Scanning Tunneling Microscopy (STM) and spin-polarized STM

Part II - spin polarized STM

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- **Spin-polarized Scanning Tunneling Microscopy**

1. The tunneling magnetoresistance effect

2. The constant current mode

3. The spectroscopic mode

4. The differential magnetic mode

5. Sp-STM beyond magnetism

Spin-polarized STM : the basic idea

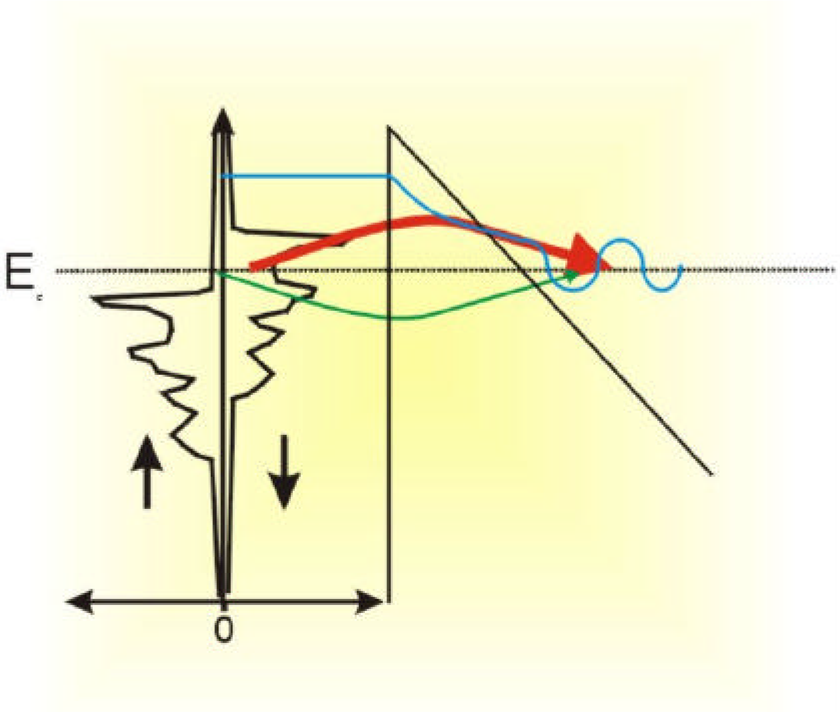
- the electrons have a spin, which is conserved during tunneling
- the magnetic moment of atoms is related to the electrons and their spin and orbital moment
- in itinerant ferromagnets and antiferromagnets, the magnetic moment is due to an imbalance in spin population

Can the electron spin in the local DOS be probed with STM?

- it would allow magnetic imaging with STM resolution
- it would allow to study also antiferromagnetic systems

Pierce, Physica Scripta 38, 291 (1988)

Field emission of spin-polarized electrons



- density of states (DOS) of the ferromagnet splits up into majority and minority electrons
- in field emission, the electrons near the Fermi edge tunnel through the surface potential barrier into free vacuum states
- the spin-polarization of the DOS is reflected in the spin-polarization of the emitted electrons

Müller et al., PRL 29, 1651 (1972)

Jullière´s experiment

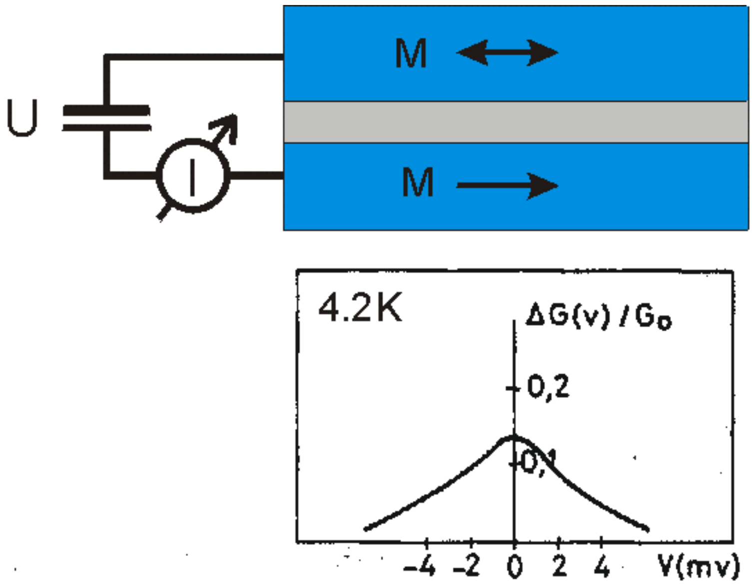


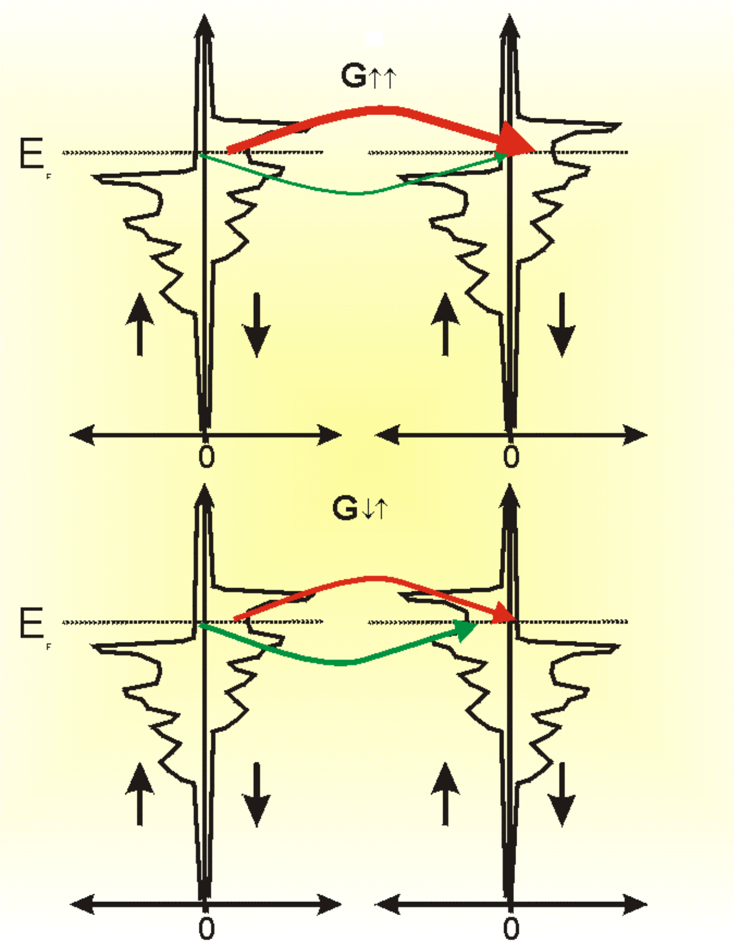
Fig. 2. Relative conductance $(\Delta G/G)_{V=0}$ of Fe-Ge-Co junctions at 4.2K. ΔG is the difference between the two conductance values corresponding to parallel and antiparallel magnetizations of the two ferromagnetic films.

- resistance is not only a function of applied voltage but also of relative orientation of magnetization
- Jullière found a 14% lower resistance for parallel orientation than for antiparallel

M. Jullière, Physics Letters 54A, 225 (1975)

The Julière model

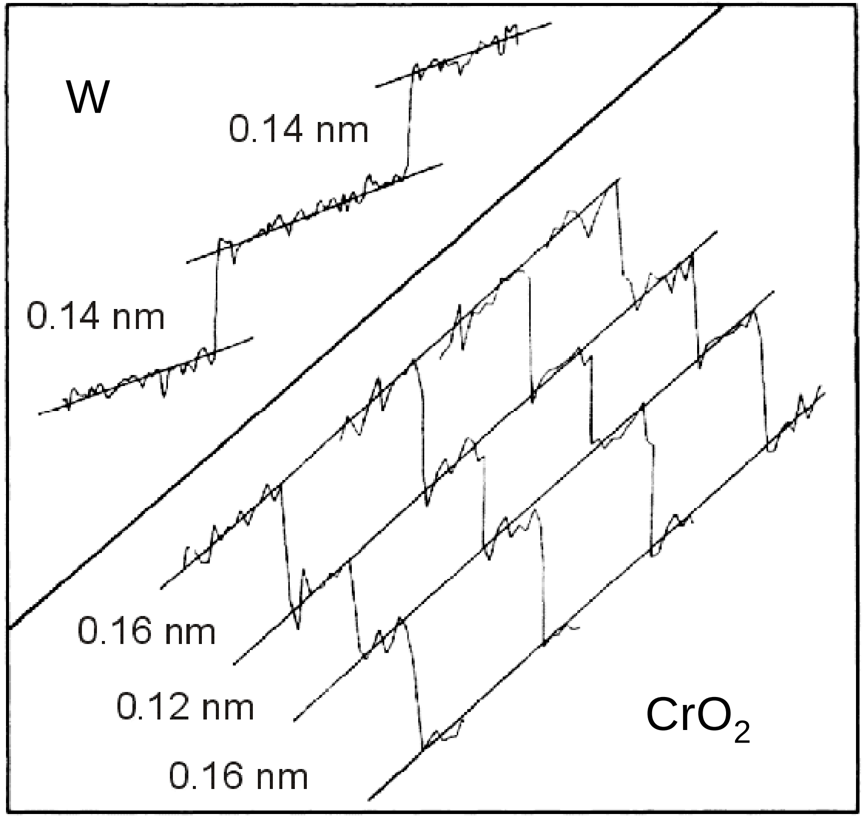
- depending on the relative orientation spins of minority/majority character tunnel into empty states of same or opposite spin
- the TMR results from the different densities of states using Fermi´s golden rule.



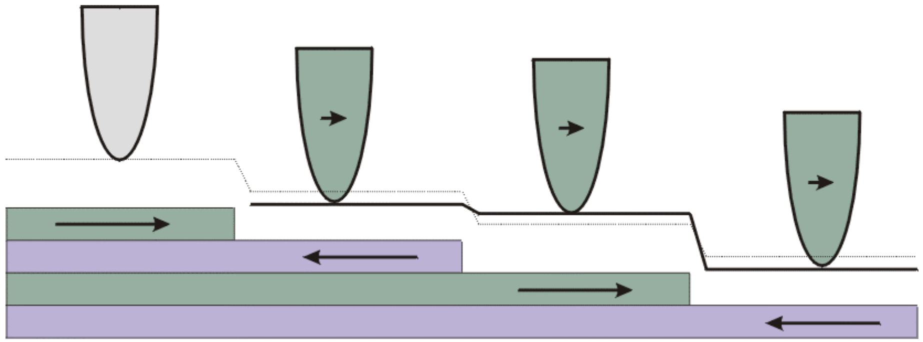
Conduction: $G=G_0(1+P_1P_2\cos\theta)$

Theory : J.C. Slonczewski, PRB 39, 6995 ´95
Experiment : T. Miyazaki et al. JMMM 139, L231 ´95

The Cr(001) surface



Cr(001) is a layer-wise antiferromagnet

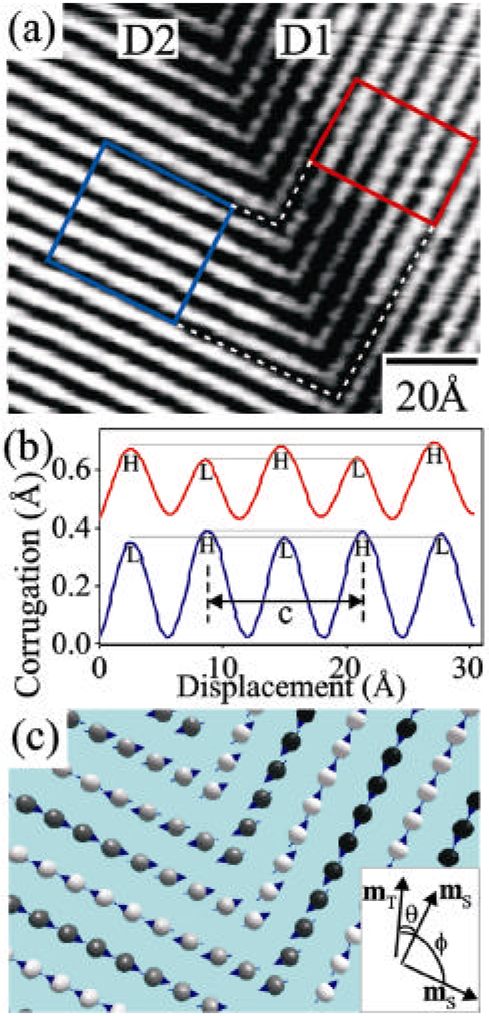


With non-magnetic W tips, the standard step height of 1.4 Å is observed
With spin-polarized CrO_2 tip, alternating 1.6 and 1.2 Å high steps were observed

Additional topographic contrast due to spin-polarized tunneling

Wiesendanger et al., PRL 65, 247 (1990)

$Mn_3N_2(010)$



- constant current images with Fe coated W tips show the Mn planes of the crystal as white lines
- crystallographic domains (D1) and (D2) can be seen
- additional corrugation of the Mn planes due to spin polarized tunneling
- corrugation is larger in D1 than in D2
- magnetic moment of Mn in D1 is more aligned to tip moment than that of domain D2

Yang et al. PRL 89, 226101 (2002)

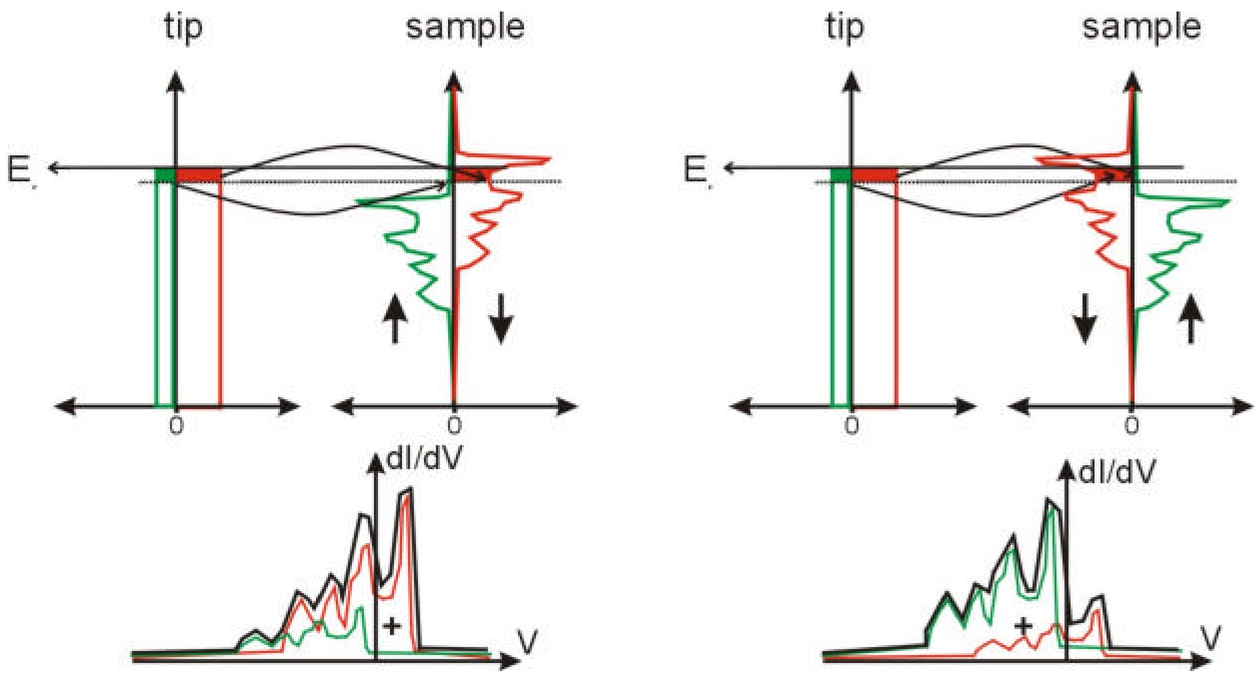
Advantages

- simplest mode of operation
- only requires a magnetic tip
- atomic resolution has been shown
- operation in high magnetic field possible

Disadvantages

- no separation of spin and topography
- only small additional topographic contrast due to spin
- highly stable STM needed
- has only been applied to antiferromagnets
- use of coated tips gives poor control over tip magnetization

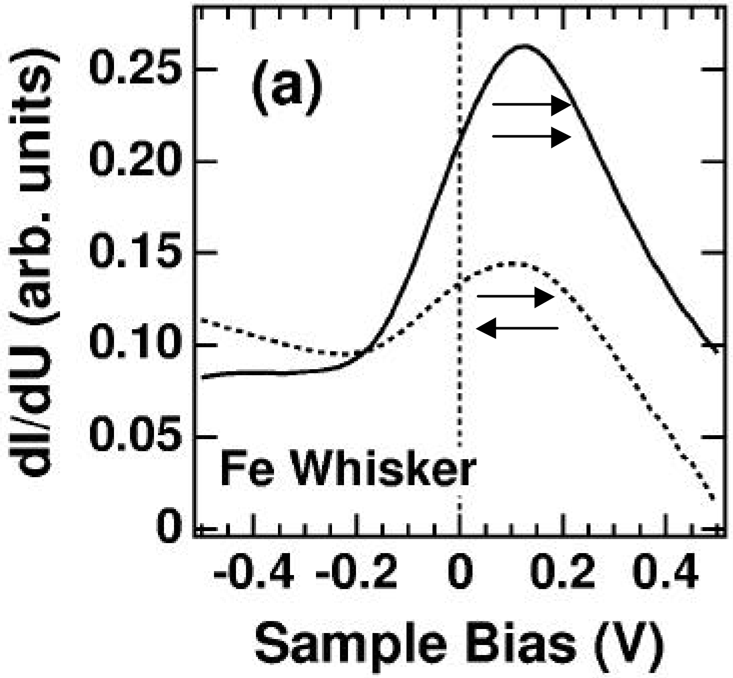
Spin-polarized scanning tunneling spectroscopy (Sp-STS)



- Within Tersoff-Hamman model, the tip has an s-wave wave function with constant DOS for both spins
- Depending on the relative orientation of the magnetizations, the observed dI/dV spectra are a linear combination of the minority and majority DOS of the sample
- The component of the magnetization along the tip magnetization can be obtained on samples with homogeneous electronic structure.

M. Bode et al. PRL 81, 4256 (1998)

Sp-STS with Fe coated W tip on Fe whisker



- Observation of well known minority surface state of Fe(001) at 130mV
- Sp-STS on both sides of whiskers, separated by a 180° wall
- Intensity of peak varies due to the relative orientation of the whisker magnetization

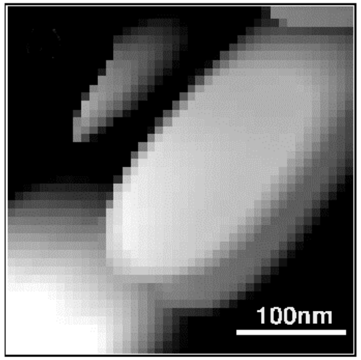
We use the surface state to obtain magnetic contrast on Fe(001).

J. Stroscio et al., PRL 75, 2960 (1995)

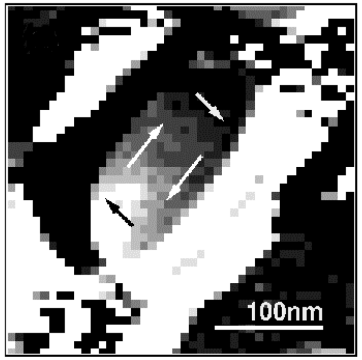
The spectroscopic mode

Fe/W(100)

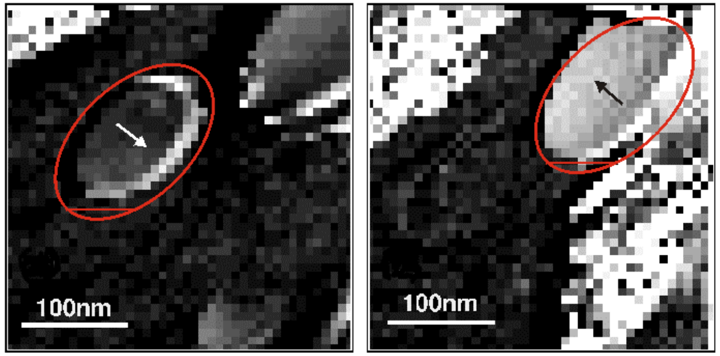
Topography



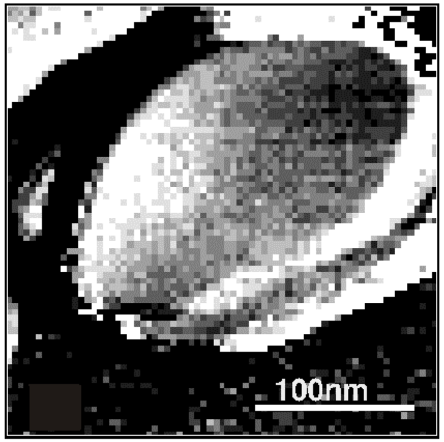
Spin



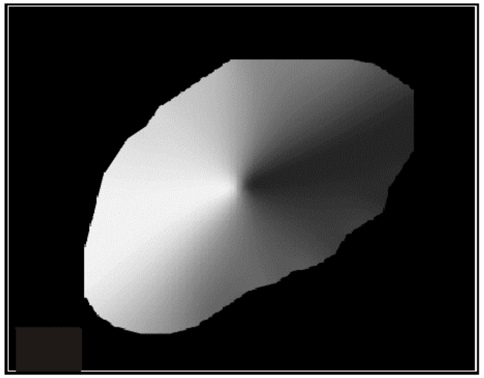
Spin in small islands



Spin



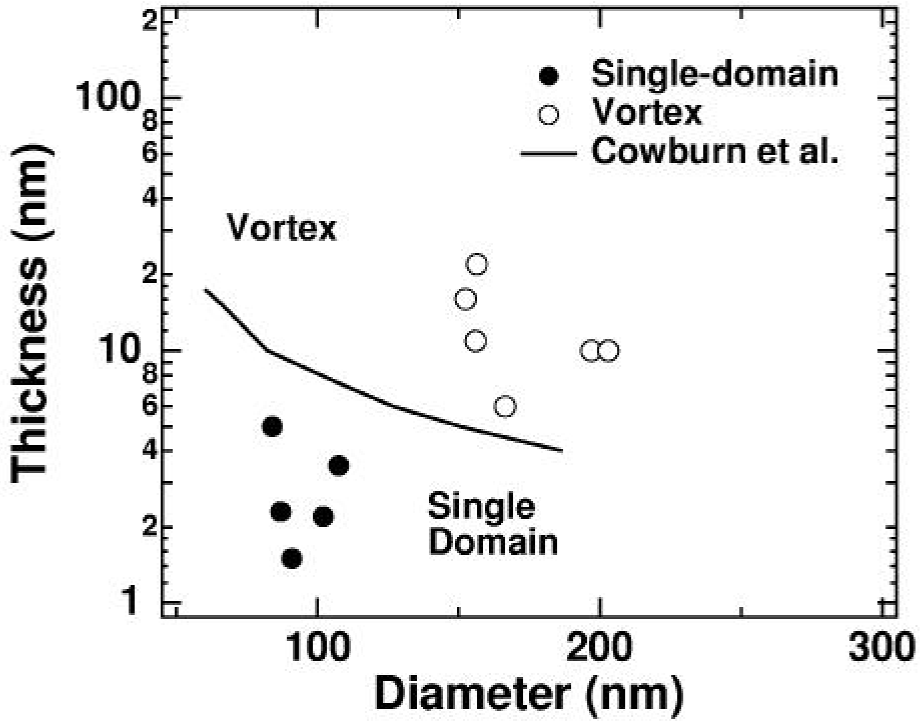
Micromagnetic calculation



- large islands show domains
- small islands are single domain
- observation of distorted vortex state that is in agreement with minimum energy configuration from simulations

The single domain limit

Experimental phase diagram



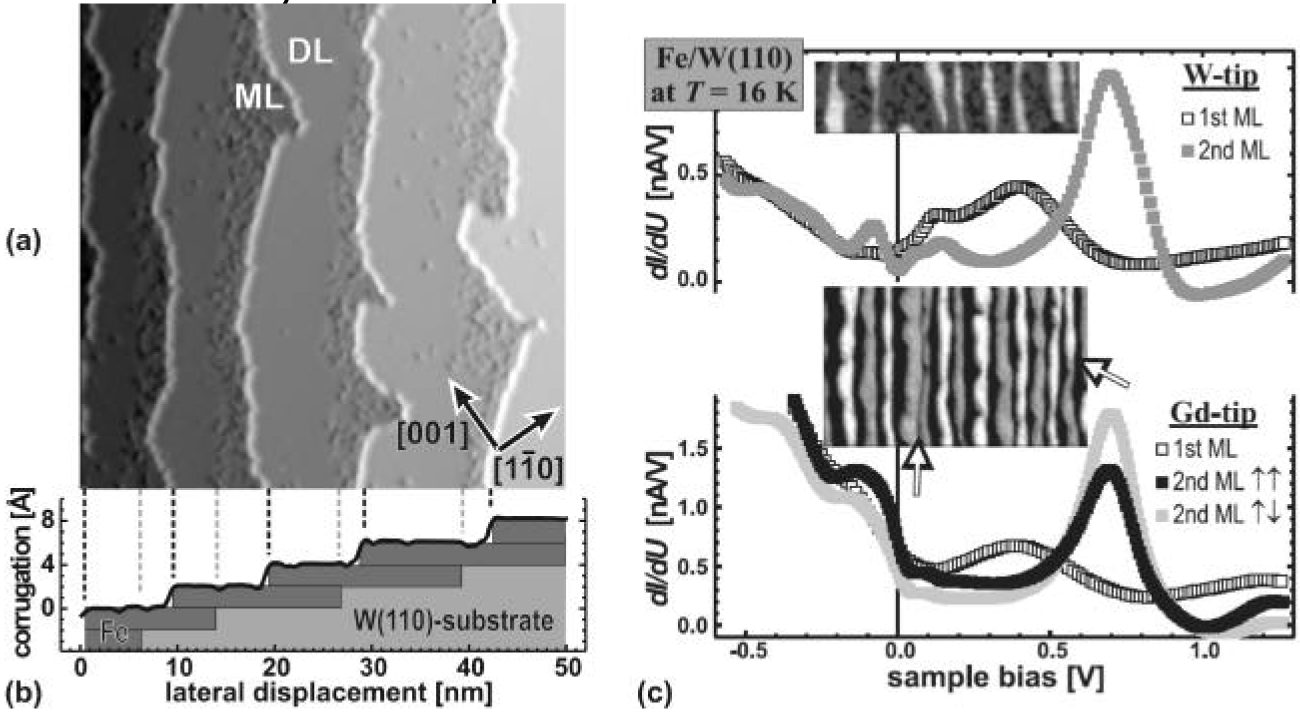
Yamasaki et al, PRL 91, 127201 (2003)

- first direct observation of the single domain limit
- good agreement with theoretical predictions

Dipolar antiferromagnets: Fe/W(110)

Double layer Fe stripes

Sp-STS with Gd coated tips

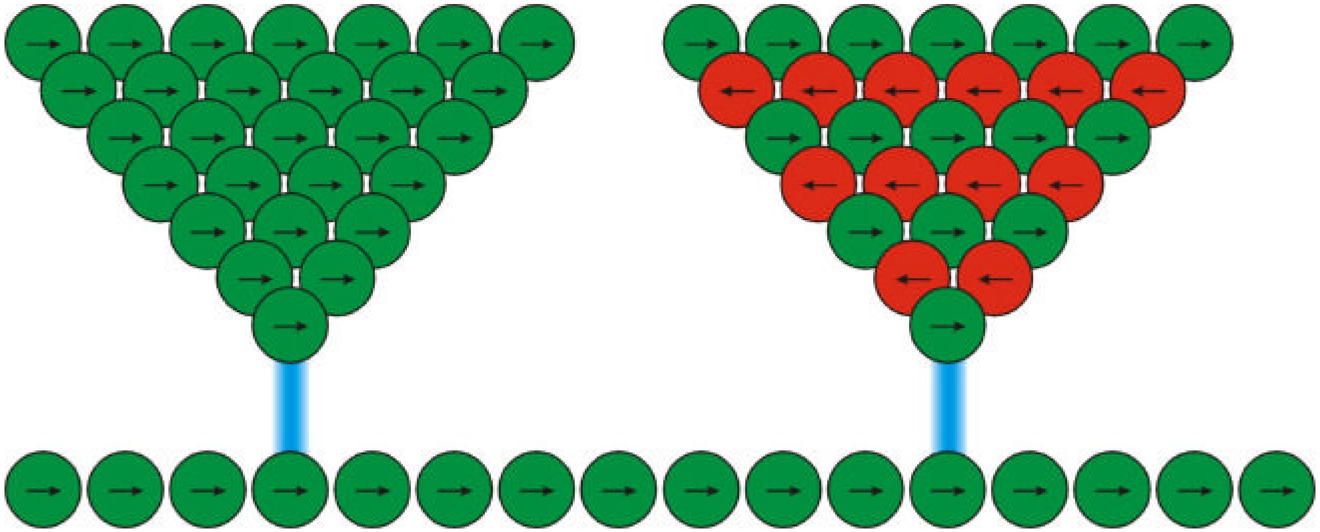


- Gd coated tips are sensitive to the perpendicular component
- DL and ML have different DOS causing a non-magnetic contrast
- alternating DL stripes show an alternating contrast

The dipolar antiferromagnetic coupling of perpendicularly magnetized Fe DL stripes was observed in real space

Pietzsch et al. PRL 84, 5212 (2000)

Using antiferromagnetic tips

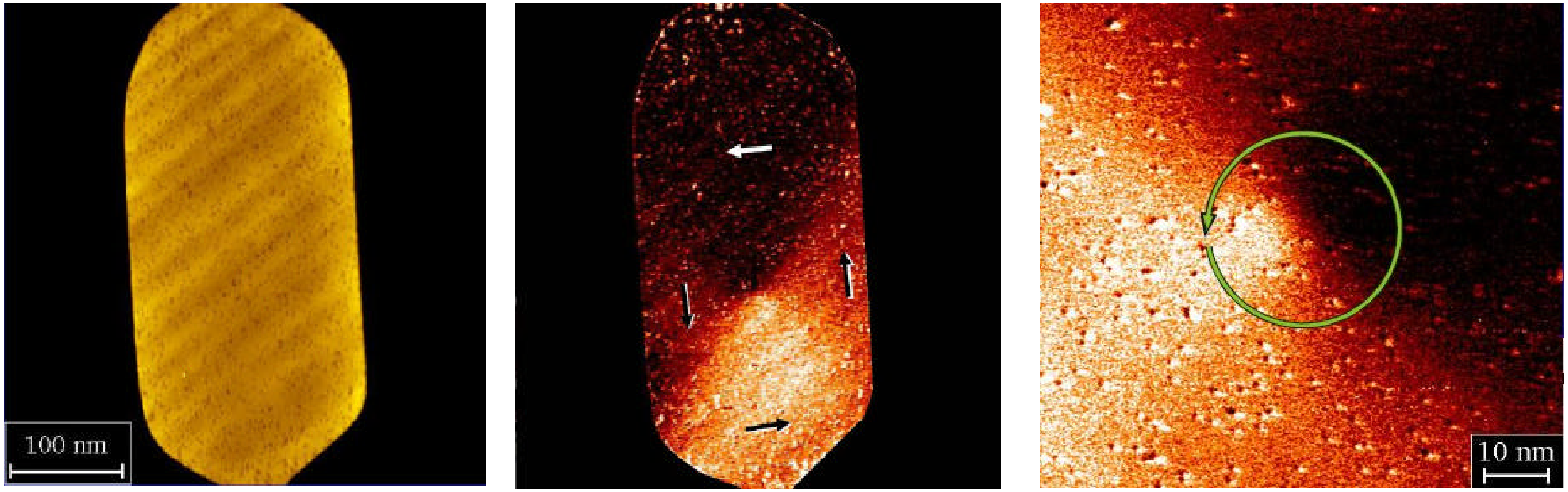


- aniferromagnetic tips have practically no stray field
- within Tersoff-Hamann model, the spin polarization of the last atom is important

Imaging vortices with antiferromagnetic tips

Fe/W(110)

Sp-STS with Cr coated tip



- high resolution imaging with stray field free Cr coated tips
- structure of vortex core resolved

Wachowiak et al. Science 298, 577 (2002)

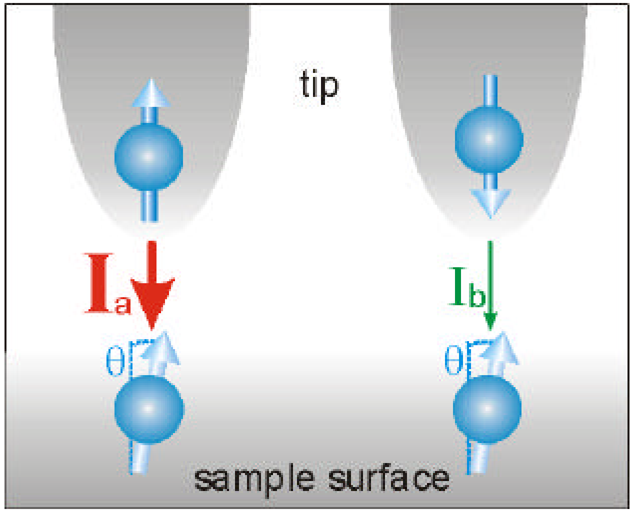
Advantages

- requires coated tips (e.g. Fe for in plane and Gd for out-of plane)
- below 1nm resolution has been shown
- operation in high magnetic field possible
- possibility to separate spin information
- antiferromagnetic tips avoid stray field
- has been applied to ferromagnets and antiferromagnets

Disadvantages

- topography contains spin information
- homogeneous electronic structure needed
- reference measurements with non-magnetic tips required
- images also contain contrast of other origin
- use of coated tips gives limited control over tip magnetization

Strict separation of spin and topography



working principle:

$I_a = I_0 (1 + P_t P_s \cos\theta)$

$I_b = I_0 (1 - P_t P_s \cos\theta)$ reversed tip magnetization

$\bar{I} = I_0$

$\Delta I = 2\, I_0 P_t P_s \cos\theta$

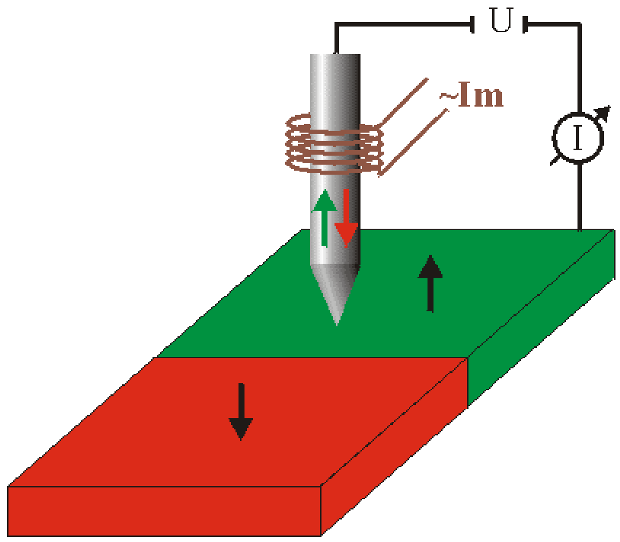
- magnetically bi-stable tip is periodically switched between opposite directions
- average tunneling current: topographic image (I)
- difference in tunneling current: proportional to spin polarization (ΔI)
- spin independent and dependent parts of current are strictly separated

→ direct measurement of spin polarization

→ sensitivity for one well-defined component of magnetization

Wulfhekel at al., APL 75, 1944 (1999)

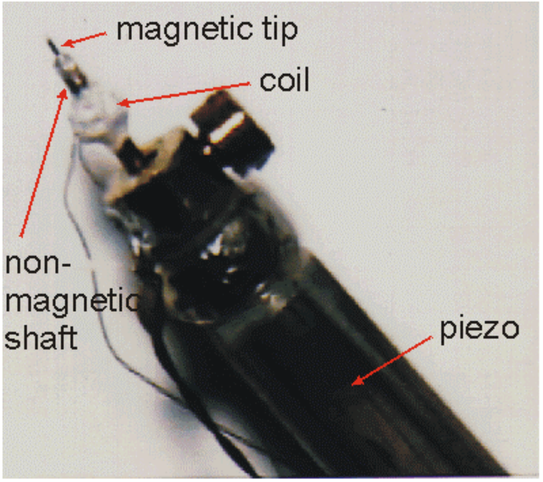
Imaging the out-of plane component

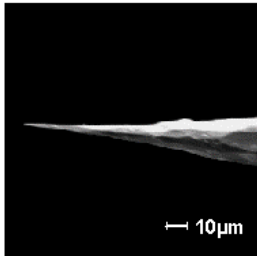


- tip is periodically switched at 20-40 kHz
- feedback loop does not react on the fast variations due to TMR
- difference in tunneling current is detected with lock-in amplifier

→ simultaneous imaging of topography and spin

Imaging the out-of plane component

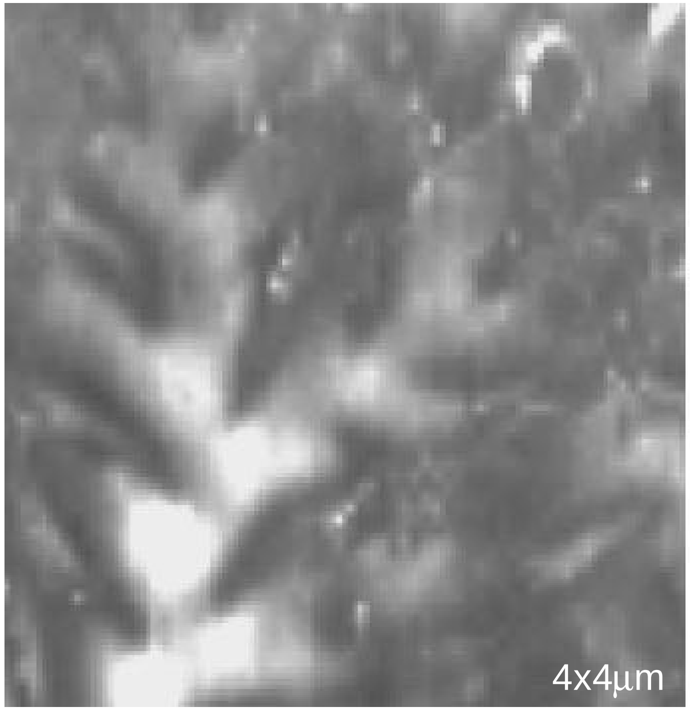




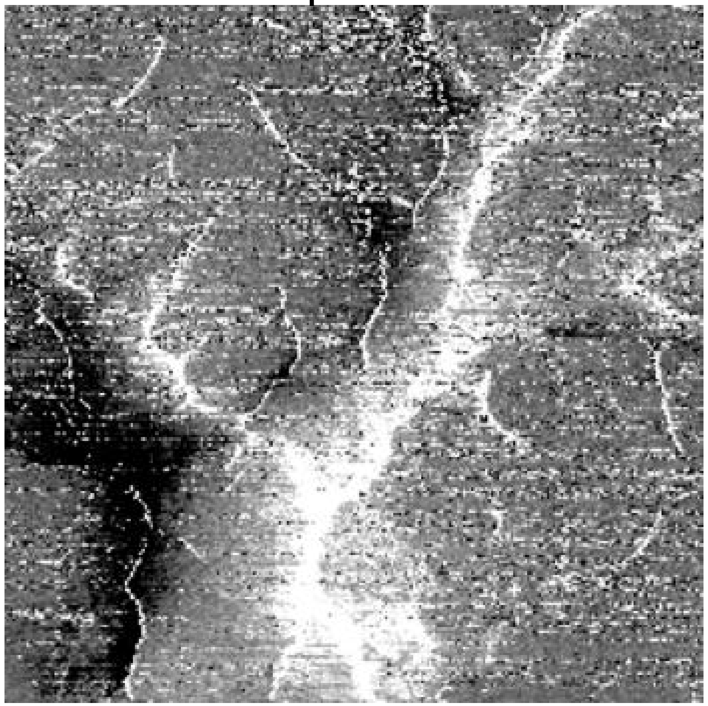
- CoFeSiB tips
- soft magnetic
- vanishing magnetostriction
- sharp tip
- thickness: 120 µm
- some stray field
- cleaned in-situ by Ar sputtering

The closure domain pattern of Co(0001)

MFM



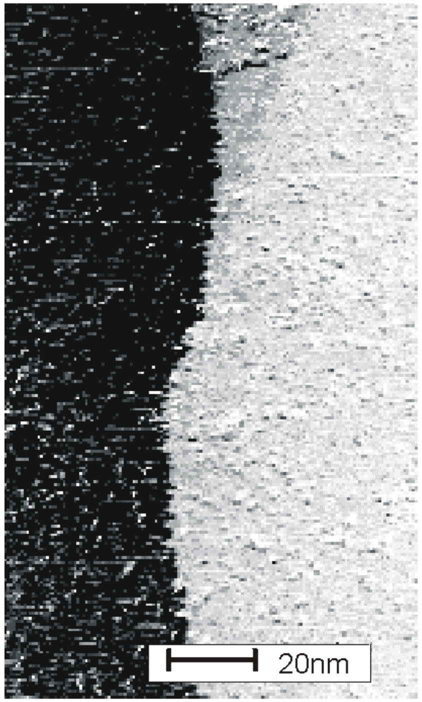
Sp-STM

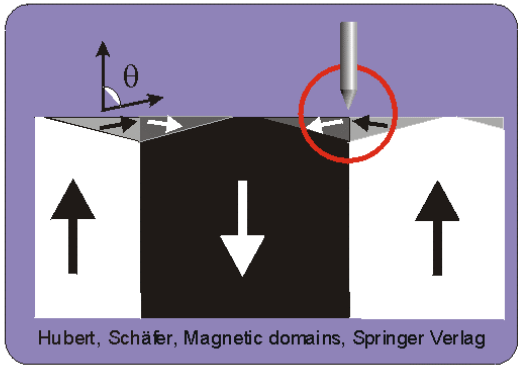


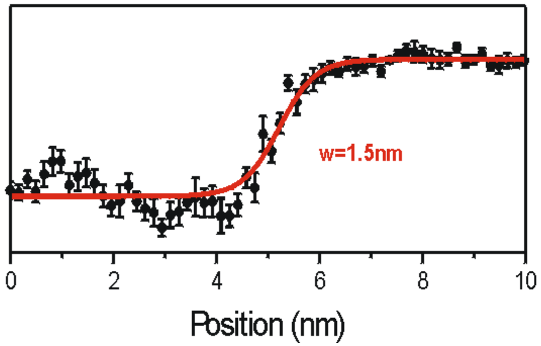
- well known dendritic closure domain pattern observed with Sp-STM
- lateral resolution better than conventional MFM
- no influence of stray field on hard magnetic sample found

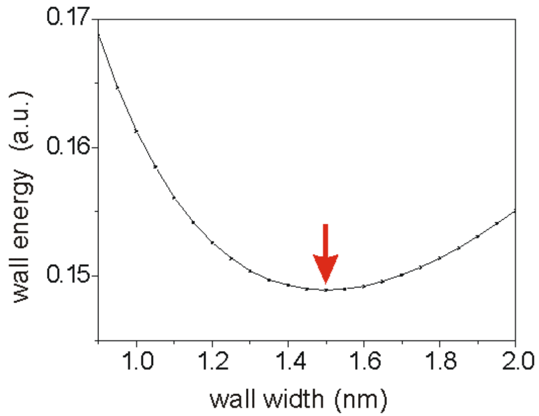
Ding et al. Materials Sci. Engin. B 84, 96 ´01

Ultra sharp domain walls in Co(0001)







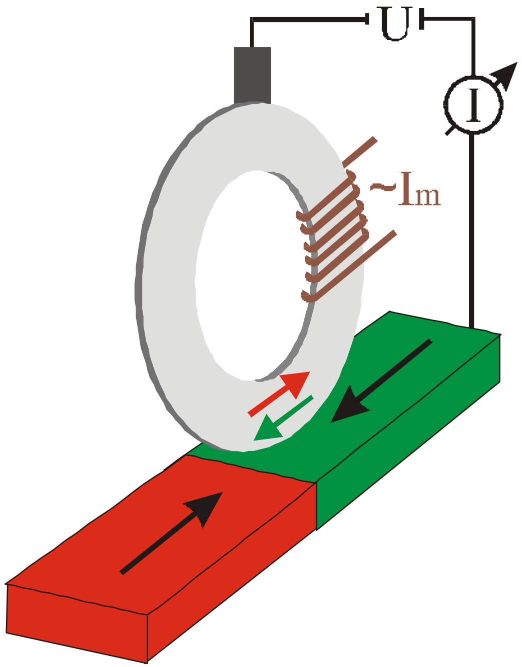


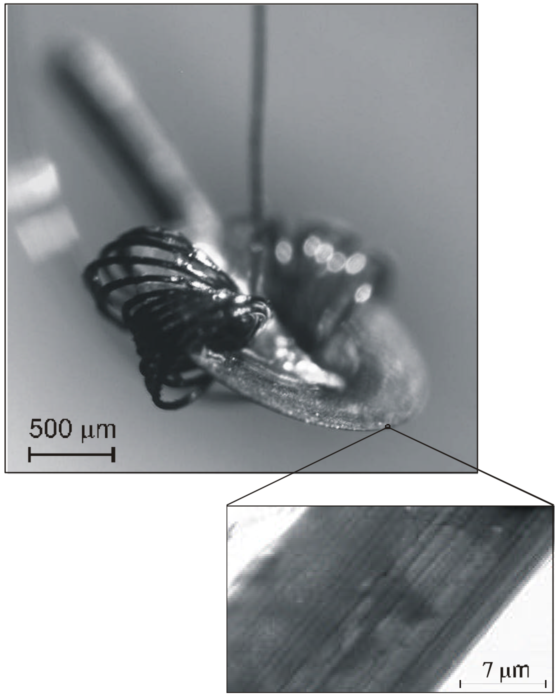
Sum of exchange and anisotropy energy of 20° wall shows minimum at 1.5 nm width.

- Extremely sharp domain walls (1.1 nm) in comparison to bulk walls (11 nm)
- Low contrast in agreement with 20° surface closure domain wall
- Micromagnetic calculations agree with experimental wall profile
- Lateral resolution better than 1 nm

Ding at al., EPL 57, 100 (2002)

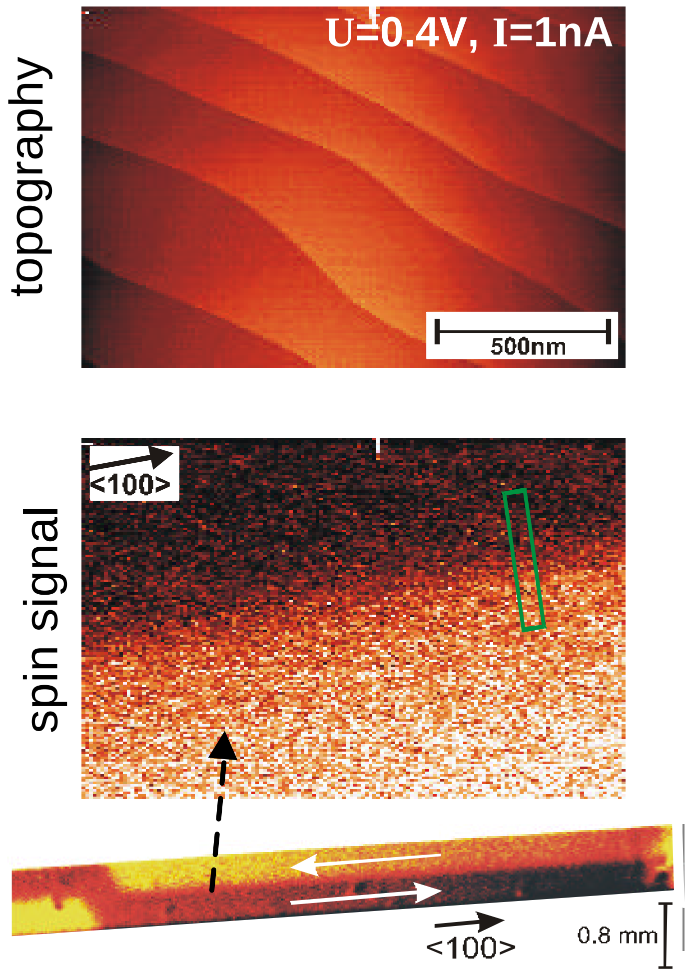
Imaging a well defined in-plane component



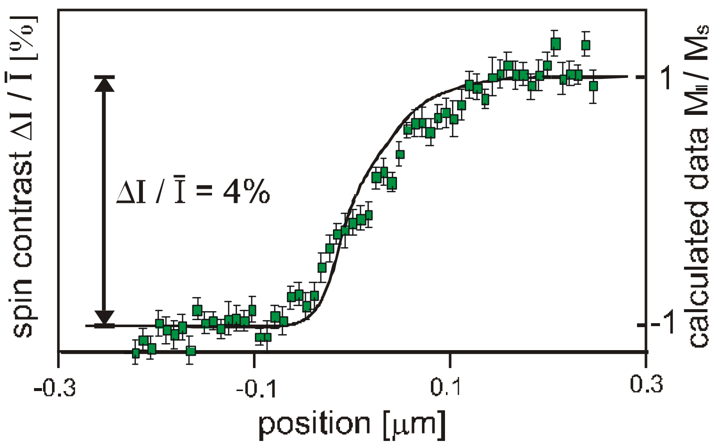


- CoFeSiB ring electrodes etched from amorphous foil
- outer diameter of the ring is 2 mm and thickness 25 μm
- perimeter: macroscopically flat
- requires flat sample surface
- flux closed: no stray field

Neel caps in 180° domain walls of Fe(001)



Kerr microscopy of Fe whisker



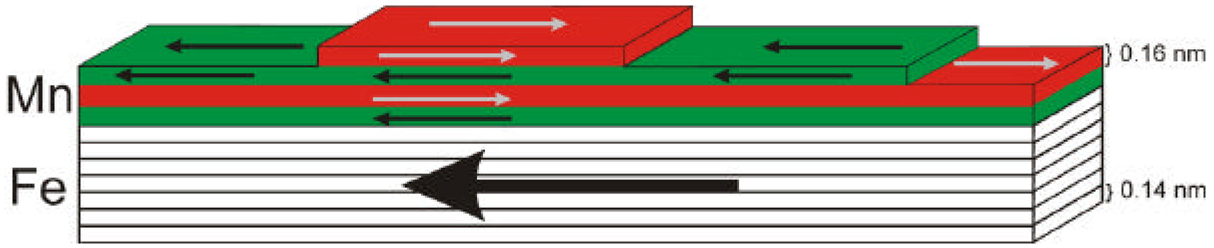
measured (■) and
calculated (-) line profile

- good agreement between experimental and theoretical wall profile
- no effect of stray field on soft whisker

→ a well-defined magnetic in plane component can be imaged with a Sp-STM

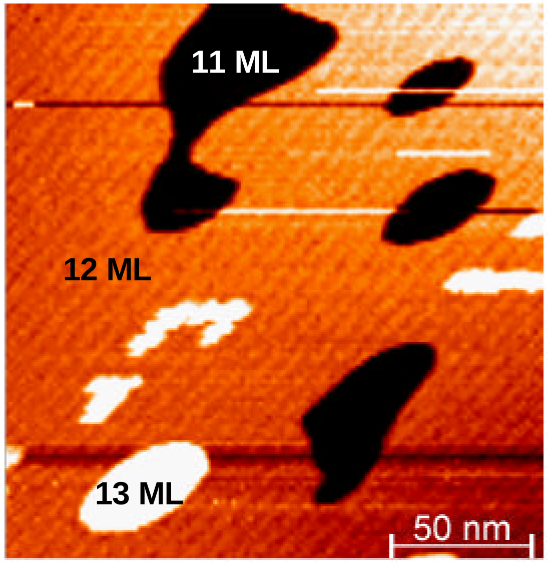
Schlickum et al., APL 83, 2016 (2003)

A topological antiferromagnet : Mn/Fe(001)

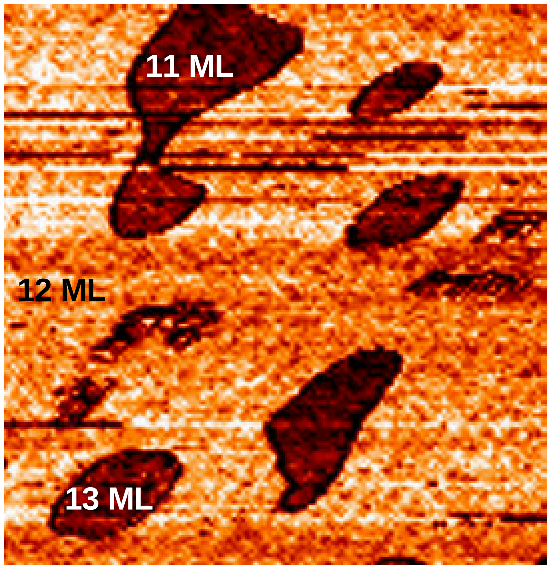


- pseudomorphic growth
- bct- structure
- layer-wise anti-ferromagnetic order

Topography



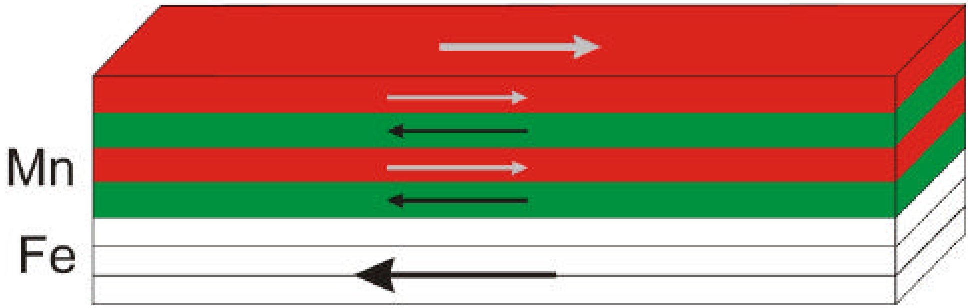
Spin



12 ML Mn on Fe(001),
T=100° C;
U=0.1 V, I=3 nA

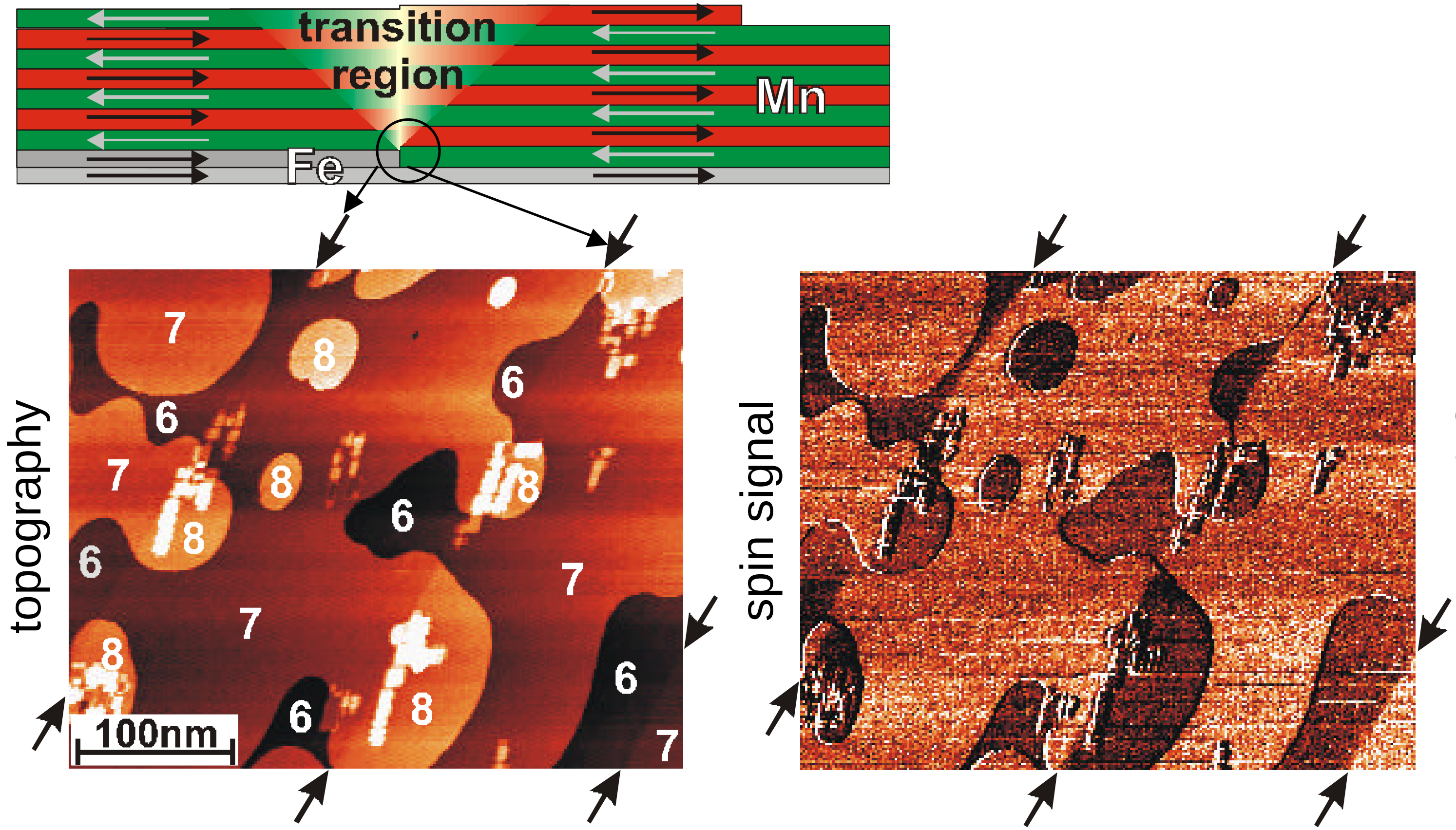
↕ Direction of sensitivity

Topological frustrations at substrate step edges



Frustration!!!

Topological frustrations



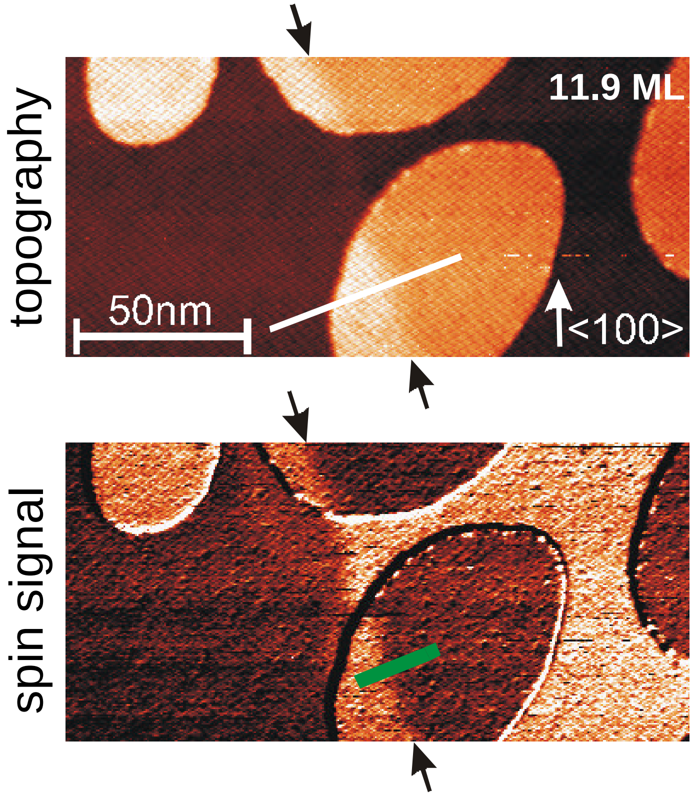
6.9 ML Mn/Fe(001), evaporation at 95°C, U=0.1V, I=3nA

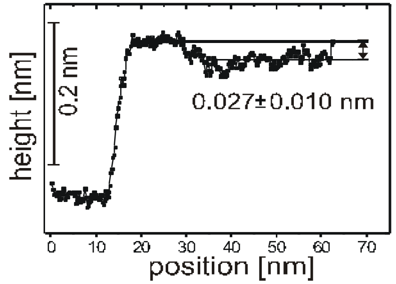
direction of sensitivity

- formation of frustrations in form of 180° domain walls along buried Fe step edges

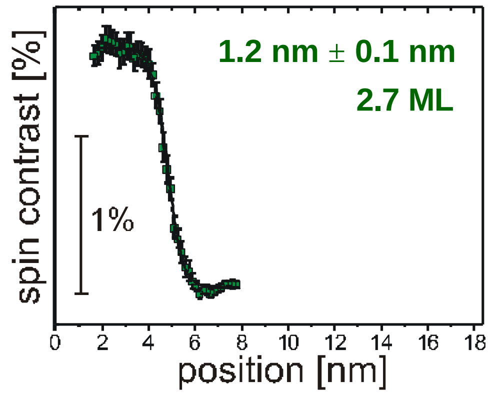
$\rightarrow$ interface coupling energy between Fe and Mn is higher than Mn domain wall energy

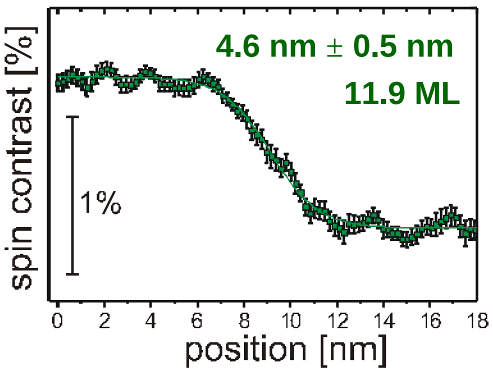
Width of enforced walls

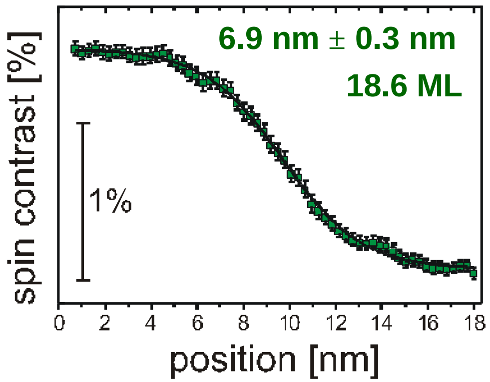




line profiles

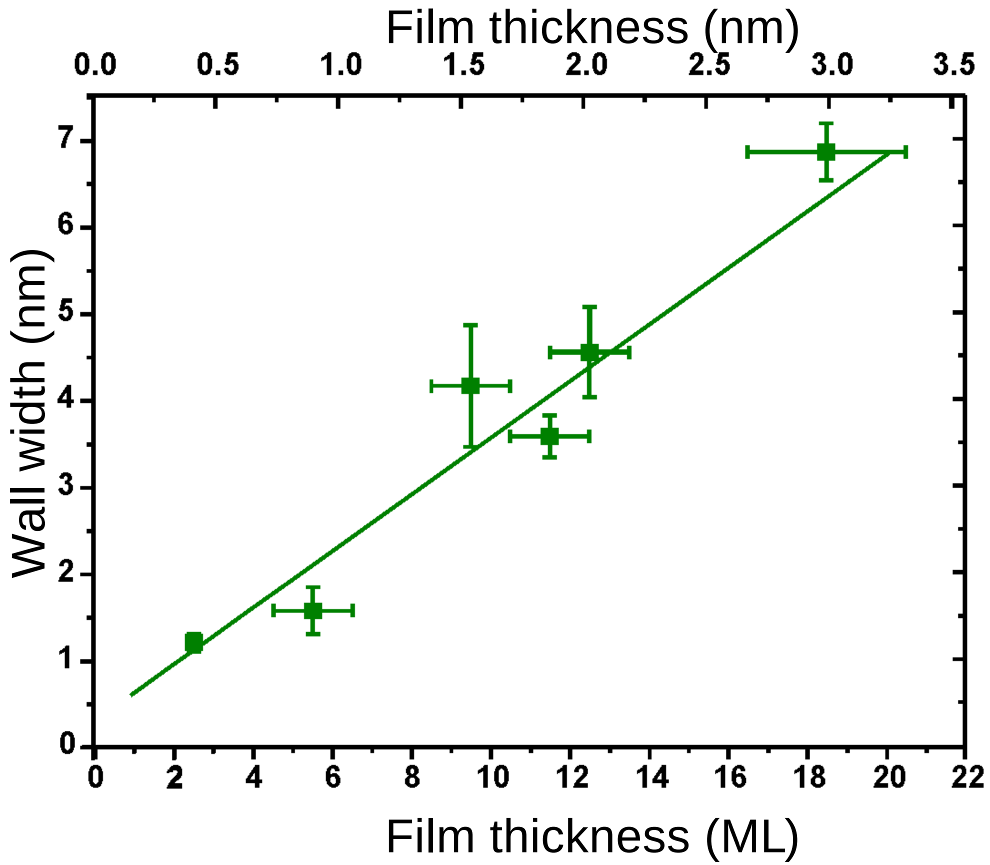






- domain wall profile fitted with standard wall profile: spin polarization $\propto \tanh(x/w)$

Widening of frustrations



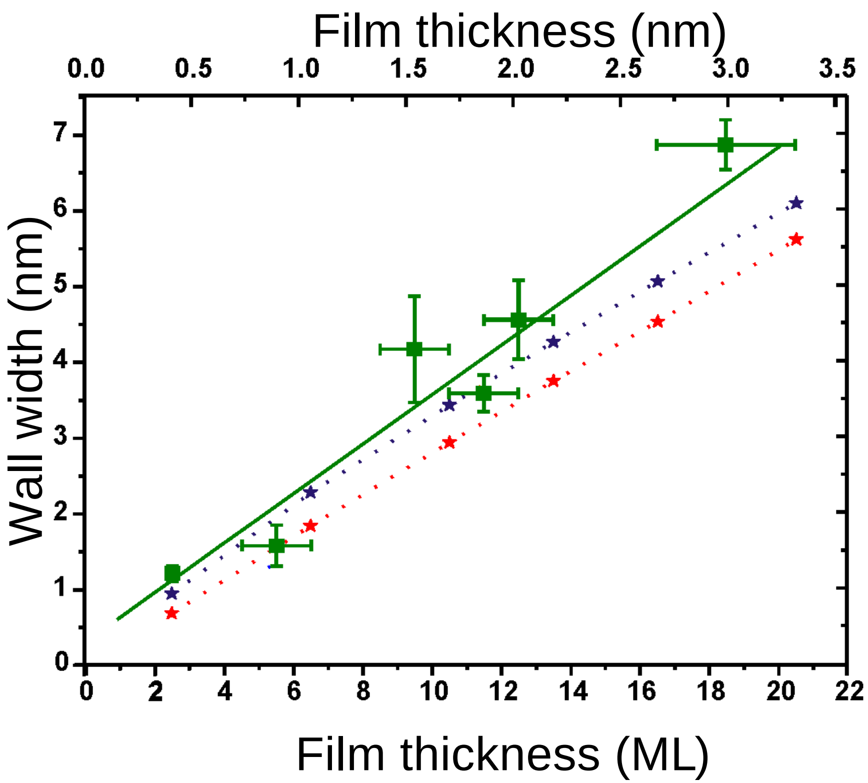
Observed: Linear widening of the frustration

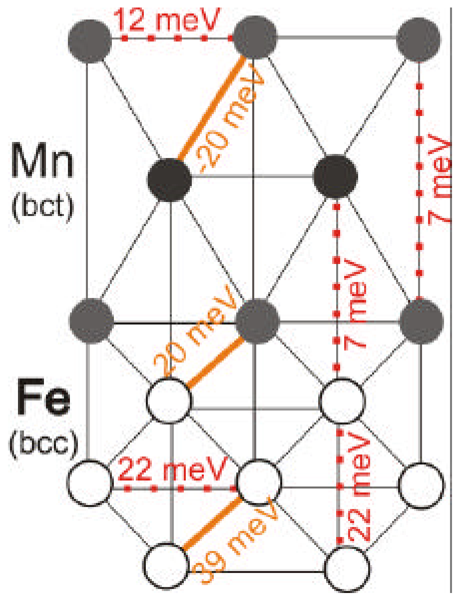
Expected: asymptotic approach to the bulk domain wall width

$\rightarrow$ Magnetic frustration much smaller than bulk domain wall

Schlickum et al., PRL92, 107203 (2004)

Heisenberg model of frustration





★ $J_{MnFe} / J_{Mn} = 1$

★ $J_{MnFe} / J_{Mn} = 1/4$

$K_{Fe} = 4.02\ \mu eV/atom$

$$E = -1/2\ \Sigma\ J_{ij} S_i\ S_j + \Sigma\ K_i(\Theta_i)$$

Good agreement between experimental and calculated wall width

Advantages

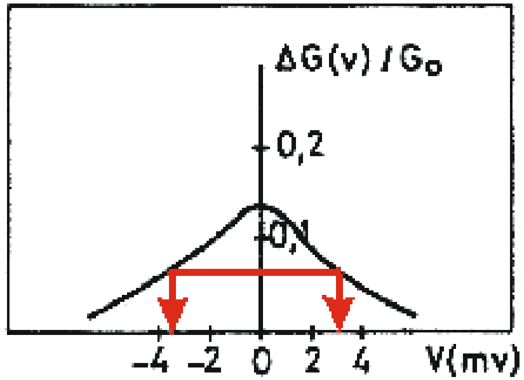
- bulk tips may be used
- below 1nm resolution has been shown
- spin information and topography are separated strictly
- ring tips avoid stray field
- has been applied to ferromagnets and antiferromagnets
- well defined direction of sensitivity
- no restrictions on DOS of sample

Disadvantages

- operation in high magnetic field impossible
- out-of plane measurements only on hard-magnetic samples
- has only been used at room temperature

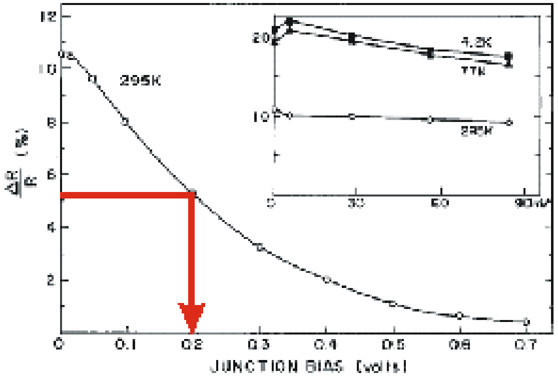
Bias voltage dependence of TMR

Fe/Ge/Co



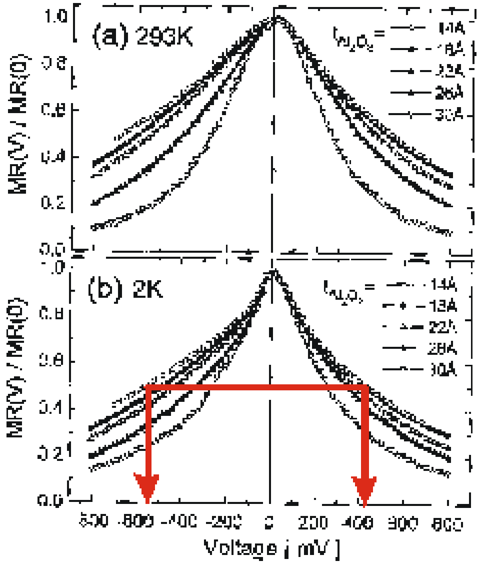
M. Julliere, Phys. Lett., 54A,225 (1975)

CoFe/Al_2O_3/Co



J.S. Moodera et al., PRL,74,3273 (1995)

CoFe/Al_2O_3/Fe

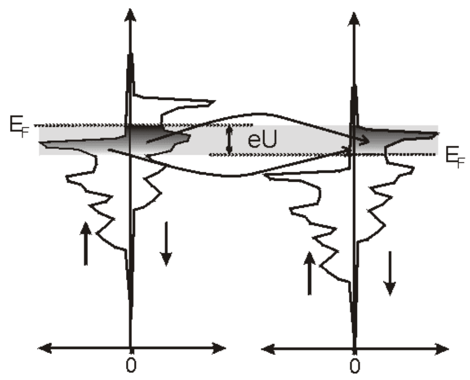


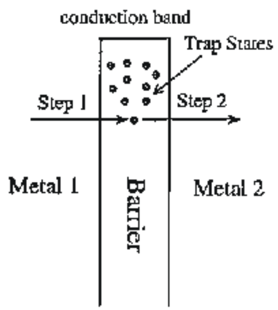
Yuasa et al. EPL 52, 344 (2000)

- strong drop of TMR with applied voltage
- large improvement of U½ over the years
- origin of drop not completely understood

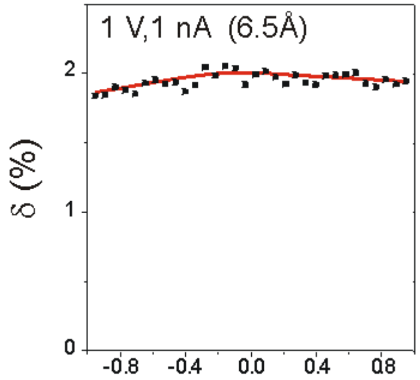
Theoretical models for bias dependence

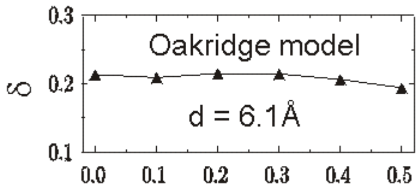
Insulator barrier	Vacuum barrier
• density of states effects	yes
• excitation of interfacial spins Zhang et al. PRL 79, 3744 (1997)	no
• magnon excitation Moodera et al. PRL 80, 2941 (1998)	yes
• impurity induced two-step tunneling Zhang, White, JAP 83, 6512 (1998)	no
• spin scattering caused by magnetic impurities Jansen, Moodera PRB 61, 9047 (2000)	no

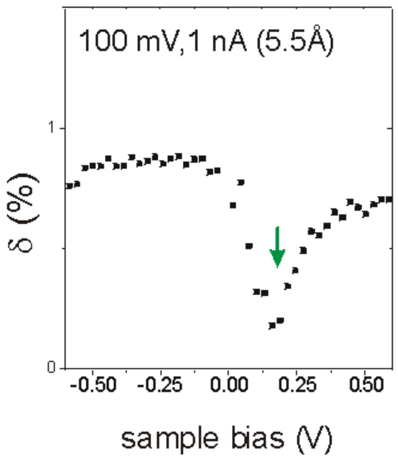




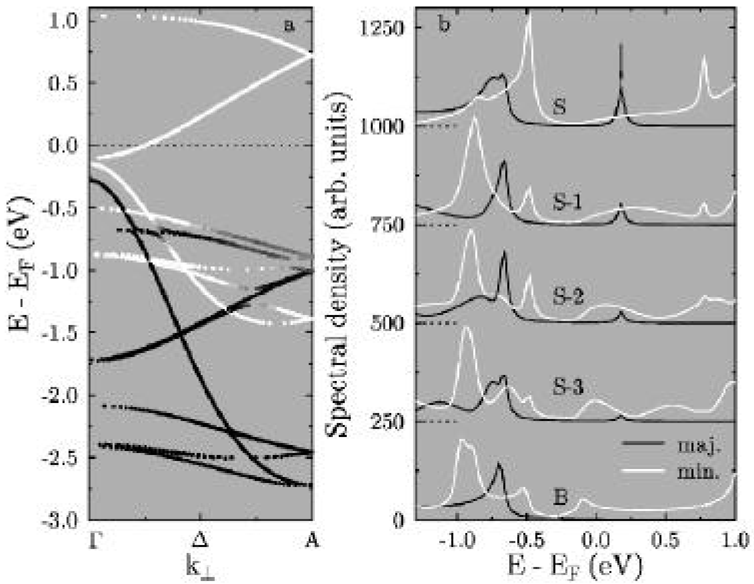
Sp-STM beyond magnetism : Co vac Co(0001) tunneling







Co(0001) band structure



positive bias
electrons from tip to sample
tip: Fermi energy
sample: half metallic empty states

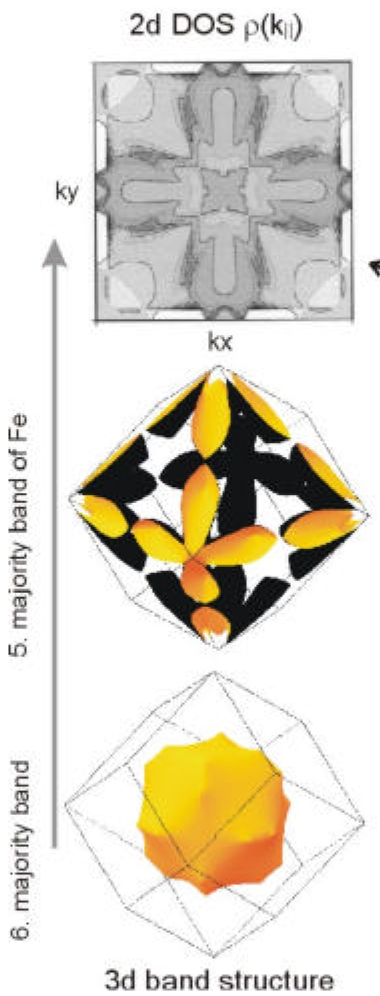
negative bias
electrons from sample to tip
sample: half metallic at Fermi energy
tips: amorphous, no sharp features

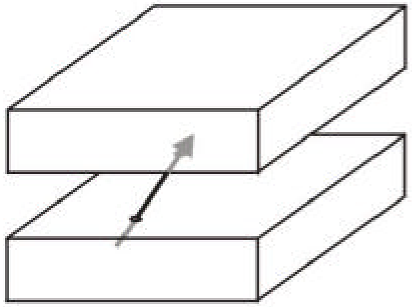
large separation: mainly states with $k_{||}=0$ are involved
small separation: states away from $k_{||}=0$ are also involved
tunneling via surface states

No significant magnon scattering observed in Co(0001)

Ding et al., PRL 90, 116603 (2003)

Ab-inito theory of spin-polarized tunneling





$$G = \frac{2\pi e^2}{\hbar}\sum_{k_\parallel} Tr\left[\rho_1(k_\parallel)T^{+}(k_\parallel)\rho_2(k_\parallel)T(k_\parallel)\right]$$

- ballistic theory : Bloch waves of one electrode scatter
  into Bloch waves of the second electrode
- transmission T through the barrier depends on in-plane momentum $k_{||}$
- maximum of transmission at the center of the Brillouin zone
- 2D DOS $\rho(k_{||})$ of both electrodes enter

MacLaren et al., PRB 59, 5470 (1999)