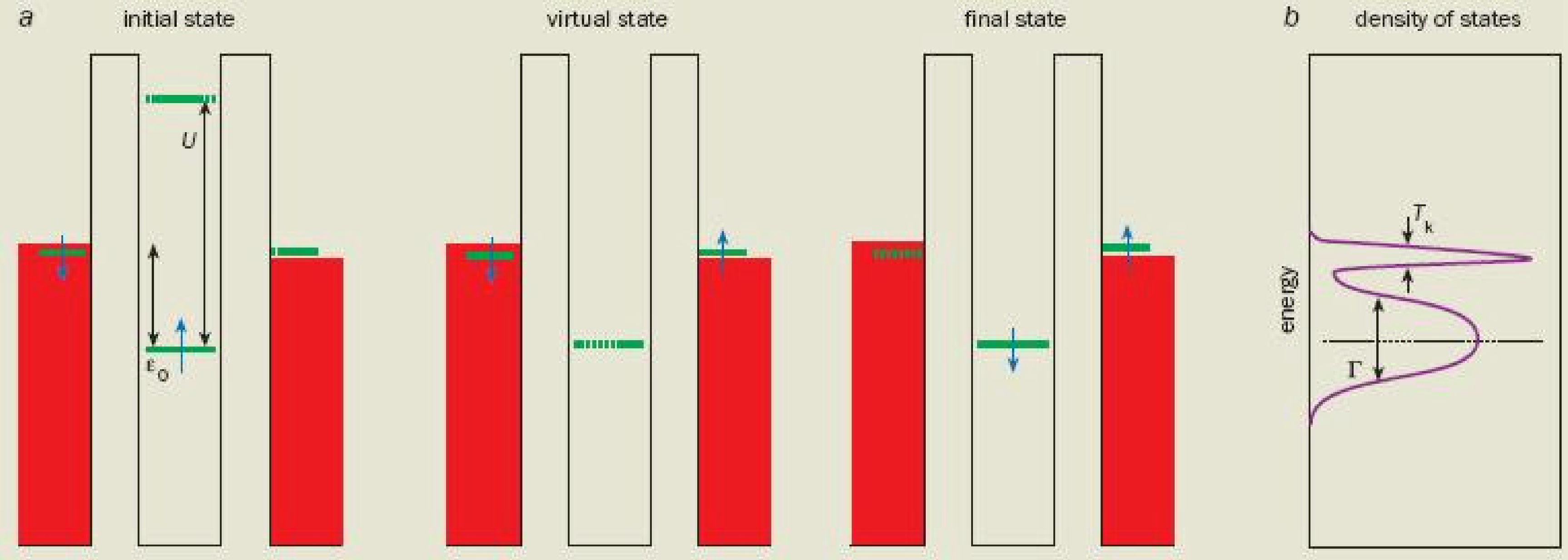
Quantum corrals



• surface state electrons are scattered by adatoms (here Fe atoms)
• a standing wave pattern emerges

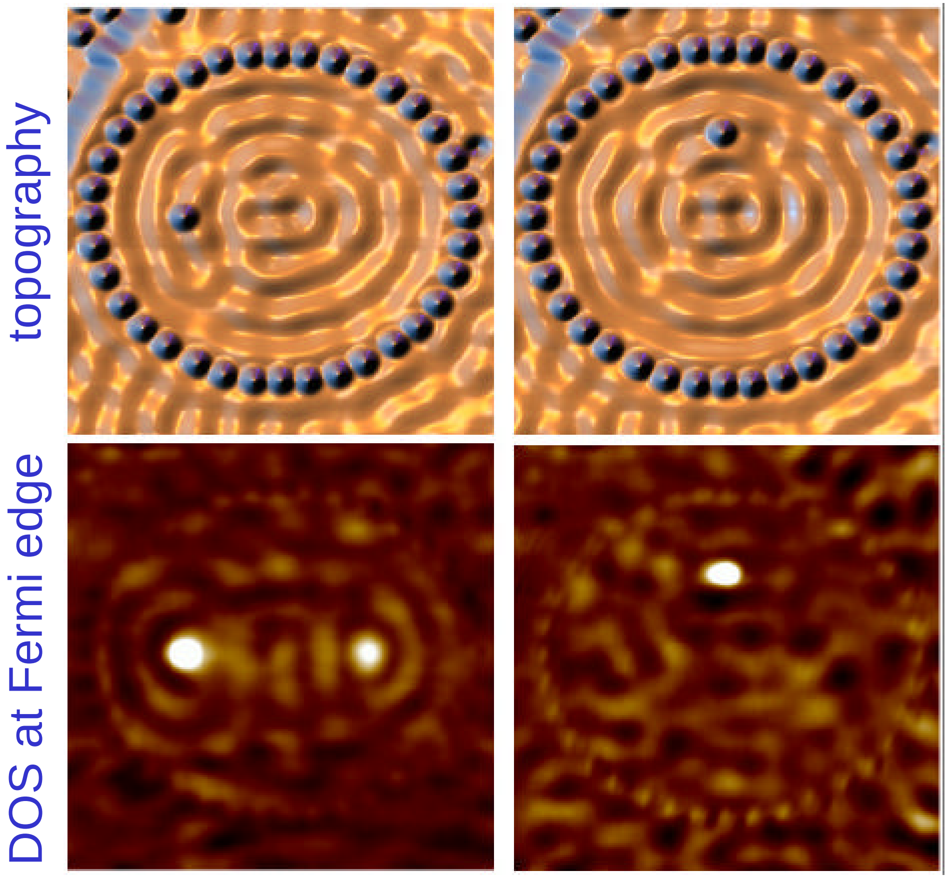
Eigler et al., IBM Almaden

The Kondo effect



- a magnetic impurity (Co) in contact with a non magnetic metal (Cu) can flip its spin by a two step process allowed due to the uncertainty principle
- the virtual intermediate state causes a shielding of the spin of the impurity and creates a peak in the density of states at the Fermi level

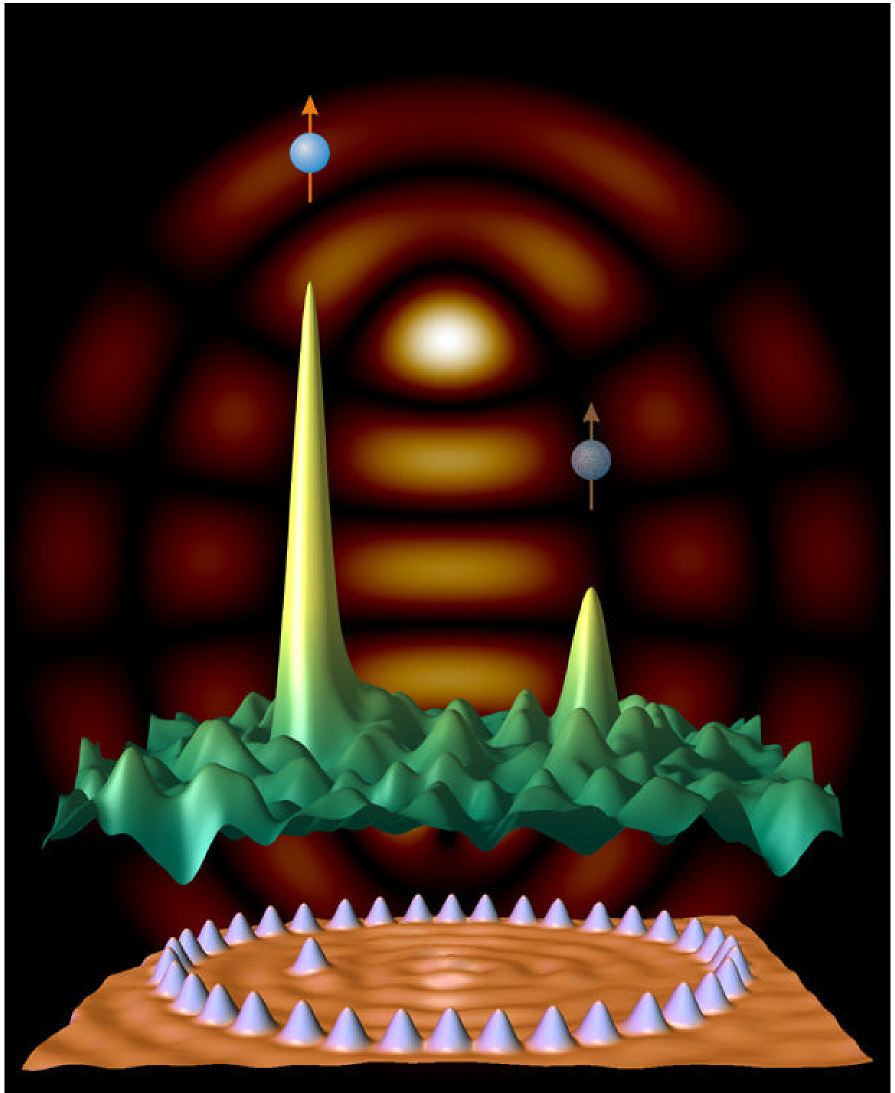
Quantum mirages



- The Co atom in the Fe quantum corral shows up in the DOS as a peak
- If moved to one focal point of the corral, a second peak in the DOS appears in the second focus
- The Kondo resonance is mirrored to the second focus by the surface state

Manoharan et al., Nature 403, 512 (2000)

Atomic manipulation with STM



Manoharan et al., Nature 403, 512 (2000)