STM and spectroscopy of nanosized ferromagnetic structures

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Ferromagnetic nanostructures

- $L_{sample} \approx L_{exch} \approx L_{domain\ wall}$

$\Rightarrow$ monodomaine (Stoner-Wohlfarth switching ?)

Bonet,PRL 83, 4188 (1999)

- Temperature could overcome anisotropy $kT \approx KV$

$\Rightarrow$ superparmagnetism

Bean, JAP 30, 120S (1959)

Néel, Ann. Geopgys. 5, 99 (1949)

- Atoms with low coordination

$\Rightarrow K_{surface}$ or M could be very high

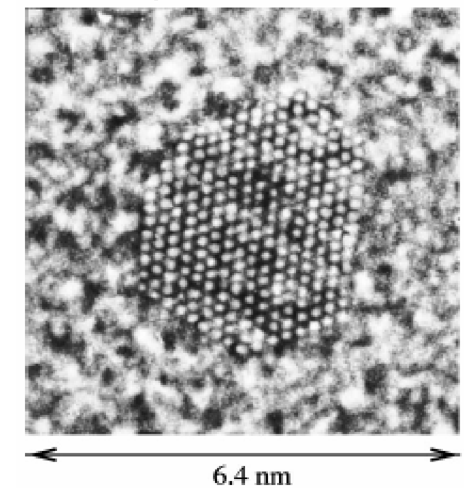
Gambardela, Science 300, 1130 (2003)

- Quantum effects (discrete states, collective tunneling)

Bernand-Mantel, APL 89, 062502 (2006)

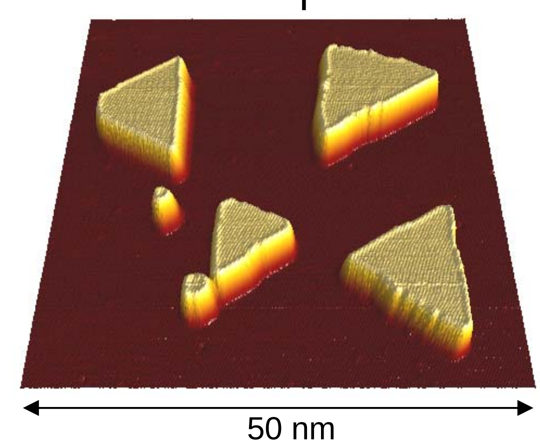
Wernsdorfer,PRL 79, 4014 (1997)

Gas phase nucleation



Jamet, PRB 69, 024401 (2004).

Thermal evaporation



Probing nanomagnetism

Imaging

See review Freeman, Science 294, 1484 (2001)

	Sensitive to	Typical resolution	Specificity
MOKE	M	500nm	Easy to use and cheap Argyle, JAP 87, 6487 (2000)
XMCD-PEEM	M	<10nm	Element specific, dynamic, synchrotron Vogel, PRB 72, 220402 (2005)
SEMPA	M	10nm	Vectorial M, surface Allenspach, JMMM 129, 160 (1994)
Lorentz	∇B	<10nm	Average over sample, no field Chapman, JMMM 200, 729 (1999)
MFM	∇B	50nm	Insulator OK, not quantitative Folks, APL 76, 909 (2000)
SP-STM	TMR	<1nm	No insulator, smooth surface, topography and spectro

Magnetometry

- SQUID, MOKE: thin films: OK

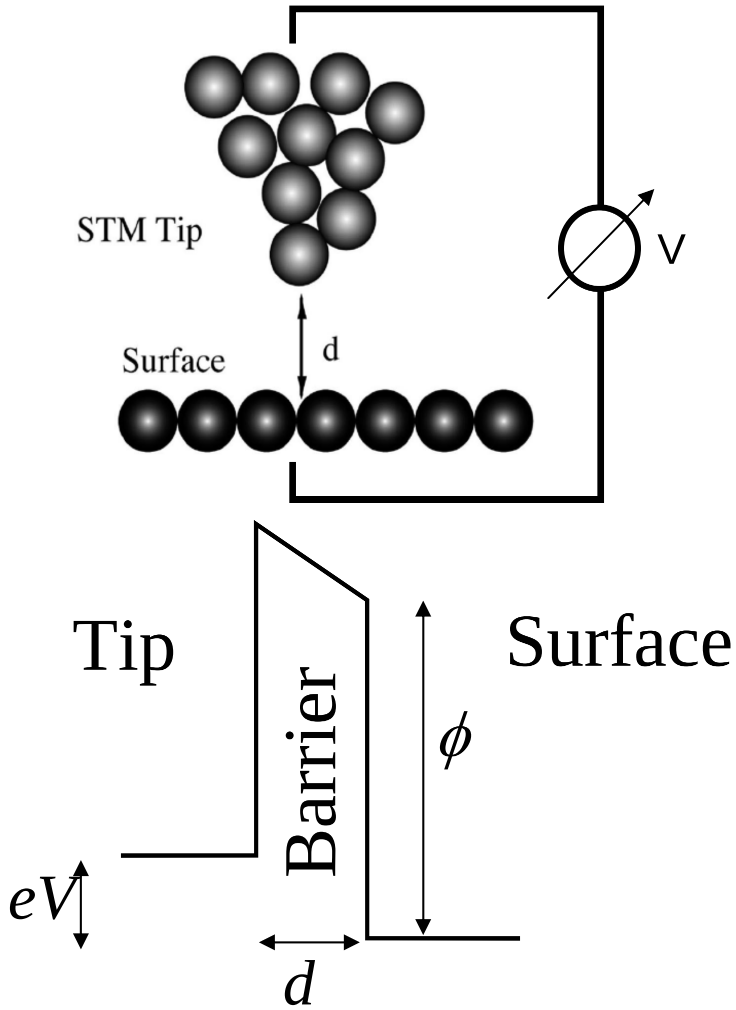
  nanoparticles : average over an assembly of identical objects Rohart, PRB 73, 165412 (2006)
- µ-SQUD: able to measure the switching field of a single nanostructure Jamet, PRB 69, 024401 (2004)

Spin dependant transport

Lithography allows to take contact up to 10~100nm

Bernand-Mantel, APL 89, 062502 (2006)
Ralph, PRL 74, 3241 (1995)

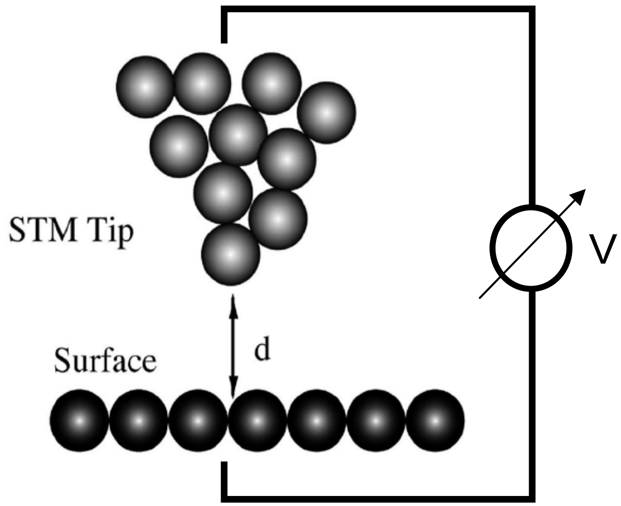
Scanning tunneling microscopy

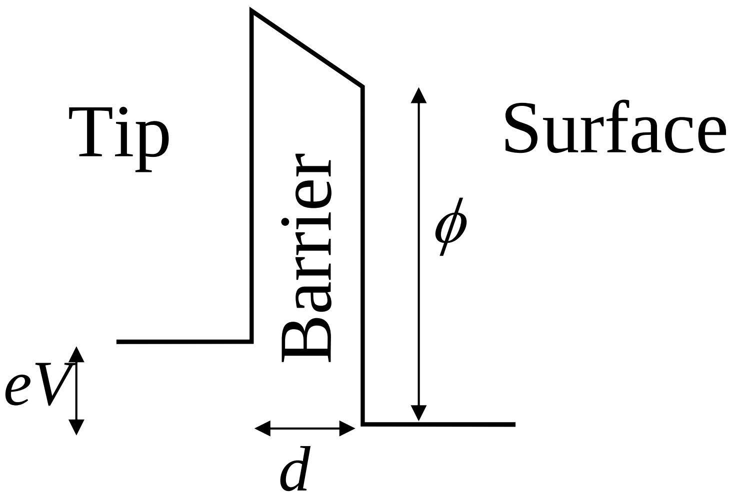


$$I_{tunnel} \propto e^{-d\sqrt{\phi - eV}}$$

Topography image a constant current

Scanning tunneling microscopy





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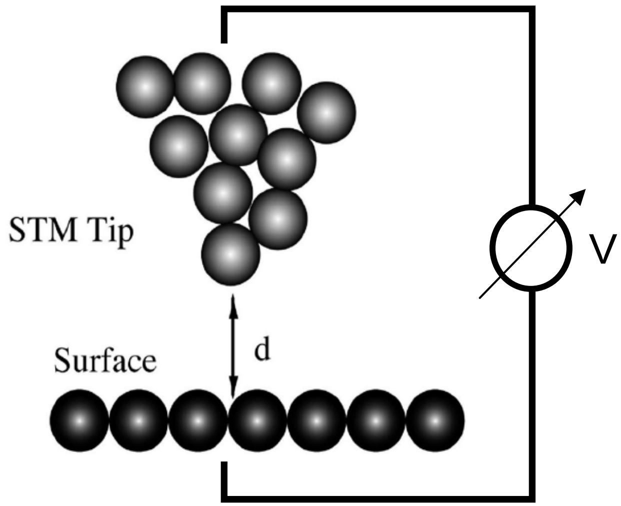

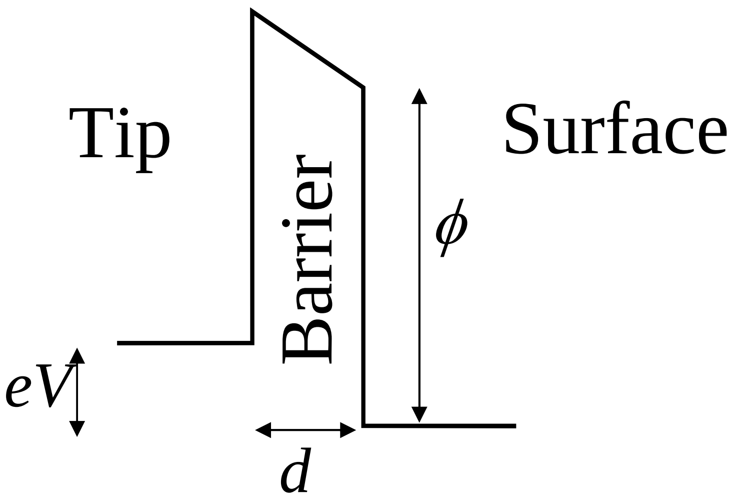

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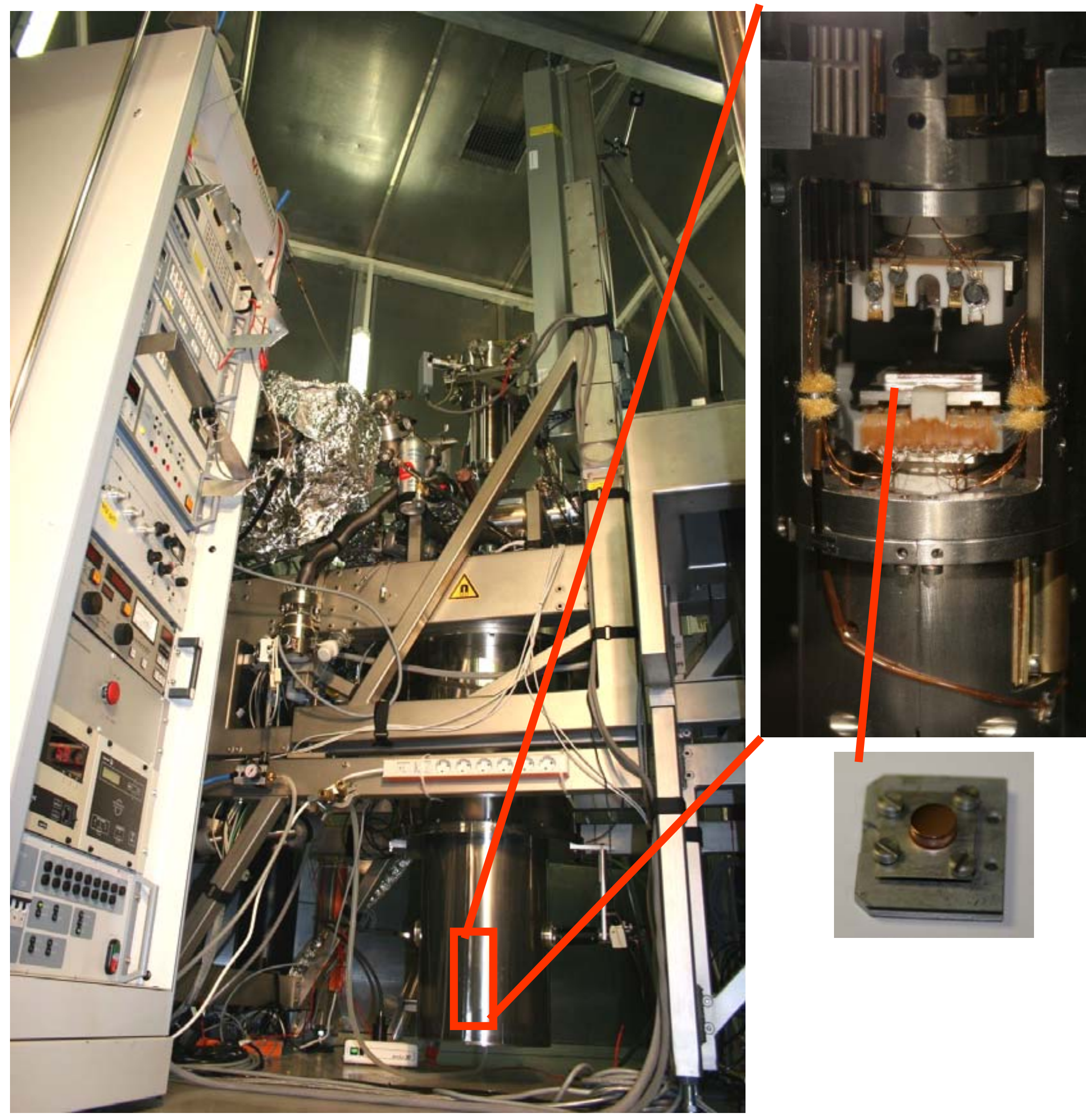
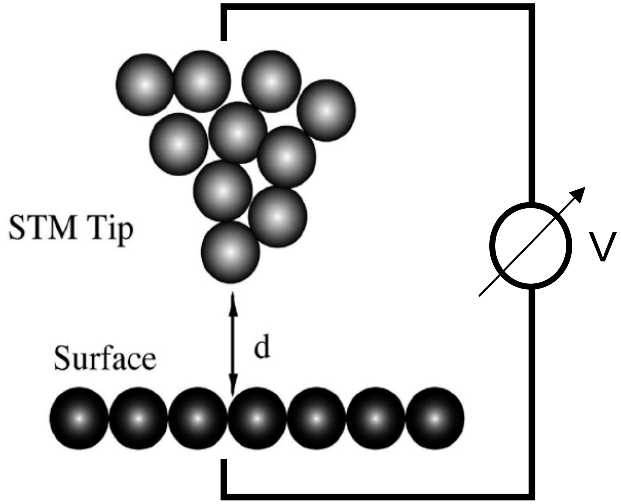
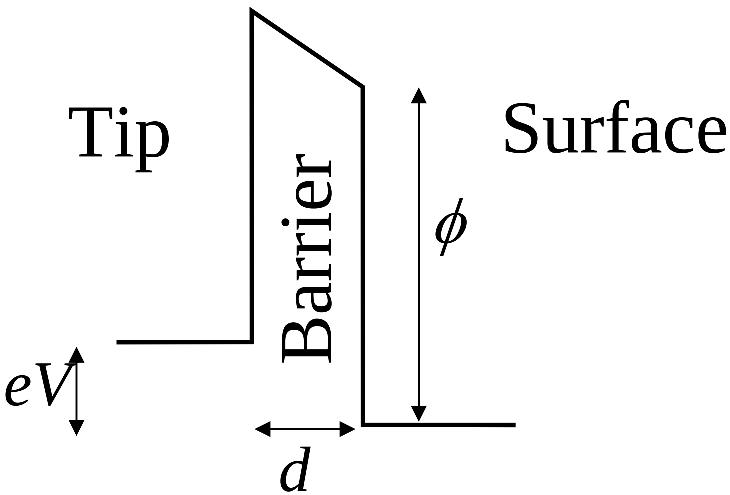


Topography image a constant current

Scanning tunneling microscopy





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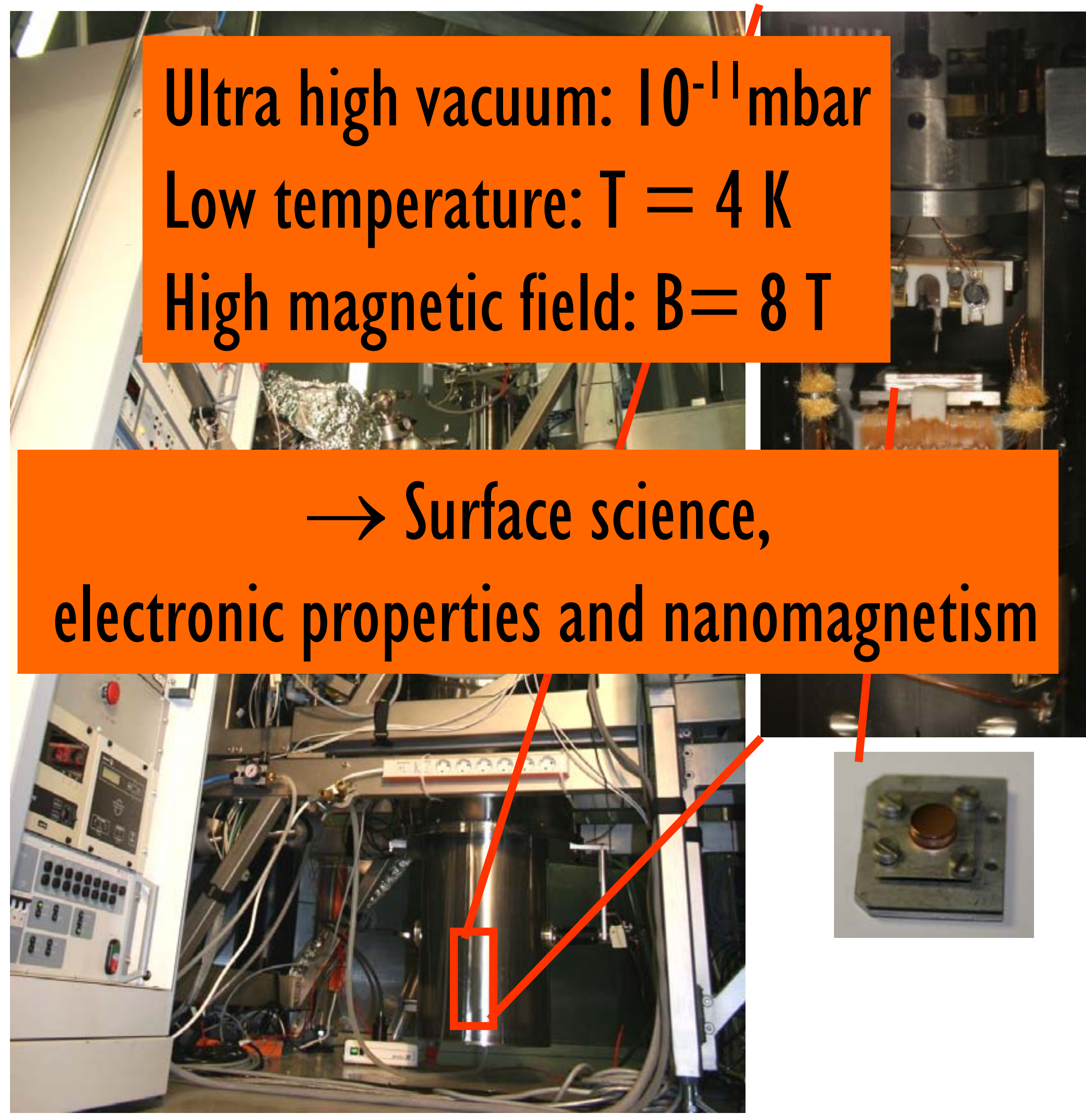


Ultra high vacuum: 10^{-11}mbar

Low temperature: T = 4 K

High magnetic field: B= 8 T

→ Surface science,

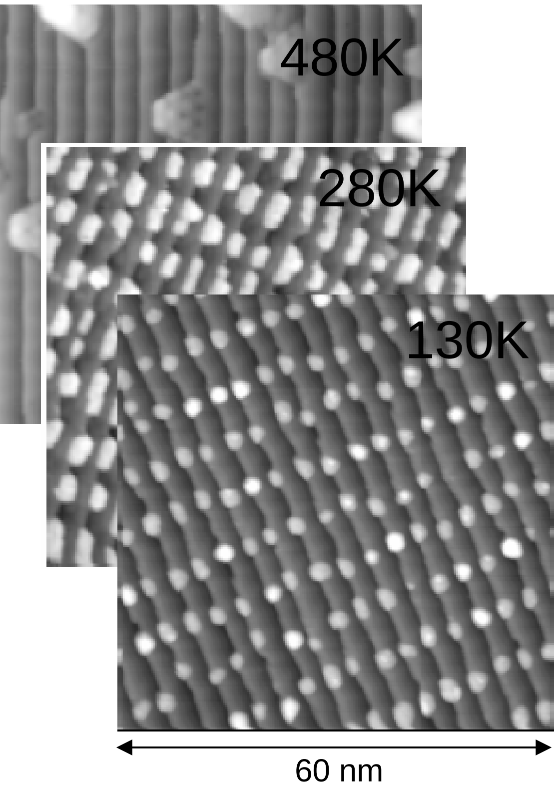
electronic properties and nanomagnetism

Growth of nanostructures studied by STM

Nanodots

Co/Au(788)

Repain, EPL 58, 730 (2002)

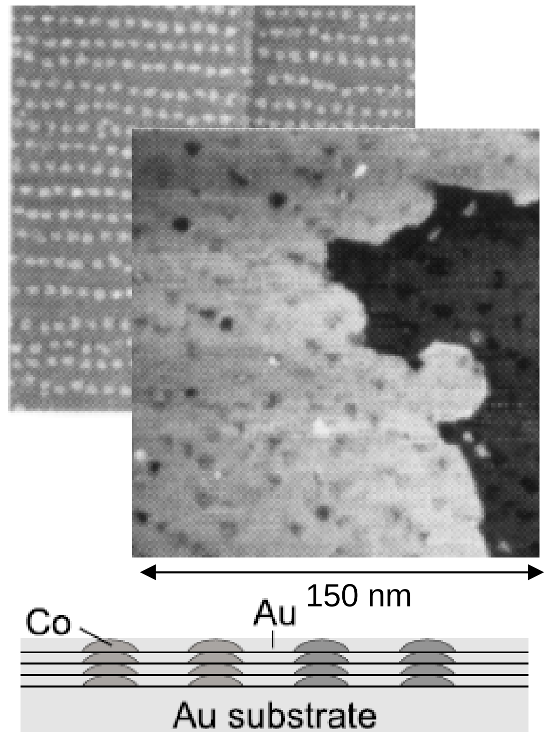


- Temperature growth ⇒ Diffusion coefficient + trap energy
- Periodical array of similar dots ⇒ Array = N x single dot

Nanopillars

Co/Au(111)

Fruchart, PRL 83, 2769 (1999)

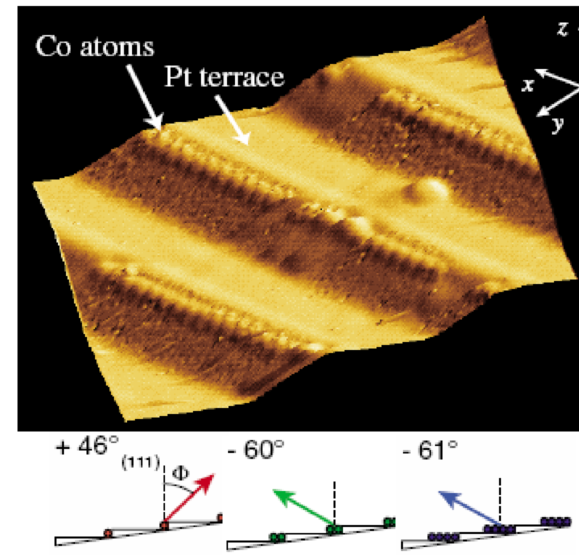


- 3D structures
- Aspect ration 2:1
- Blocking temperature: from 20 K to 300K

1D chains

Co/Pt(997)

Gambardella, JPhysCondMat 15, 2533 (2003)



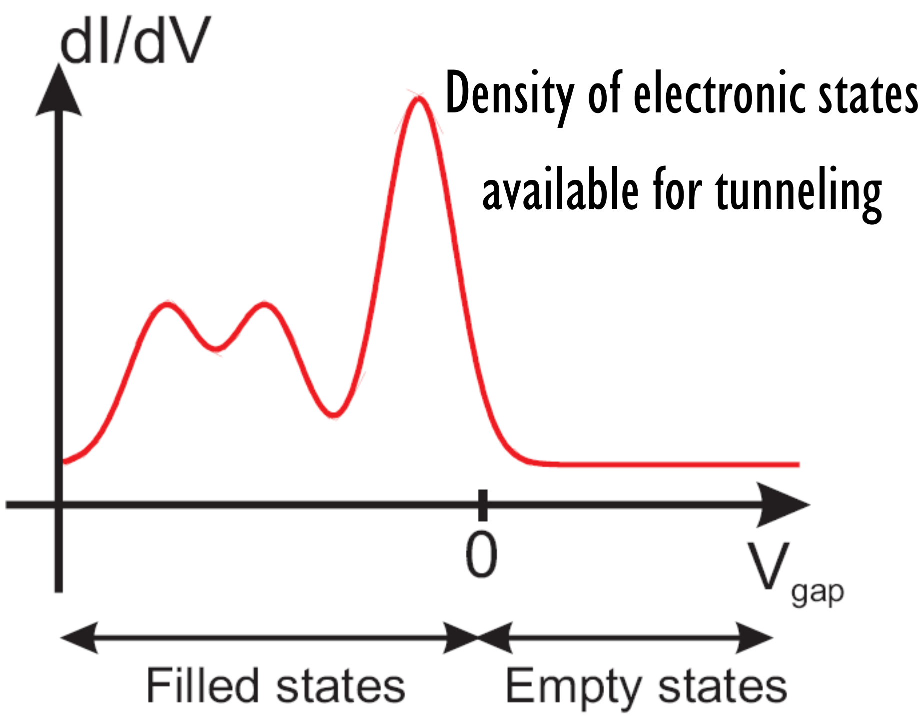
- Chains width of 1, 2 or 3 atoms
- Ferromagnetic behavior with very high magnetic moment
- Reduce dimensionality ⇒ strong magnetic anisotropy

Scanning tunneling spectroscopy

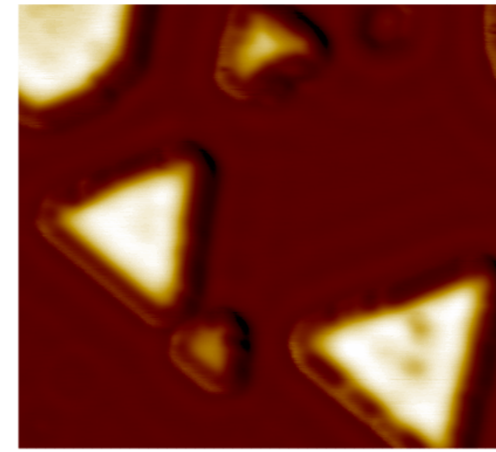
$$I(\mathbf{r})_{tunnel} \propto \int_0^{eV} \mathrm{LDOS}(\mathbf{r},\mathrm{E})\,\mathrm{d}\varepsilon$$

$$\mathrm{LDOS}(\mathbf{r},\mathrm{E}) = \sum_{\nu} |\psi_{\nu}(\mathbf{r})|^2 \delta(E - E_{\nu})$$

$$\frac{\mathrm{d}I}{\mathrm{d}V}(\mathbf{r},E) \propto \mathrm{LDOS}(\mathbf{r},\mathrm{E})$$

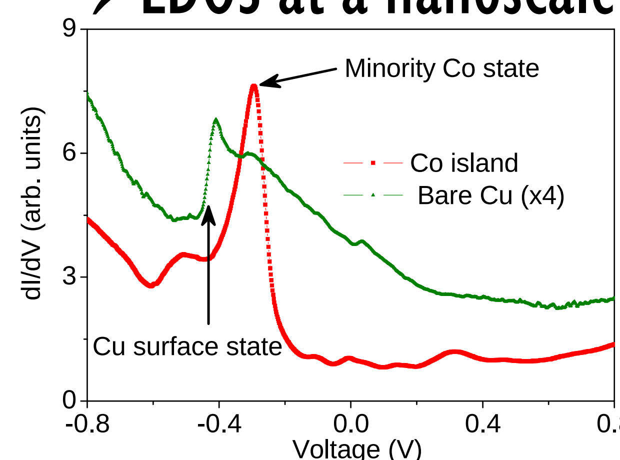


LDOS map
→ Electronic structures



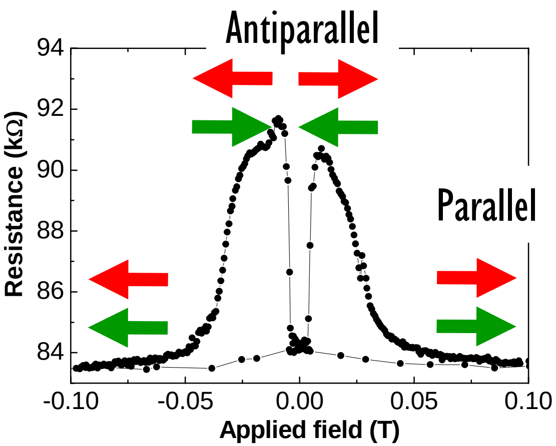
Co on Cu, 40x40nm

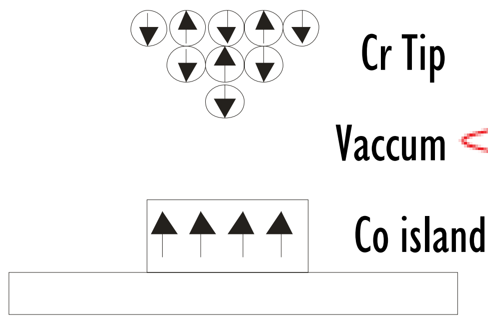
Point spectroscopy
→ LDOS at a nanoscale

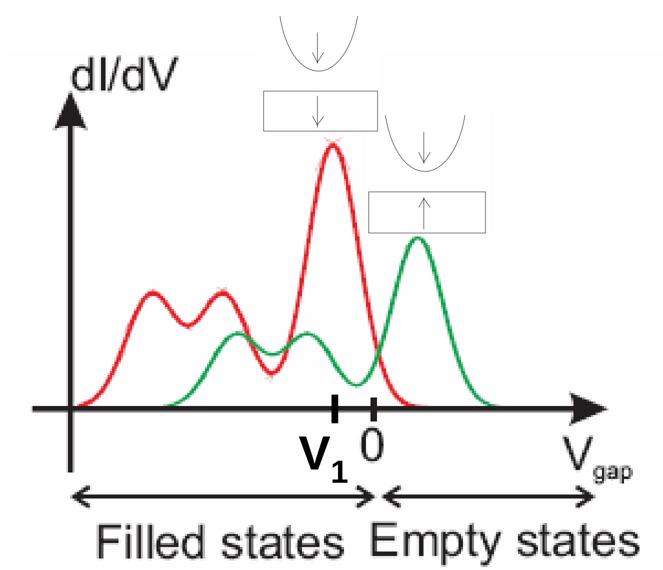


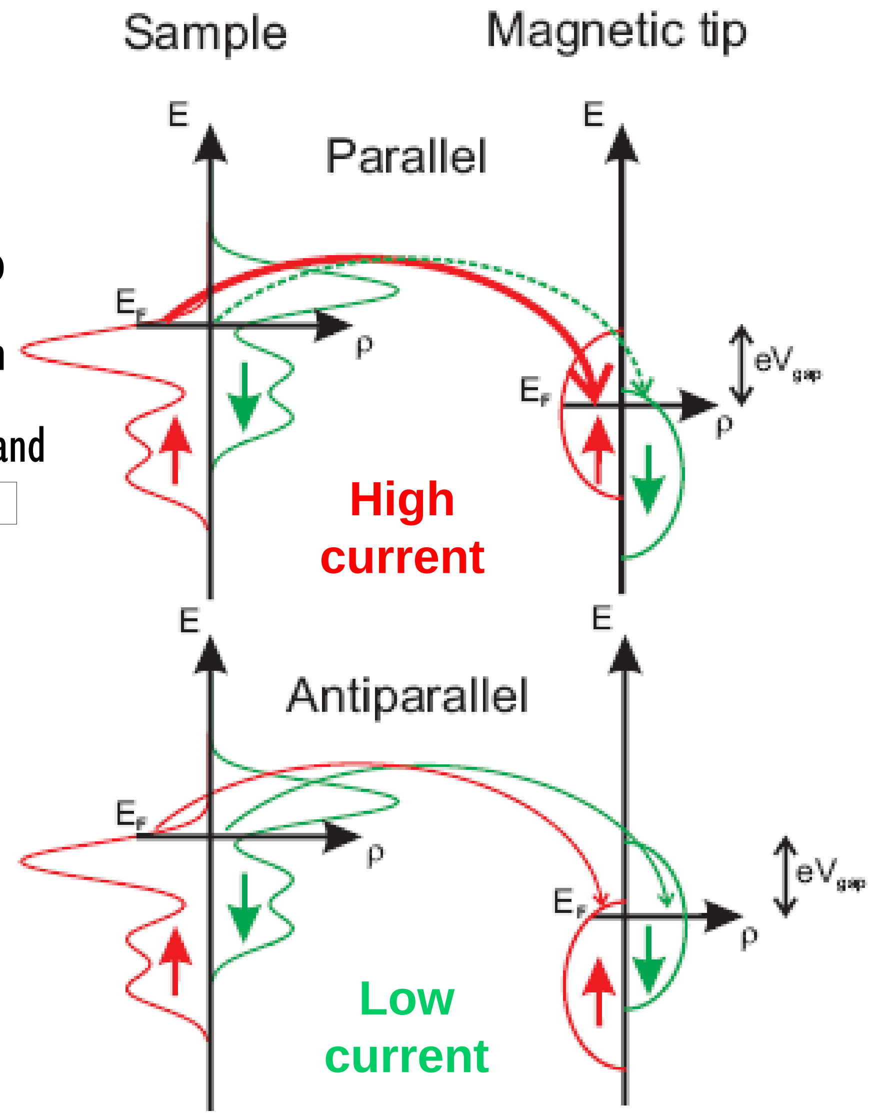
Principle of Spin-Polarized STM

Magnetic tunnel junction with vacuum









Bode, Getzlaff, Wiesendanger, Phys. Rev. Lett. 81, 4256 (1998).

Wulfhekel, Kirschner, Appl. Phys. Lett. 75, 1944 (1999)

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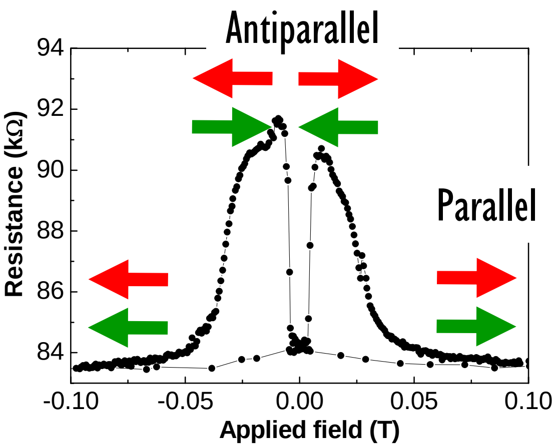

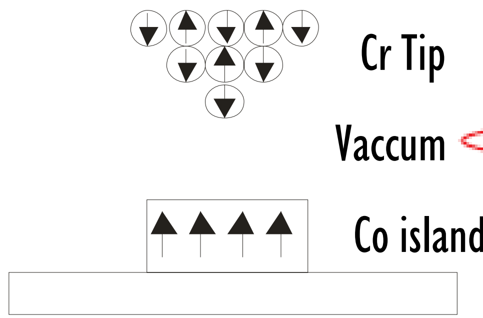

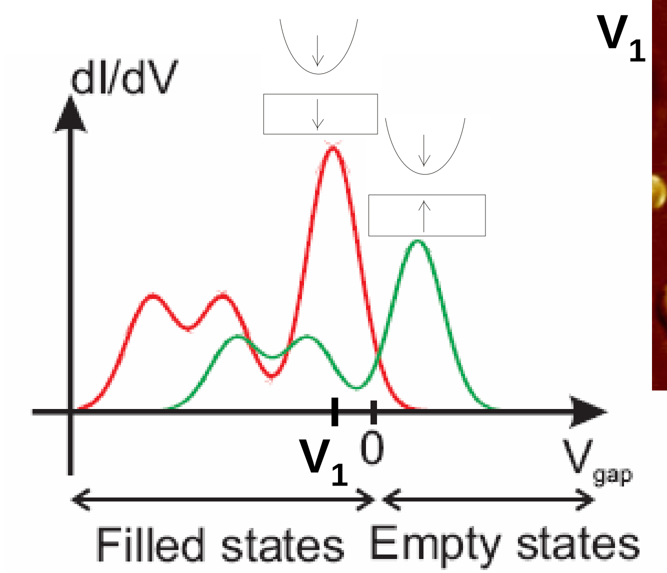

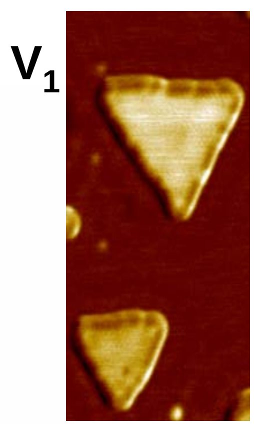

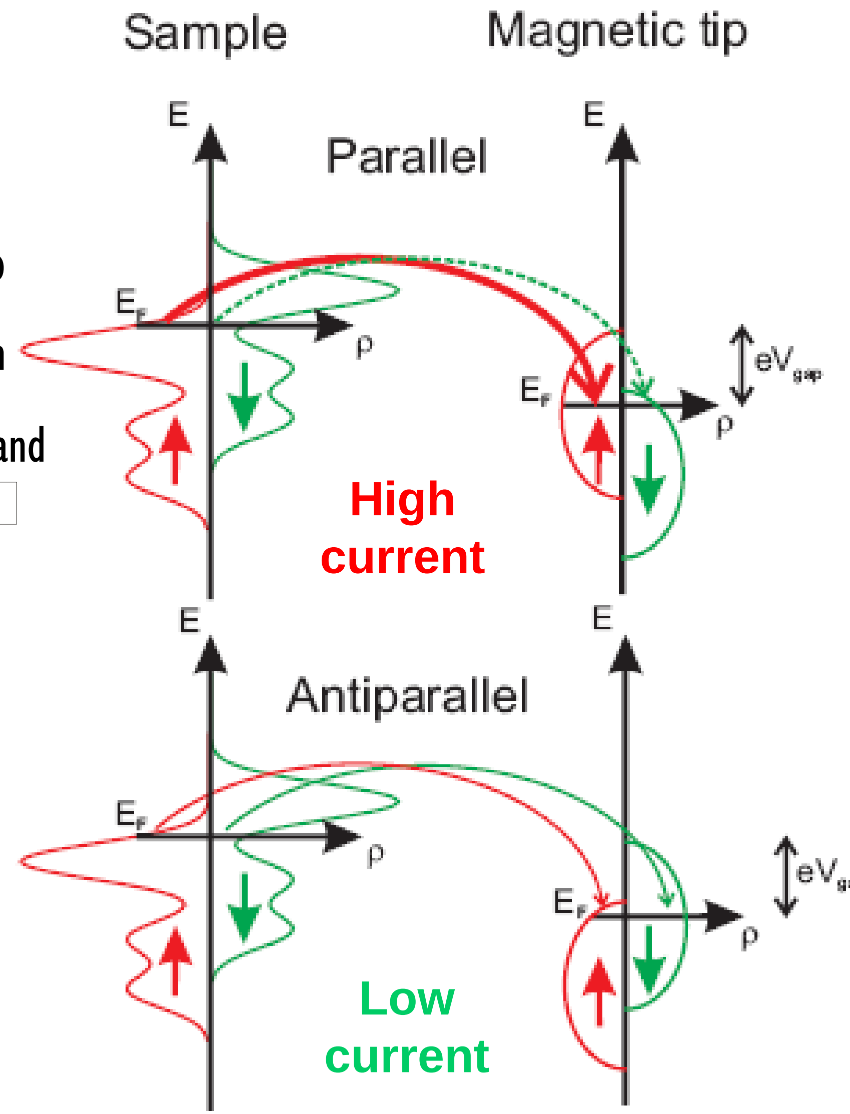

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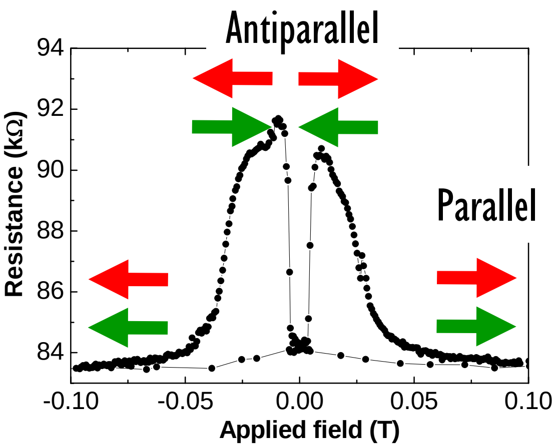
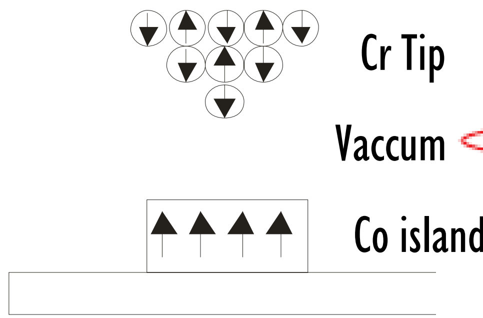
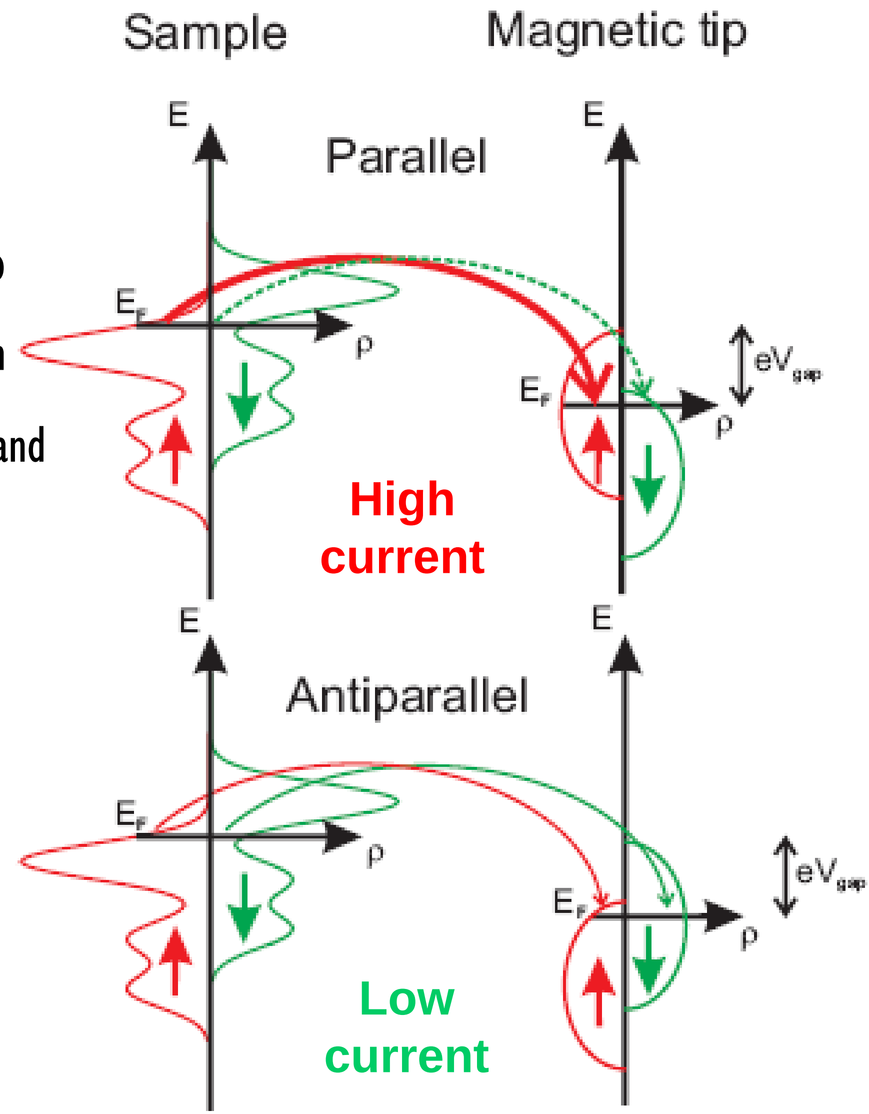
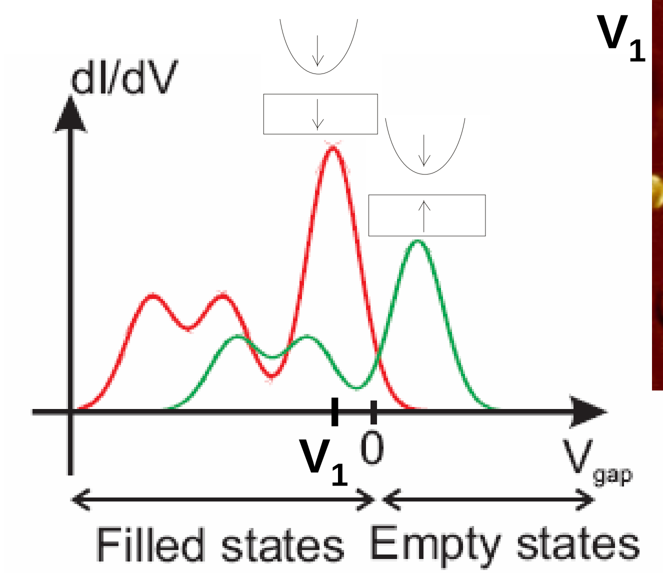
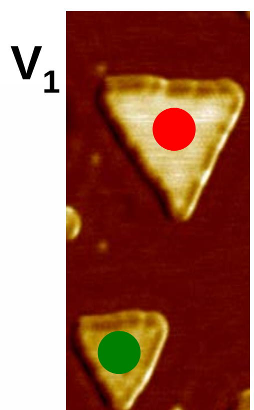










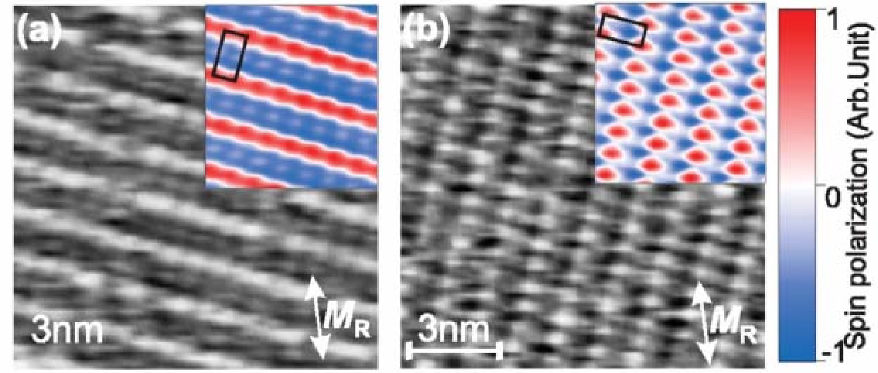
Bode, Getzlaff, Wiesendanger, Phys. Rev. Lett. 81, 4256 (1998).

Wulfhekel, Kirschner, Appl. Phys. Lett. 75, 1944 (1999)

Nanomagnetism: imaging of spin structure

- "Spin maps" made at constant current and at fixed voltage
- Spin sensitivity of the tip in or out of plane

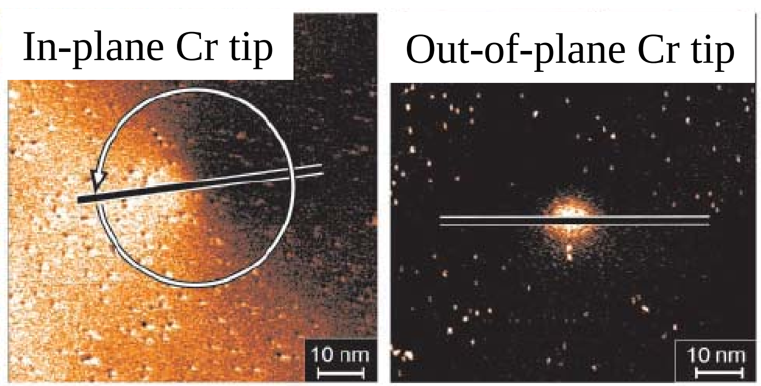
Magnetic surface reconstruction



1ML of Mn on Fe(001)

Gao, PRL 98, 107203 (2007))

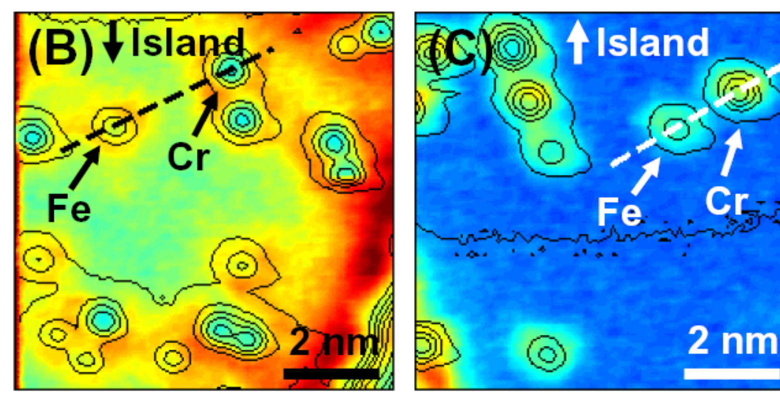
Magnetic nanostructures



Vortex in Fe island on W(110),

Wachoviak, Science 298, 577 (2002)

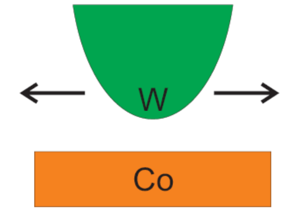
Single magnetic atoms



Atoms on Co islands

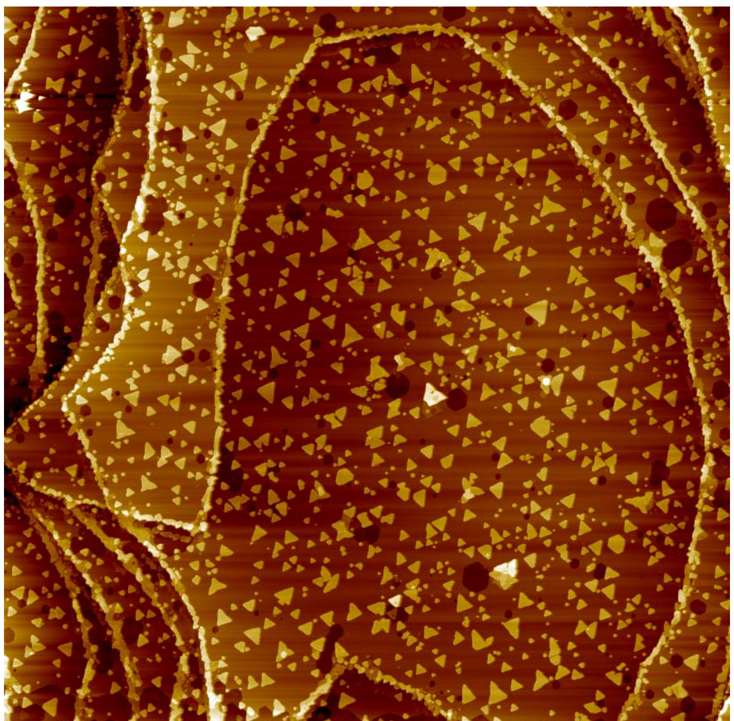
Yayon, PRL 99, 067202 (2007)

Co island on Cu(111)



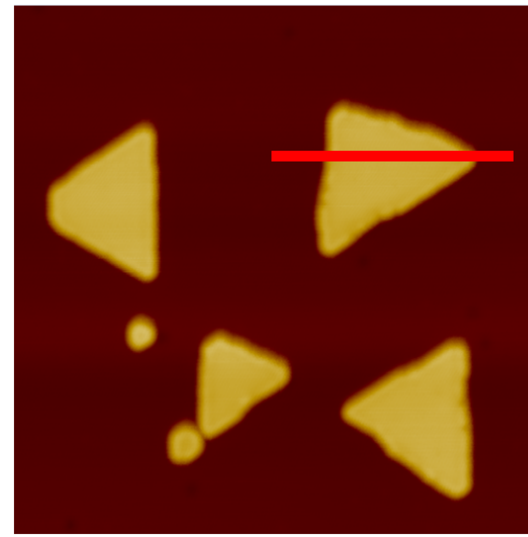
Co deposition at 300K on Cu(111)

⇒ Step edge decoration

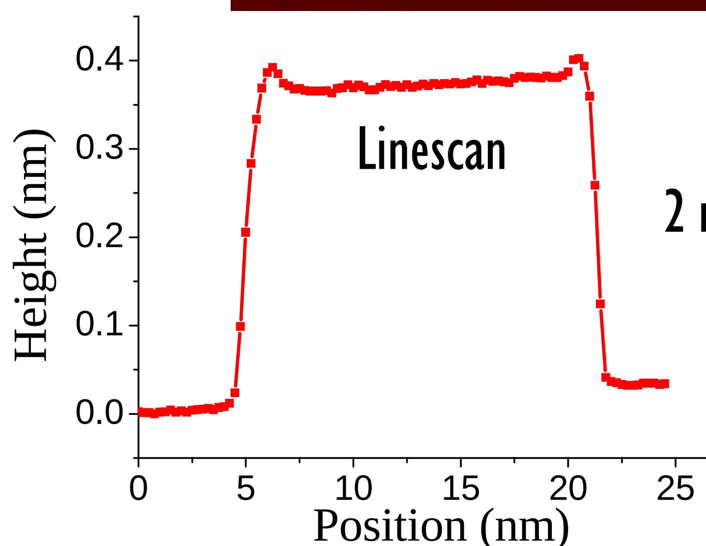


750 x 750 nm², -0.8 V, 1 nA

⇒ Triangular Co islands

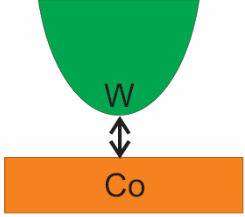


50 x 50 nm², -0.36 V, 1 nA

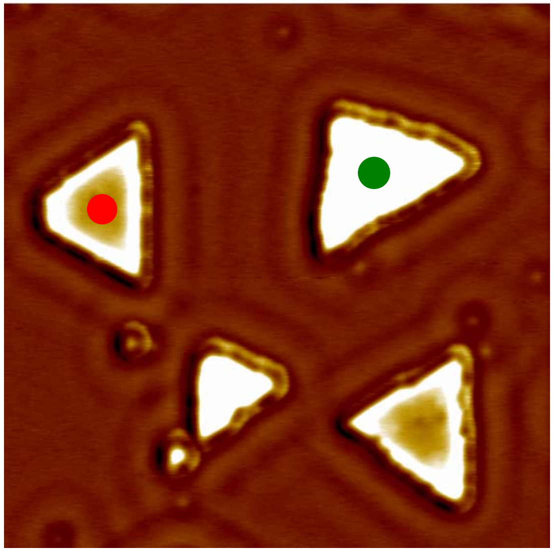


2 monolayer high island

Spectroscopy on a single island

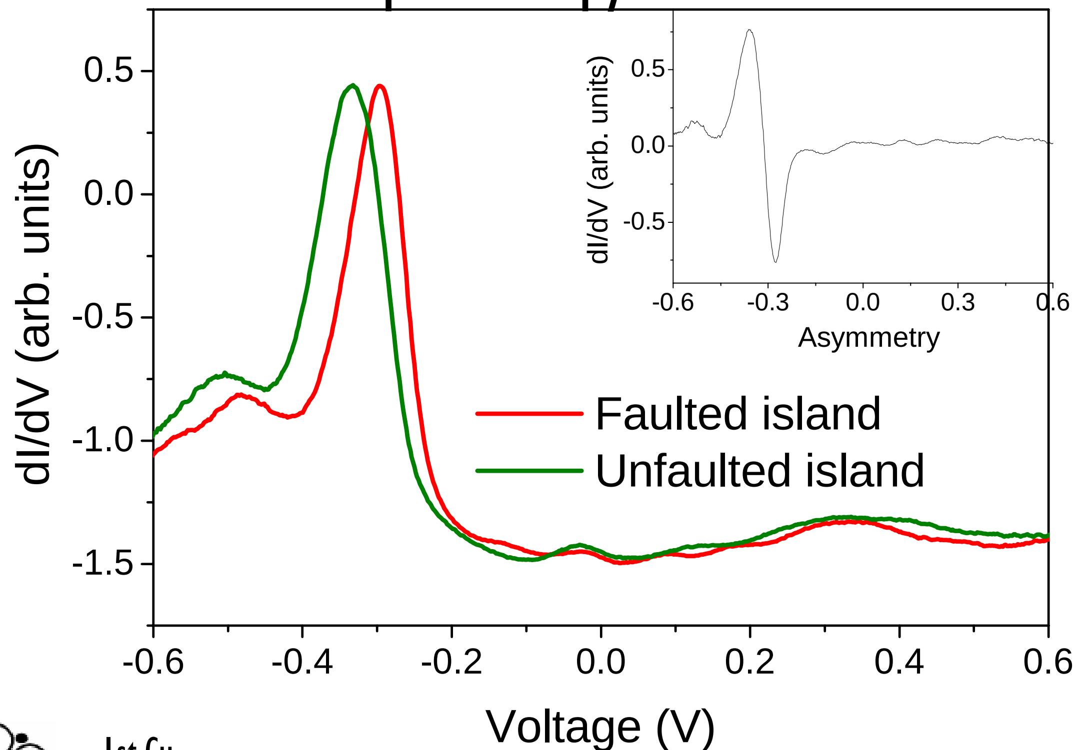


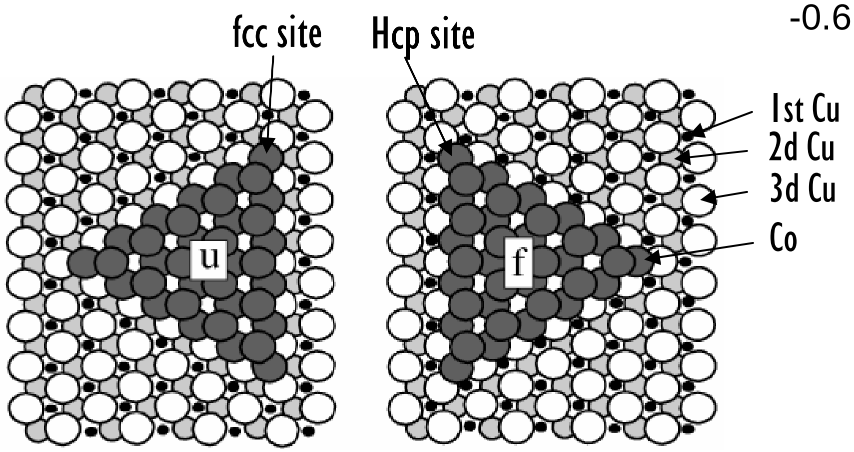
dI/dV image

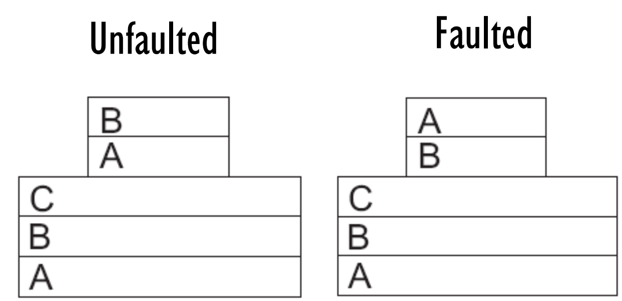


50 x 50 nm^2, -0.36 V, 1 nA

Point spectroscopy on the island



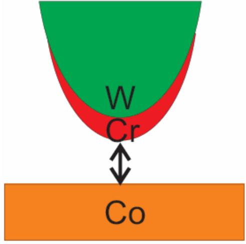




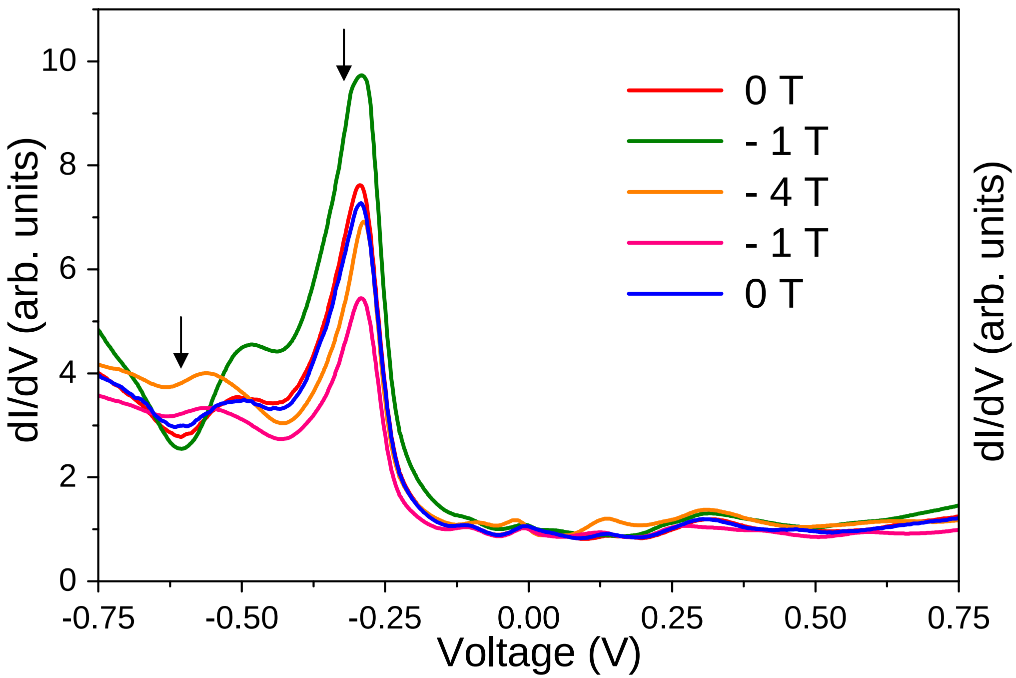
Vazquez de Parga, Garcia-Vidall, Miranda, PRL 85, 4365 (2000) and Pietzsch, Kubtzka, Bode, Wiesendanger, PRL 92, 057202 (2004)

Spectroscopy on a single island

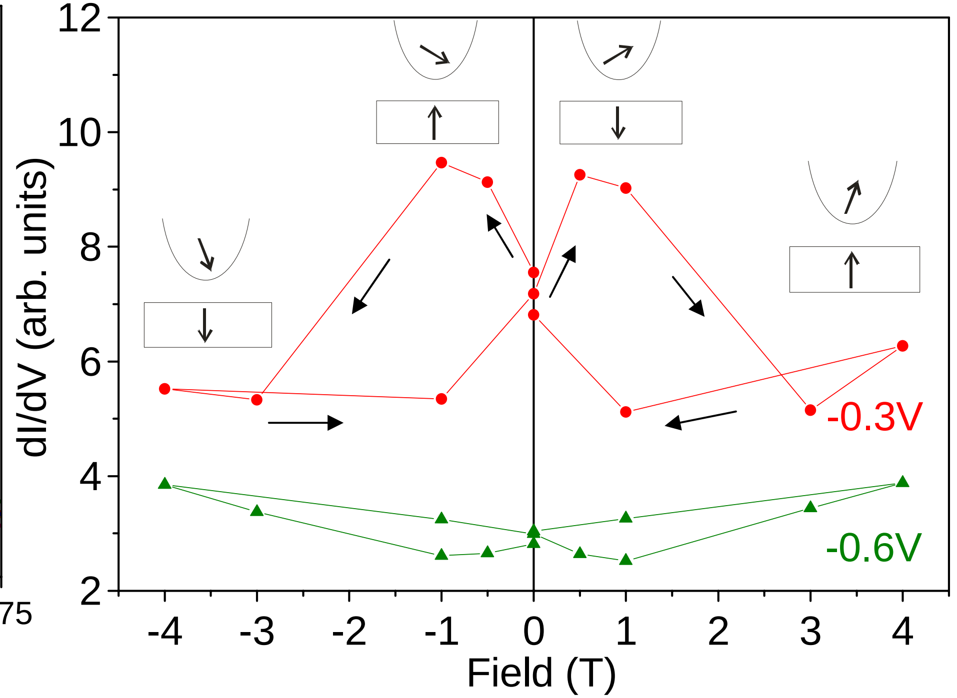
I(V) and dI/dV(V) curves measured at island center



In field spectroscopy

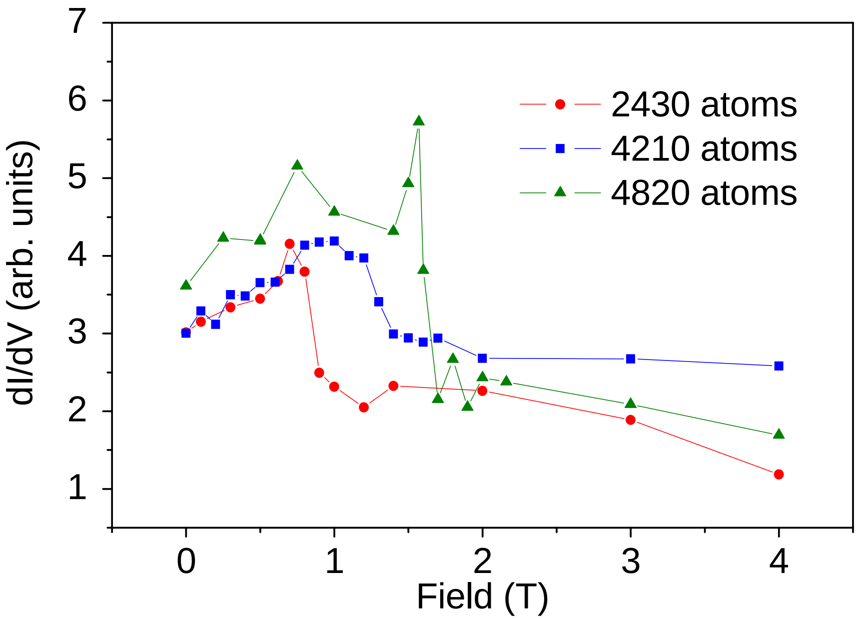


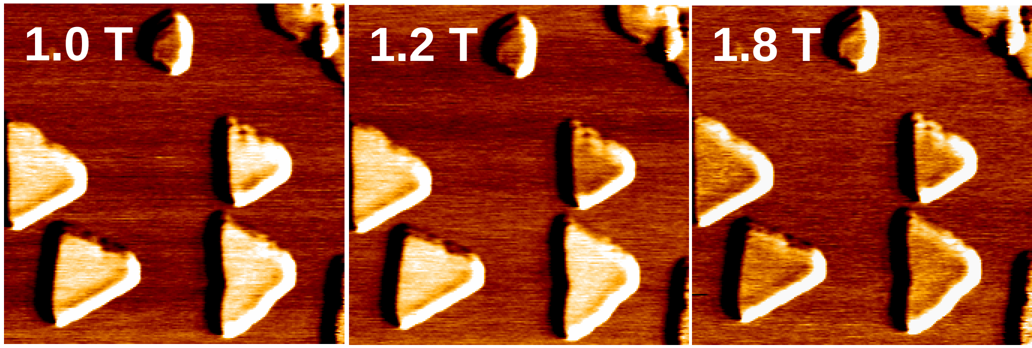
Extraction of the hysteresis cycle at different voltages

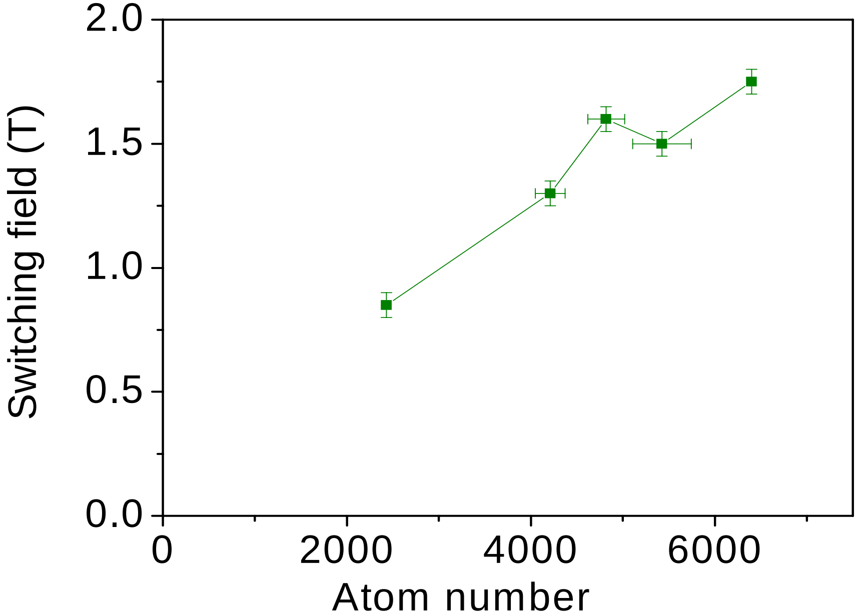


- TMR hysteresis loop of a single nanostructure
- Understanding the relative magnetic orientation of tip and sample
- Measure the TMR at a nanoscale

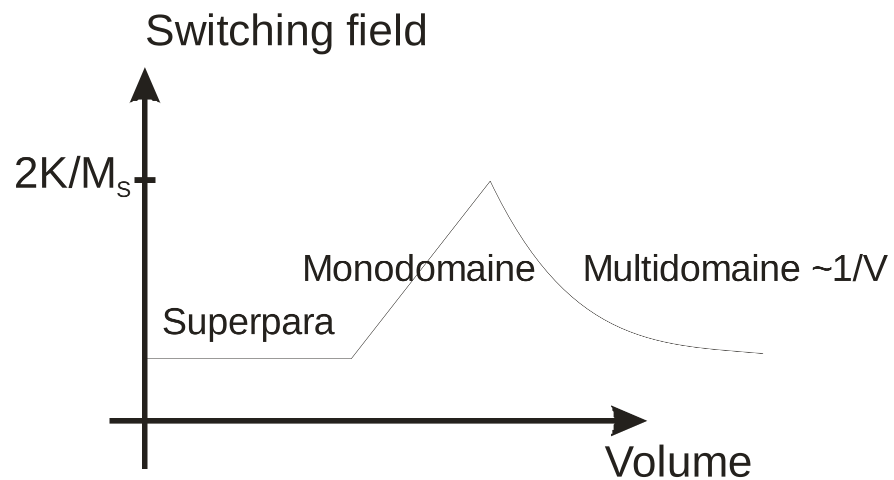
Size dependence of the switching field



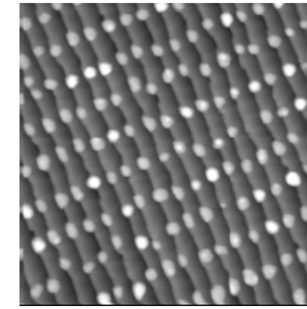




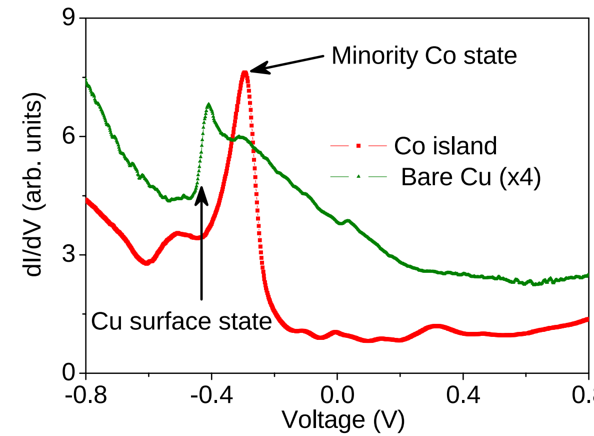
Regime between superparamgnetism and multi-domain island



Conclusion

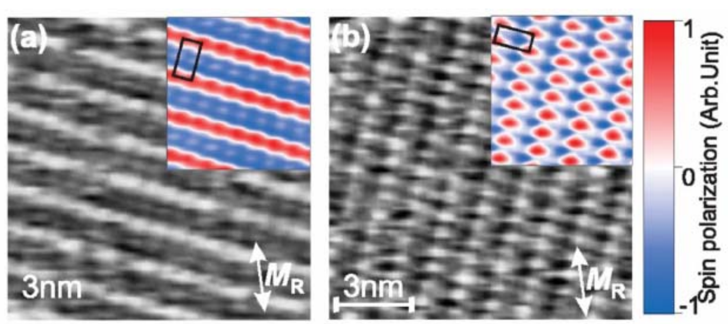


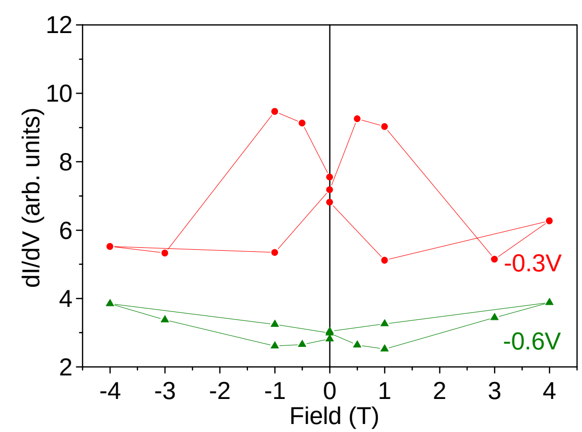
- STM: study of growth, structure and organization of ferromagnetic nanostructures (films, dots, pillars, chains…)

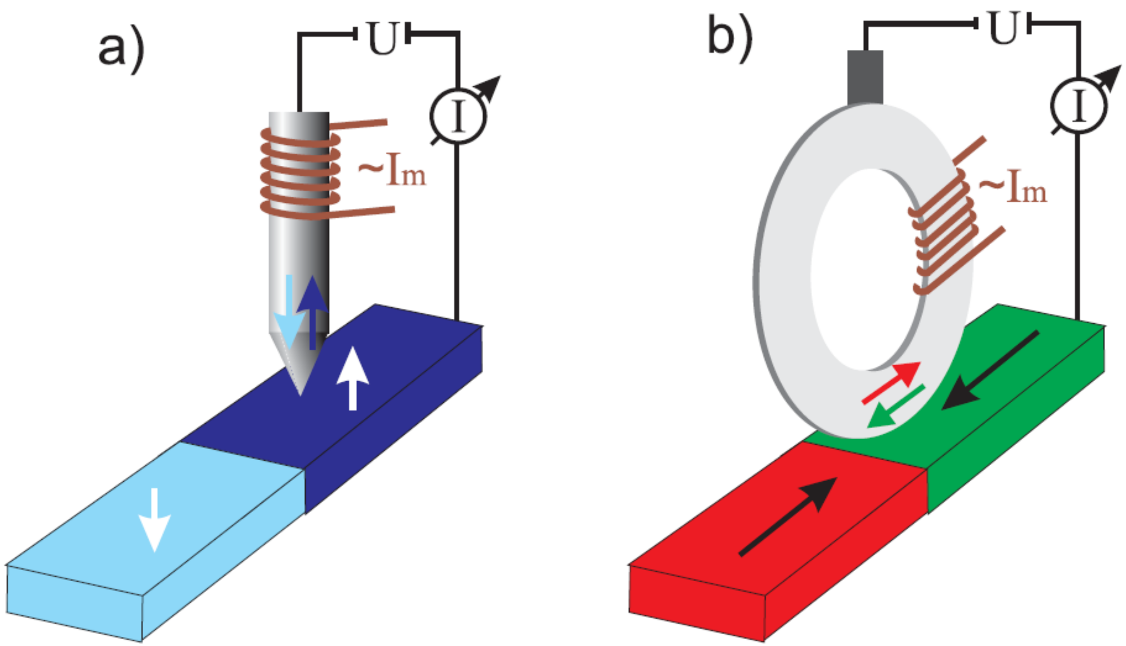


- STS: - mapping of the electronic structure (standing waves)
  - locales density of states on nanostructures
  - structure caracterisation

- SP-STM: - spin map in and out of plane with atomic resolution
  - spin dependant transport (TMR) at a nanoscale
  - study of switching of a single nanoobject






a)
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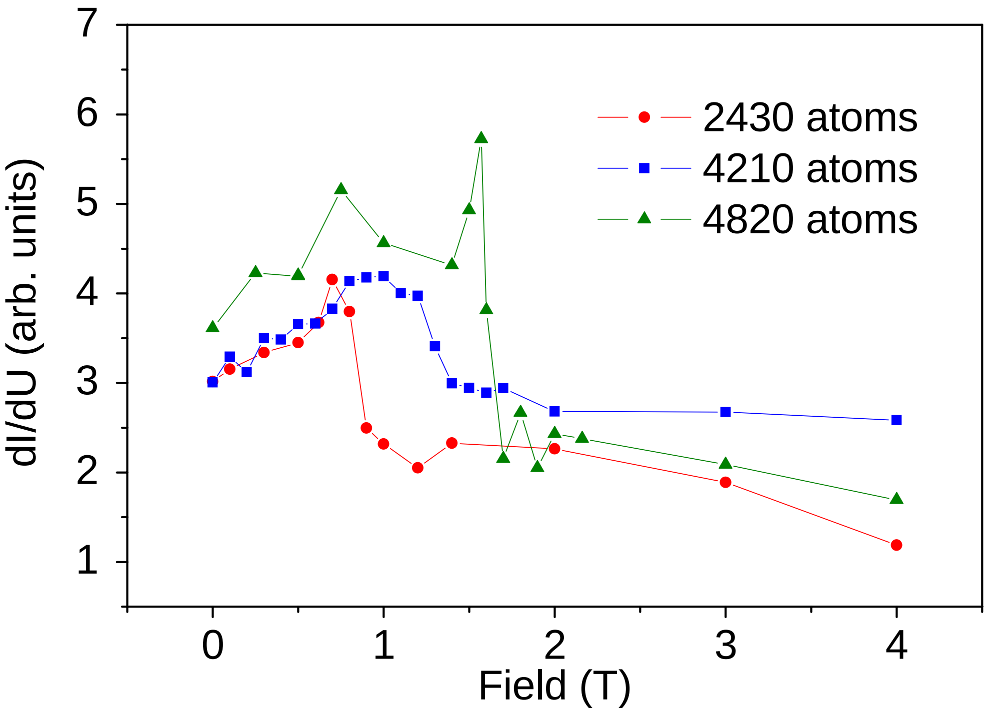
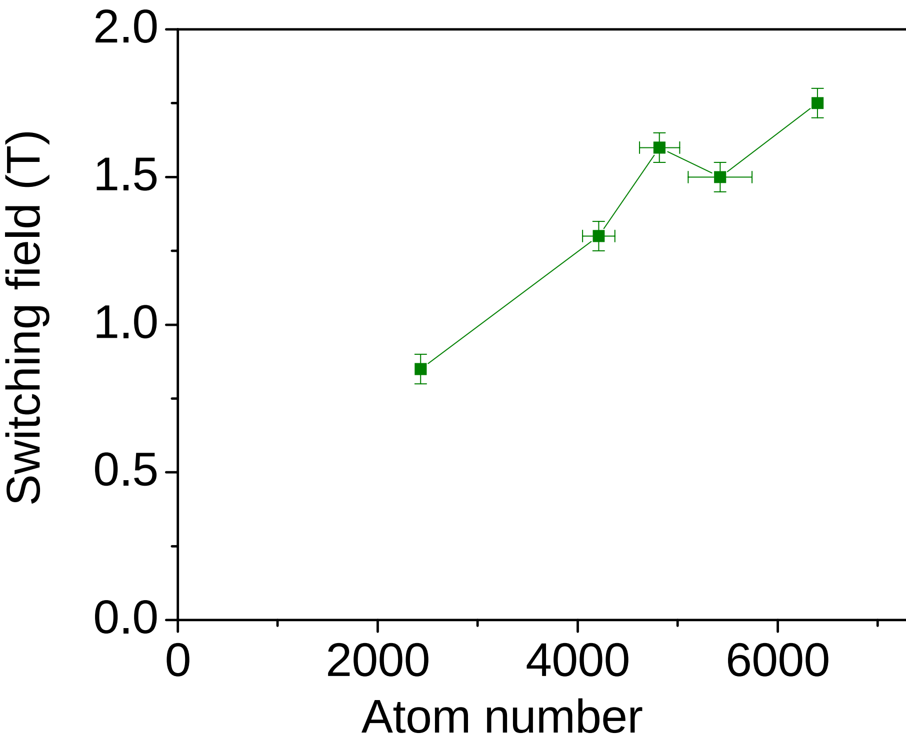
Size dependence of the island switching field





Observation of Magnetic Hysteresis at the Nanometer Scale by Spin-polarized Scanning Tunneling Spectroscopy

O. Pietzsch, A. Kubetzka, M. Bode, R. Wiesendanger, Science 292, 2053 (2001)

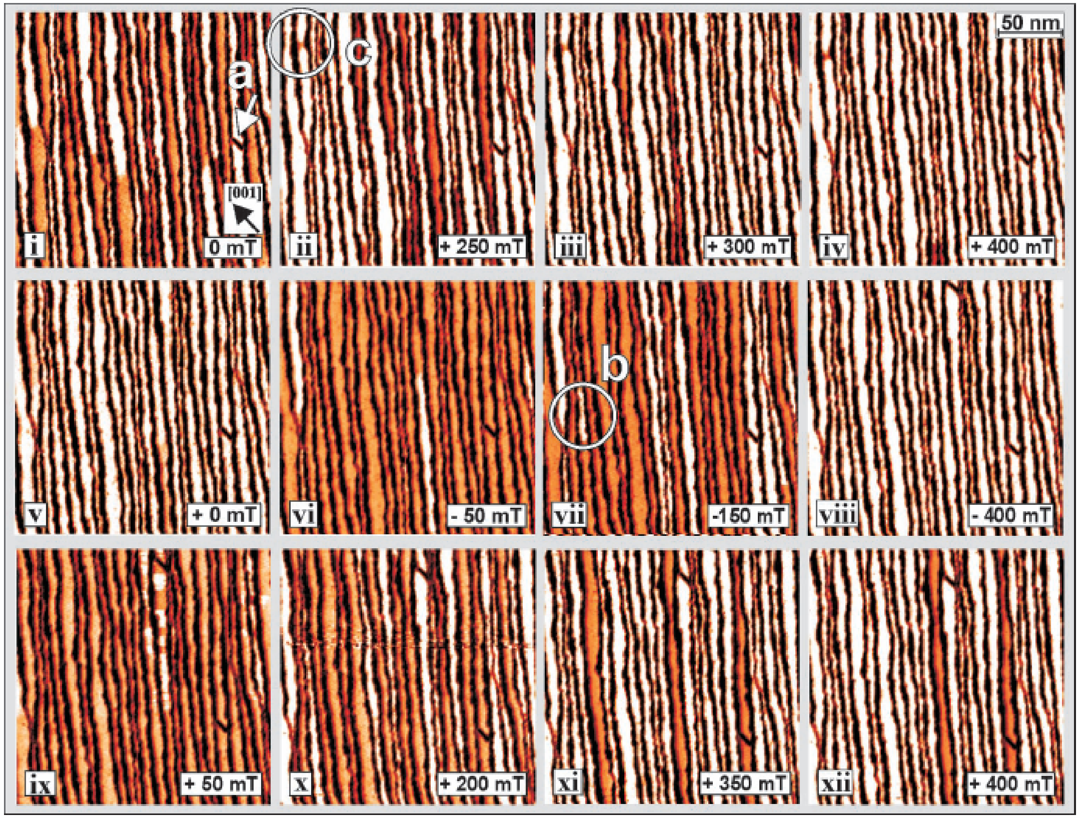


Fig. 1. Twelve images selected from a series of 24 taken at field values as indicated (*17*). Scan range is 200 nm by 200 nm. Because of the growth conditions (see text), a system of alternating ML and DL Fe stripes emerges on the W terraces. When measured with a ferromagnetic probe tip with perpendicular anisotropy, DL stripes show a two-stage contrast in the conductance map. It arises from the out-of-plane magnetization of DL stripes, being either parallel or antiparallel to the tip magnetization (spin valve effect). As a guide to the eyes, a dislocation line (a) is marked. Dark domains progressively vanish as positive field increases, and at saturation, only bright domains remain. High remanence is observed. A small negative field of −50 mT is sufficient to switch the tip magnetization whereas the sample stays almost unaffected. A contrast reversal results [compare (v) and (vi)]. At negative saturation, all stripes are once again bright (viii). Circles (b) and (c) refer to the enlarged views given in Figs. 3 and 4. Tunneling parameters: $I = 0.5$ nA, $U = +700$ mV.

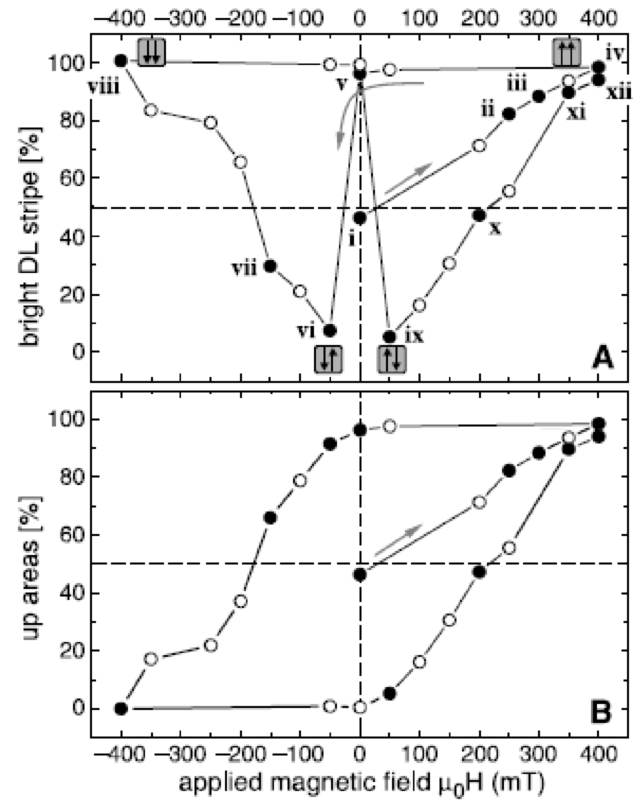
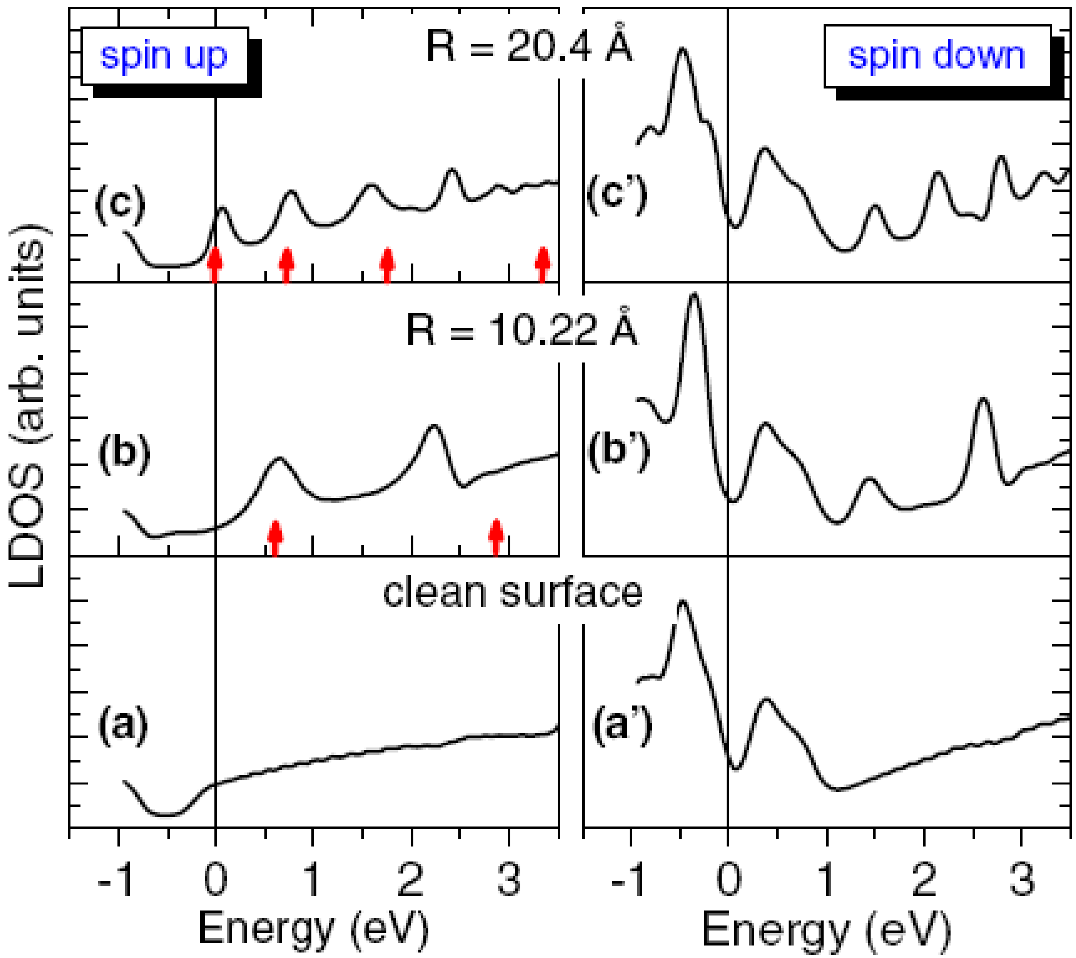


Fig. 2. Hysteresis curves obtained from the distribution of bright domains (A) and stripes with $+z$ magnetization (↑) (B). The butterfly curve in (A) shows properties of the complete tunneling junction consisting of two ferromagnetic electrodes, whereas the curve in (B) displays only sample properties. Arrow symbols in (A) indicate the relative alignment of tip and sample magnetization. Roman numbers at solid circles correspond to the images shown in Fig. 1.

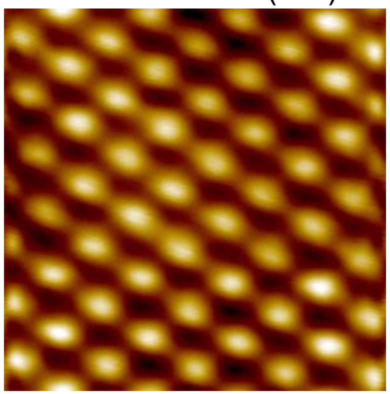
L. Niebergall, V. S. Stepanyuk, J. Berakdar, and P. Bruno, PRL 96, 127204 (2006)



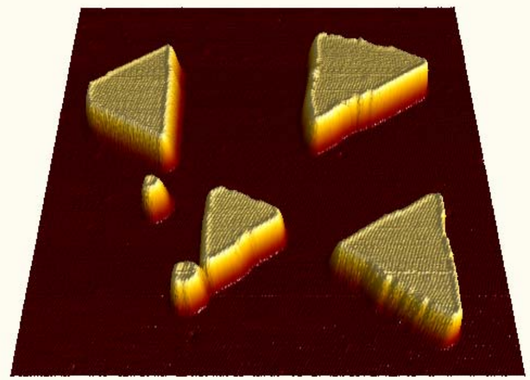
Introduction: context of SP-STM

Surface Science
Scanning tunneling microscope

Atomic resolution Cu(111), 2x2nm

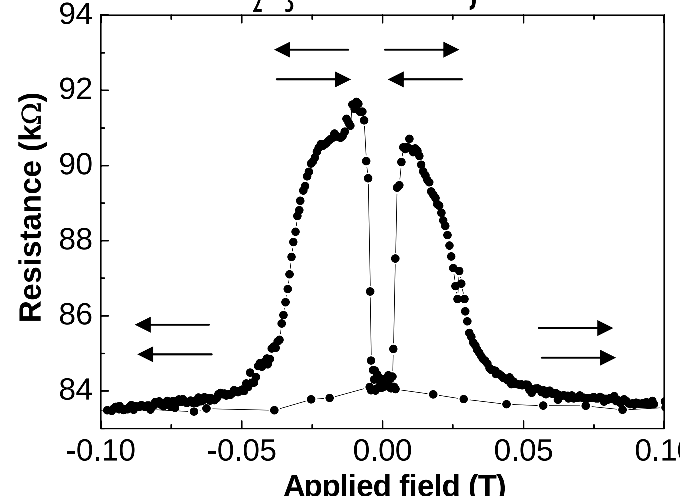


Co nanostructure on Cu(111) 50x50nm

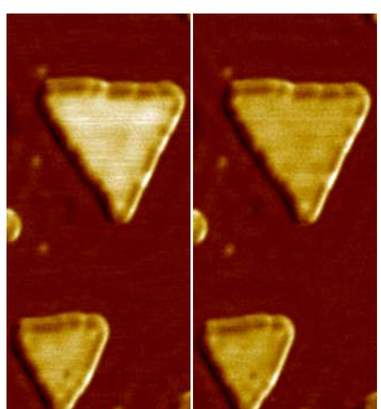


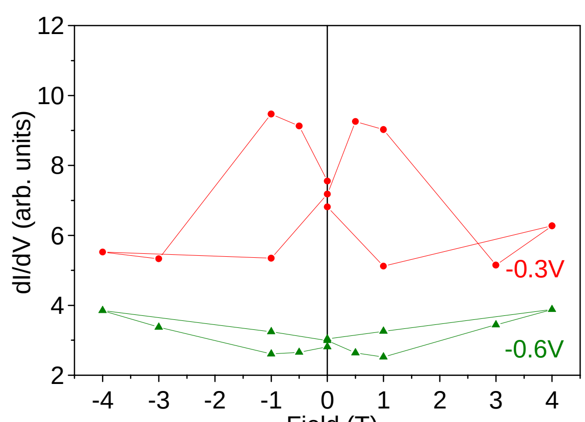
Spintronic
Tunnel Magnetoresitance

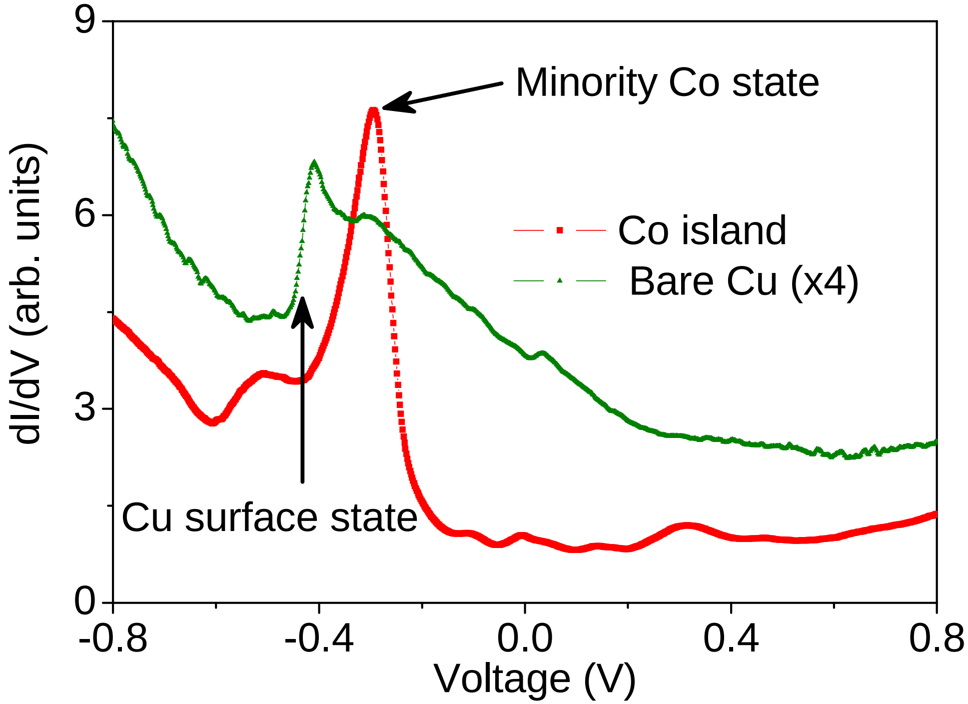
$Co/Al_2O_3/NiFe$ tunnel junction



Spin-polarized STM







Minority Co state
Co island
Bare Cu (x4)
Cu surface state
dI/dV (arb. units)
Voltage (V)
9
6
3
0
-0.8
-0.4
0.0
0.4
0.8

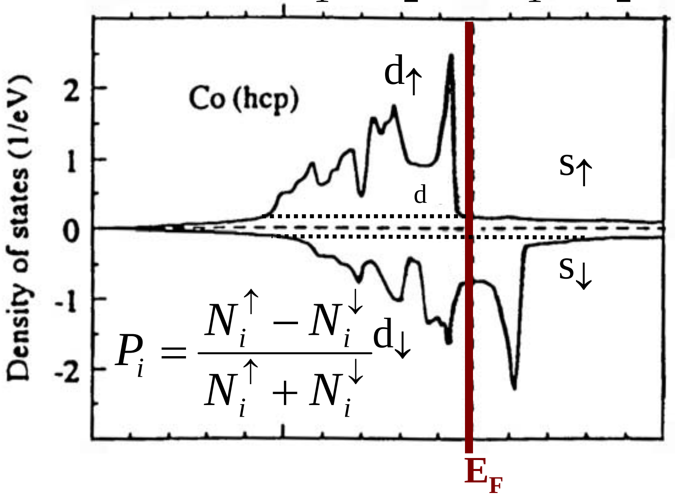
Principe of TMR

Jullière model:

- Spin is conserved during tunneling
- Conductance ∝ DOS of electrodes

$$G^{P} \propto N_1^{\uparrow}.N_2^{\uparrow} + N_1^{\downarrow}.N_2^{\downarrow}$$

$$G^{AP} \propto N_1^{\uparrow}.N_2^{\downarrow} + N_1^{\downarrow}.N_2^{\downarrow}$$



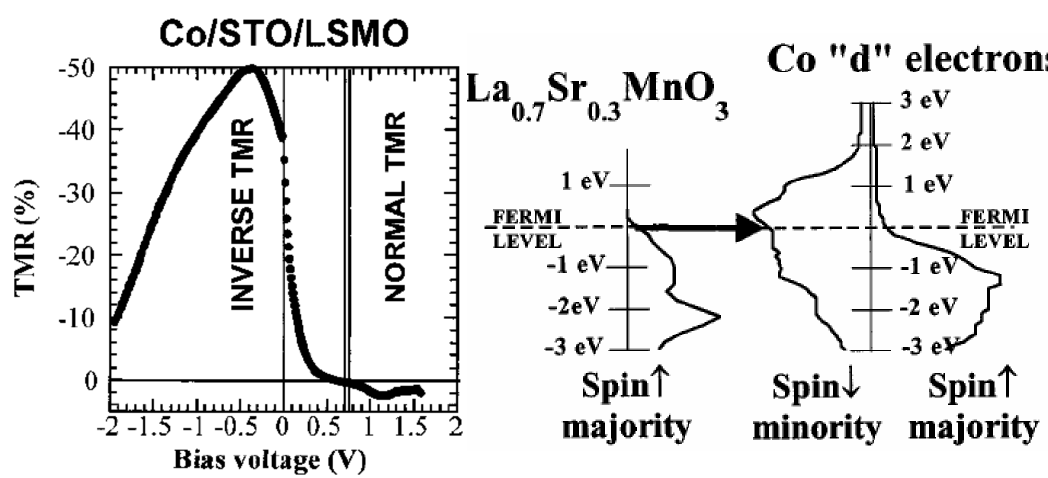
$$P_i = \frac{N_i^{\uparrow} - N_i^{\downarrow}}{N_i^{\uparrow} + N_i^{\downarrow}}$$

$$TMR \equiv \frac{G^{P} - G^{AP}}{G^{P} + G^{AP}} = P_1 P_2$$

$$G = G_0 (1 + P_1 P_2 \cos(\overrightarrow{M}_1, \overrightarrow{M}_2))$$

Open questions:

- TMR sign, depend only of $P_1 P_2$?
- Interface electrode/barrier ?
- Voltage dependence ?
- Influence of the DOS ?

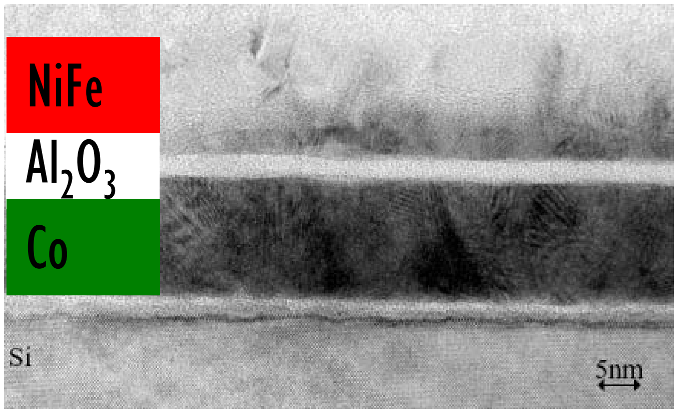


Teresa et al. Science 286, 507 (1999)

Tunnel Magnetoresistance (TMR)

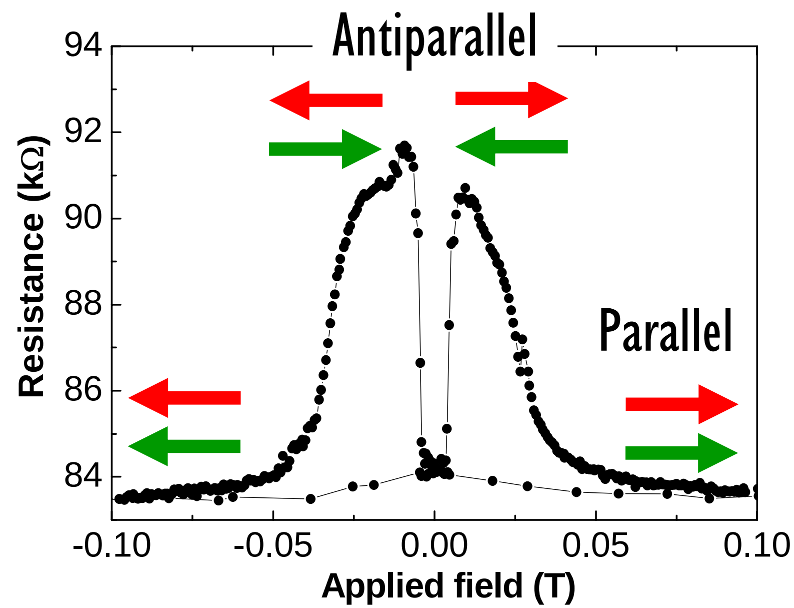
Jullière Phys. Lett. 54A, 225 (1975), Moodera et al. PRL 74, 3273 (1995)

Trilayer: ferro/insulator/ferro

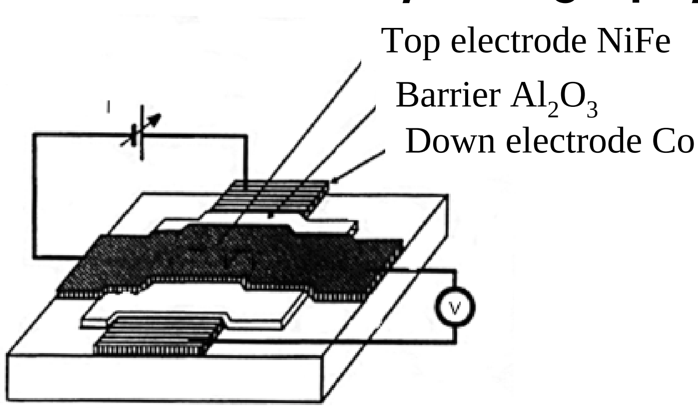


TEM view of a magnetic tunnel junction grown by sputtering

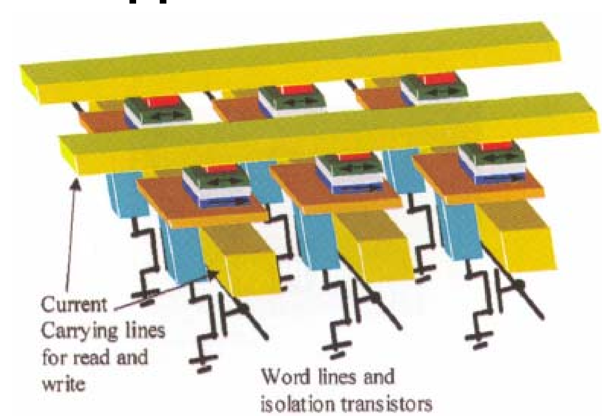
Transport



Contacts made by lithography



Application: MRAM



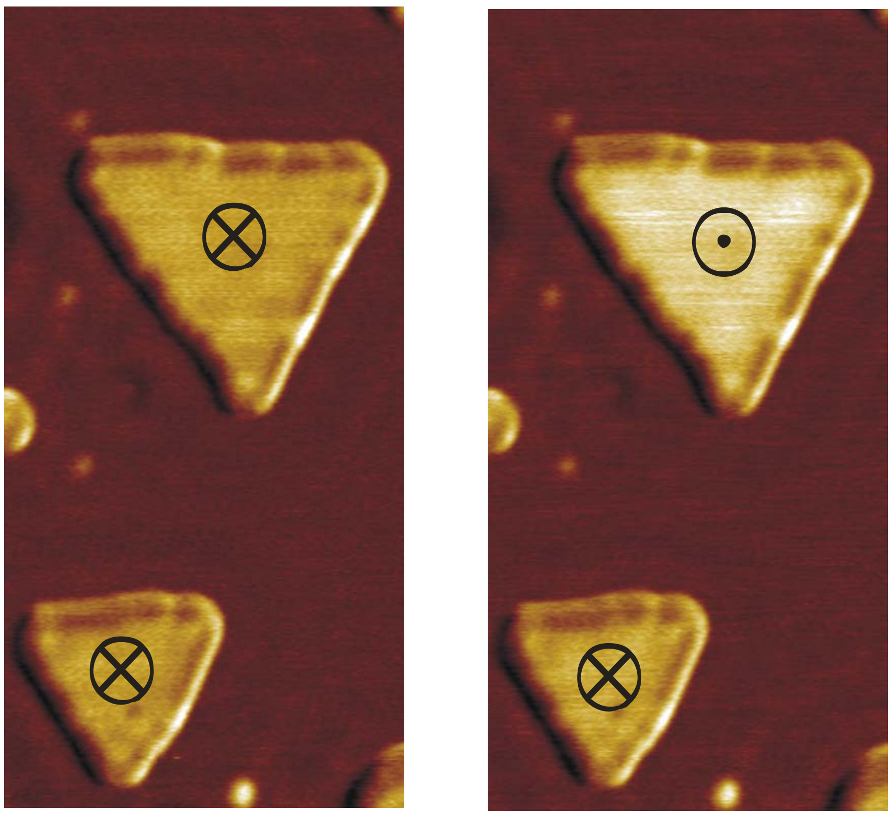
Magnetic contrast

External field out of plane

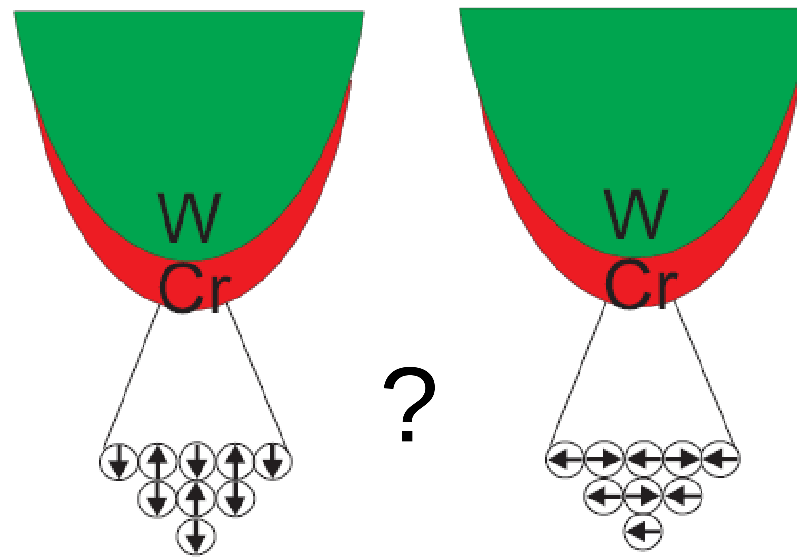
Sample

« Parallel » « Antiparallel »

dI/dV, 40nmx20nm, -0.53V, 1nA



Cr coated W tip

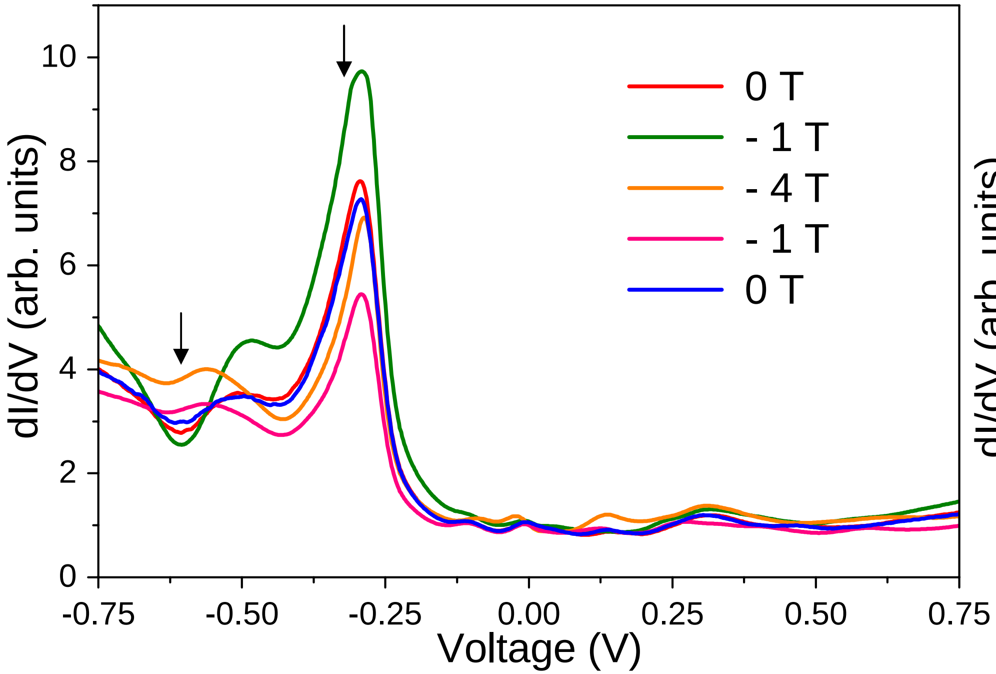


SP-STM image: incomplete information on the magnetic configuration

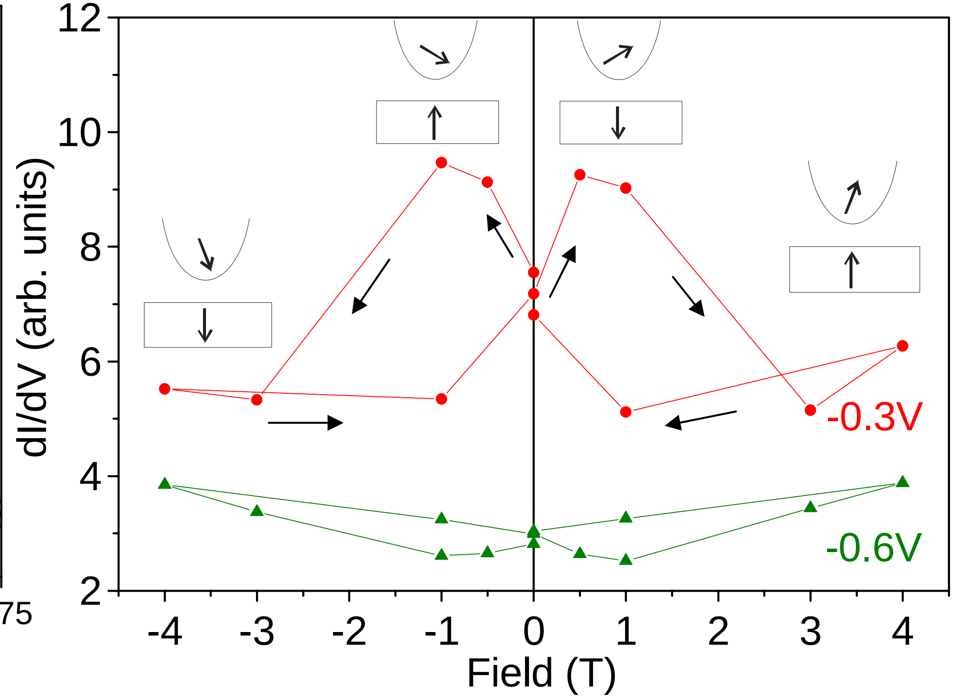
Spin dependent transport on a single island

I(V) curves measured at island center

In field spectroscopy



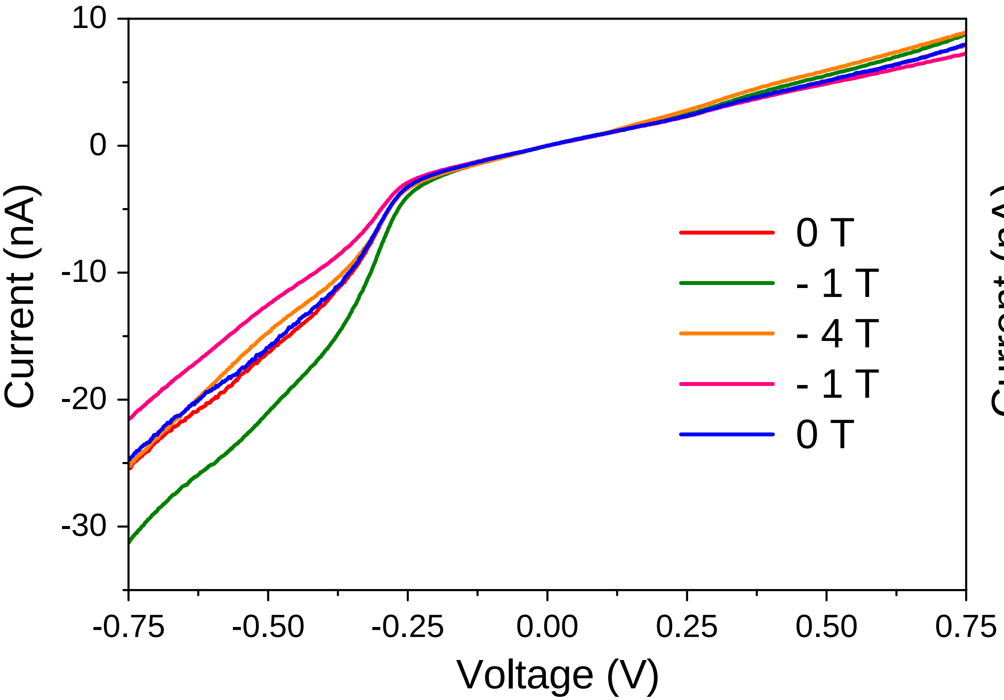
Extraction of the hysteresis cycle at different voltages

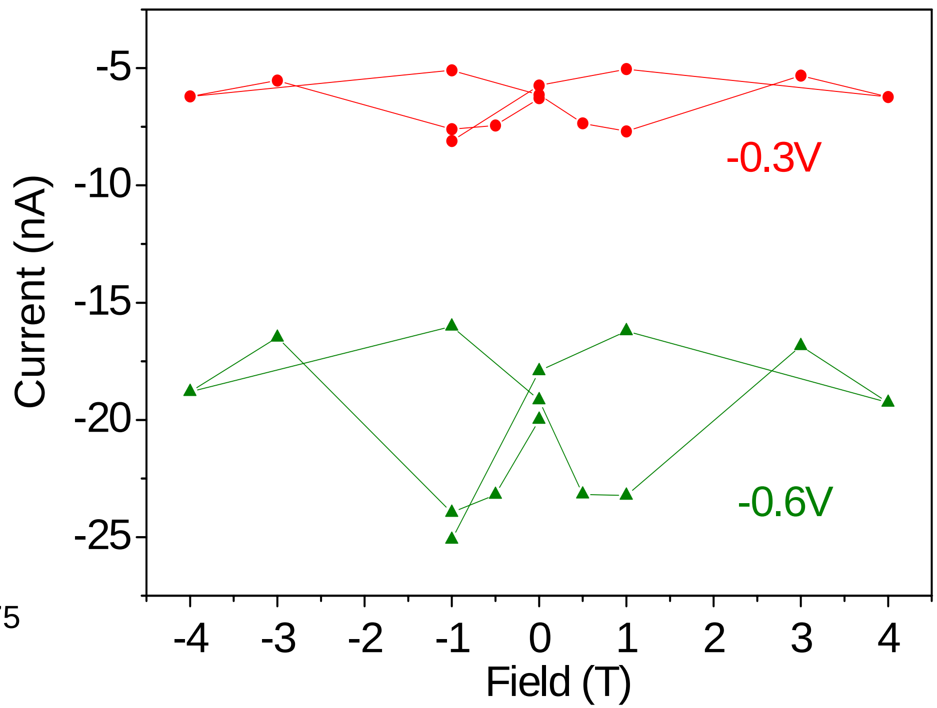


- Measure the relative magnetic orientation of tip and sample
- Understanding of the magnetic configurations, what is « parallel » and « antiparallel »

TMR at a nanoscale

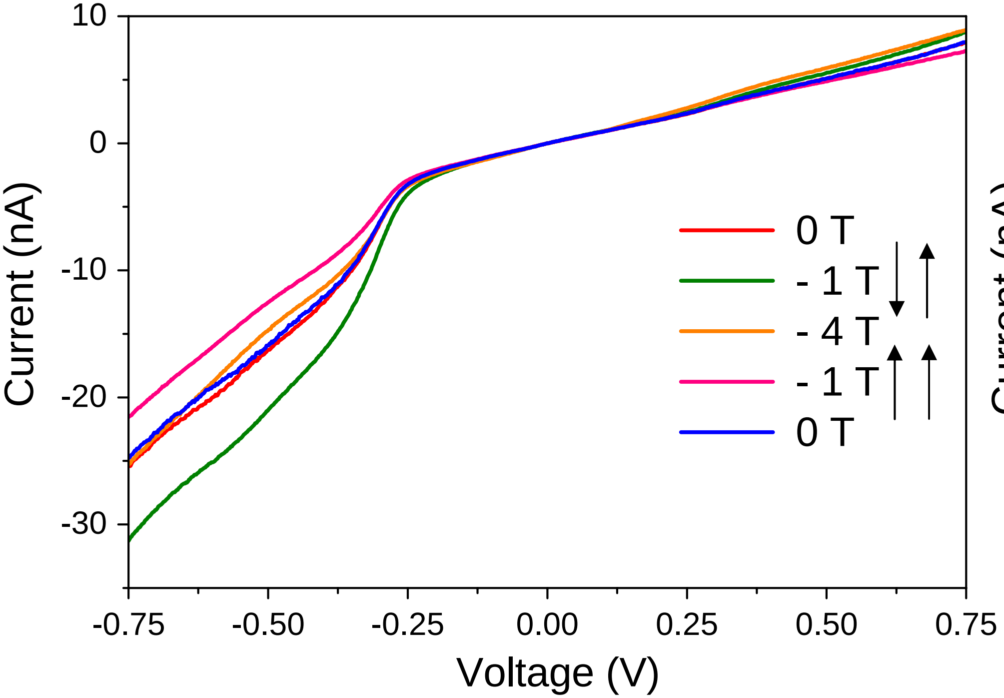
$$TMR \equiv \frac{I^{P} - I^{AP}}{I^{P} + I^{AP}}$$

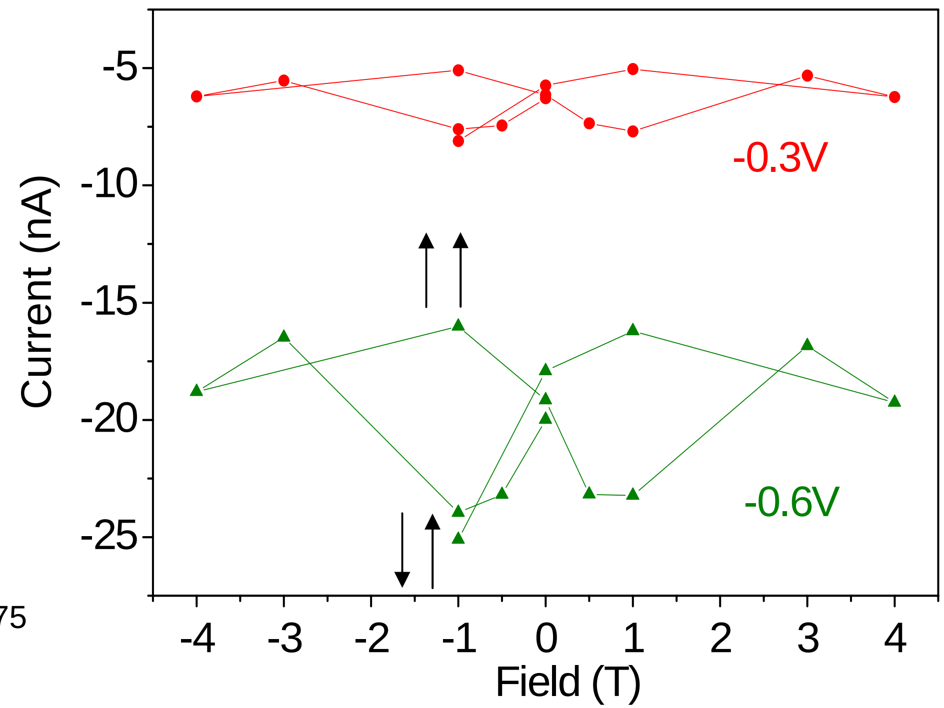




TMR at a nanoscale

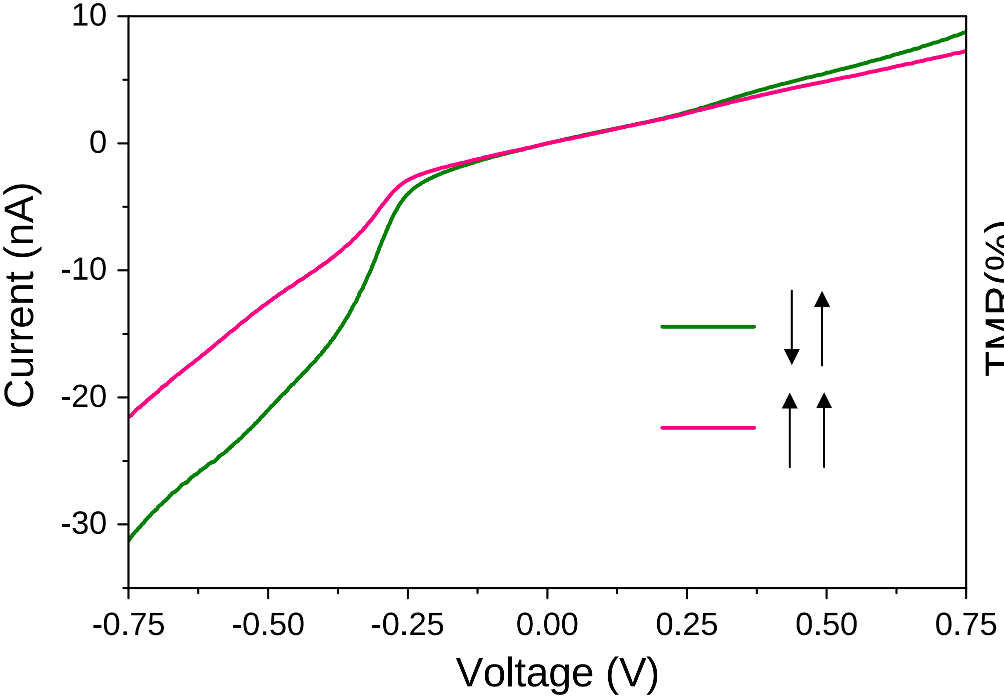
$$TMR \equiv \frac{I^{P} - I^{AP}}{I^{P} + I^{AP}}$$

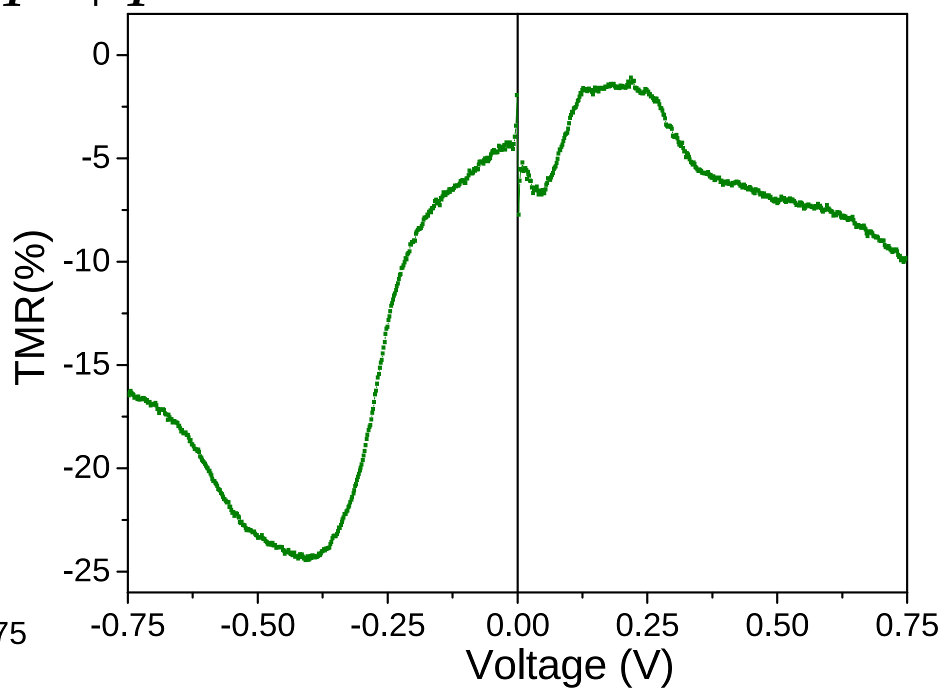




TMR voltage dependence

$$TMR \equiv \frac{I^{P} - I^{AP}}{I^{P} + I^{AP}}$$

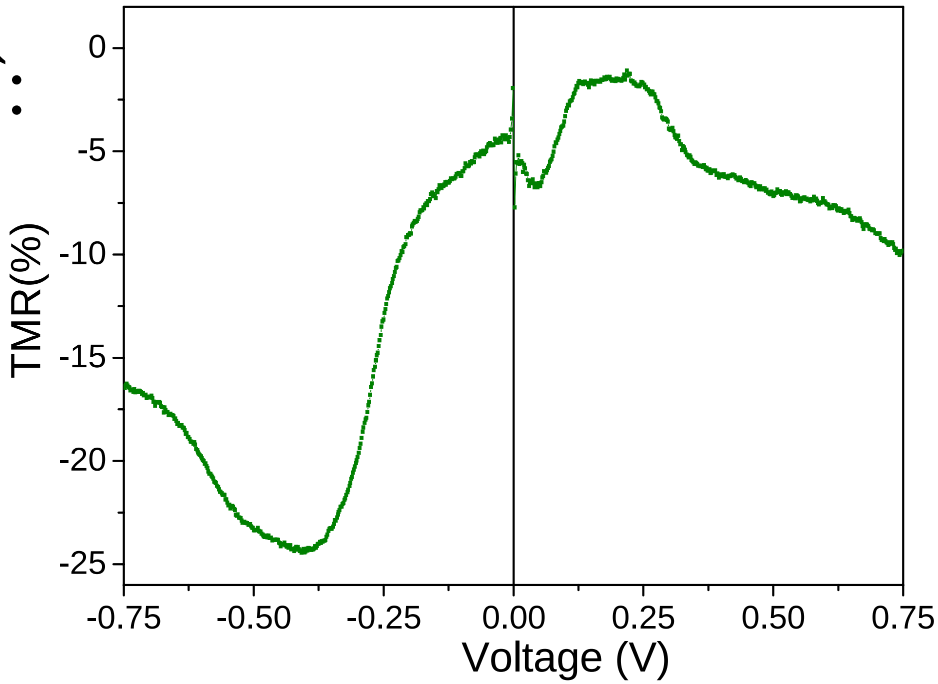


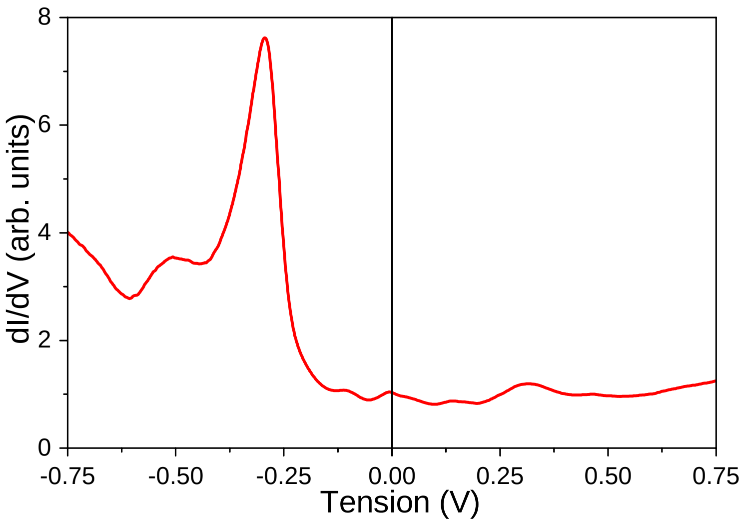


TMR voltage dependence

- Higher current for ↑↓ than for ↑↑: TMR negative for all energy

- Shape can be understand from the LDOS dependence





TMR voltage dependence

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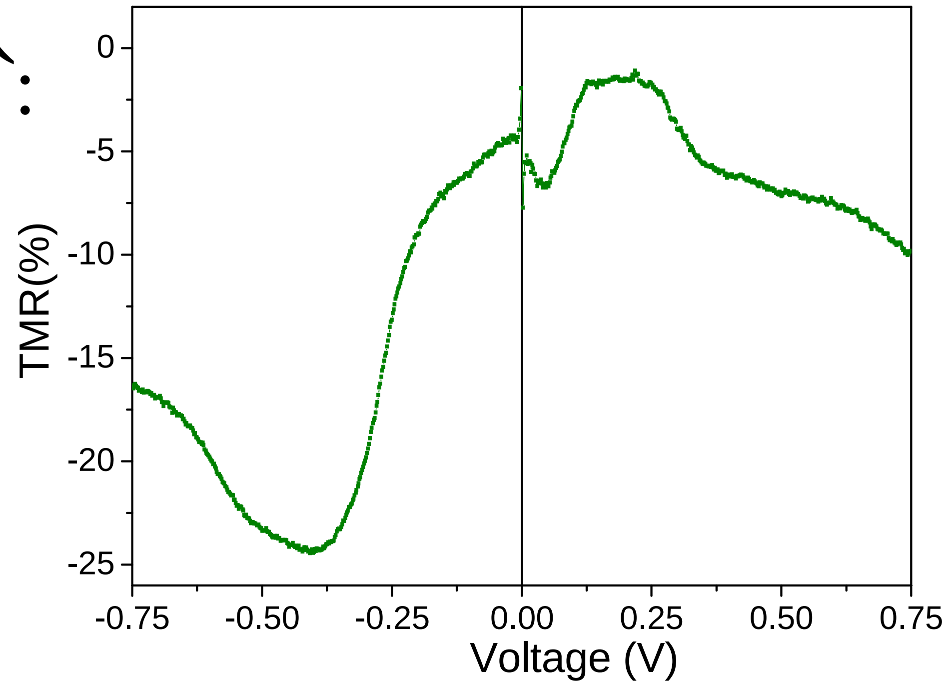

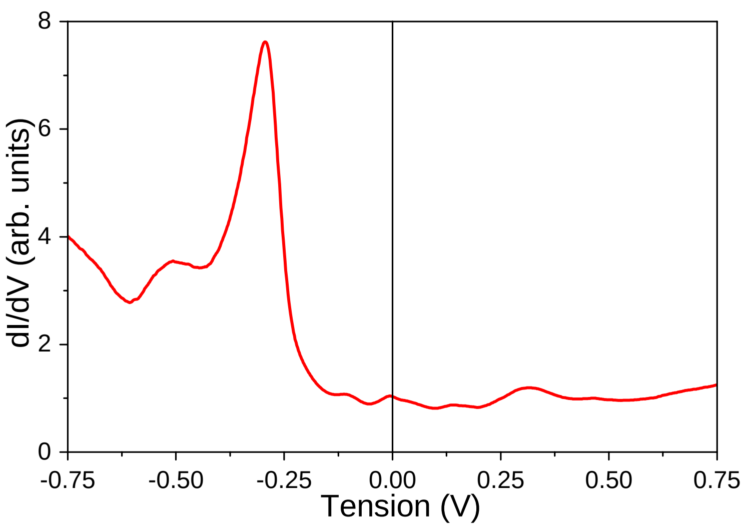

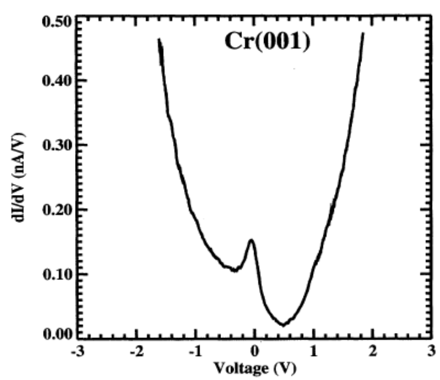

Stroscio et al. PRL 75, 2960 (1995)