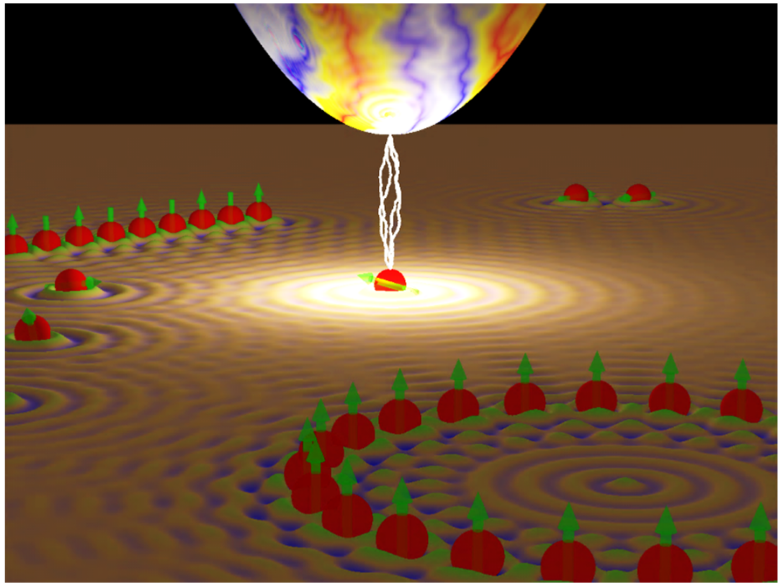
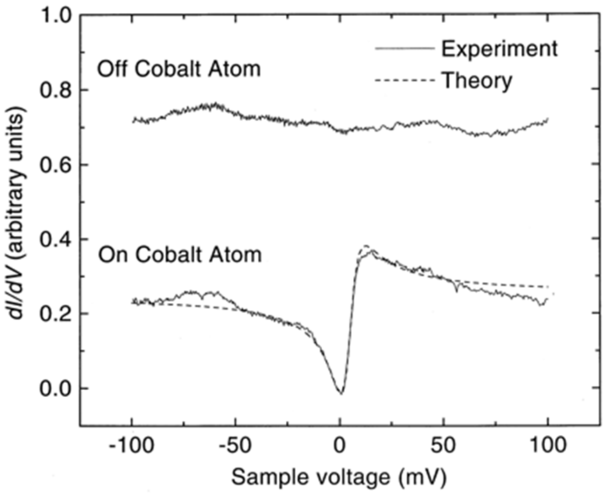
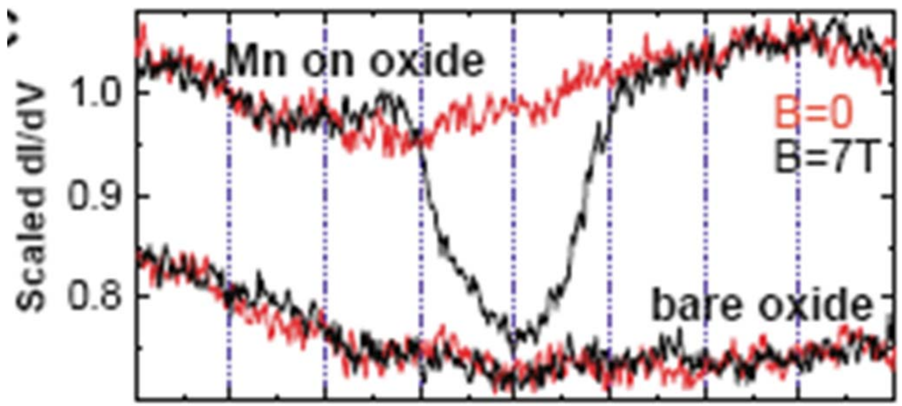
Spin Detection and Manipulation with SPM

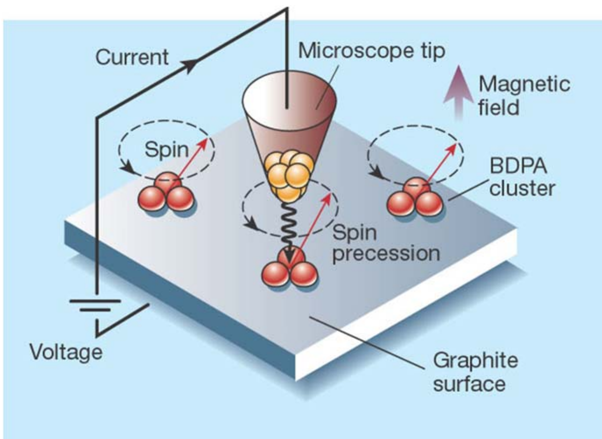


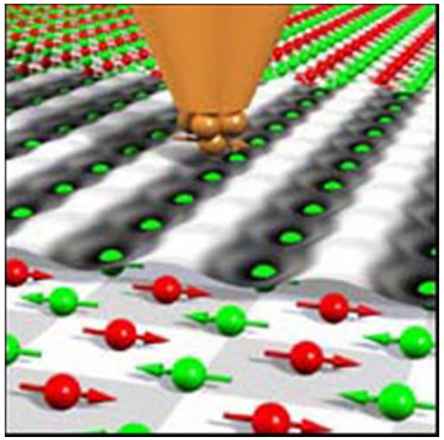
基于扫描探针显微镜的分析方法

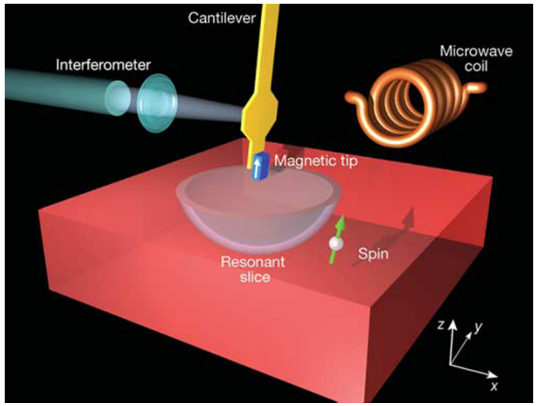
Single Spin Detection with SPM









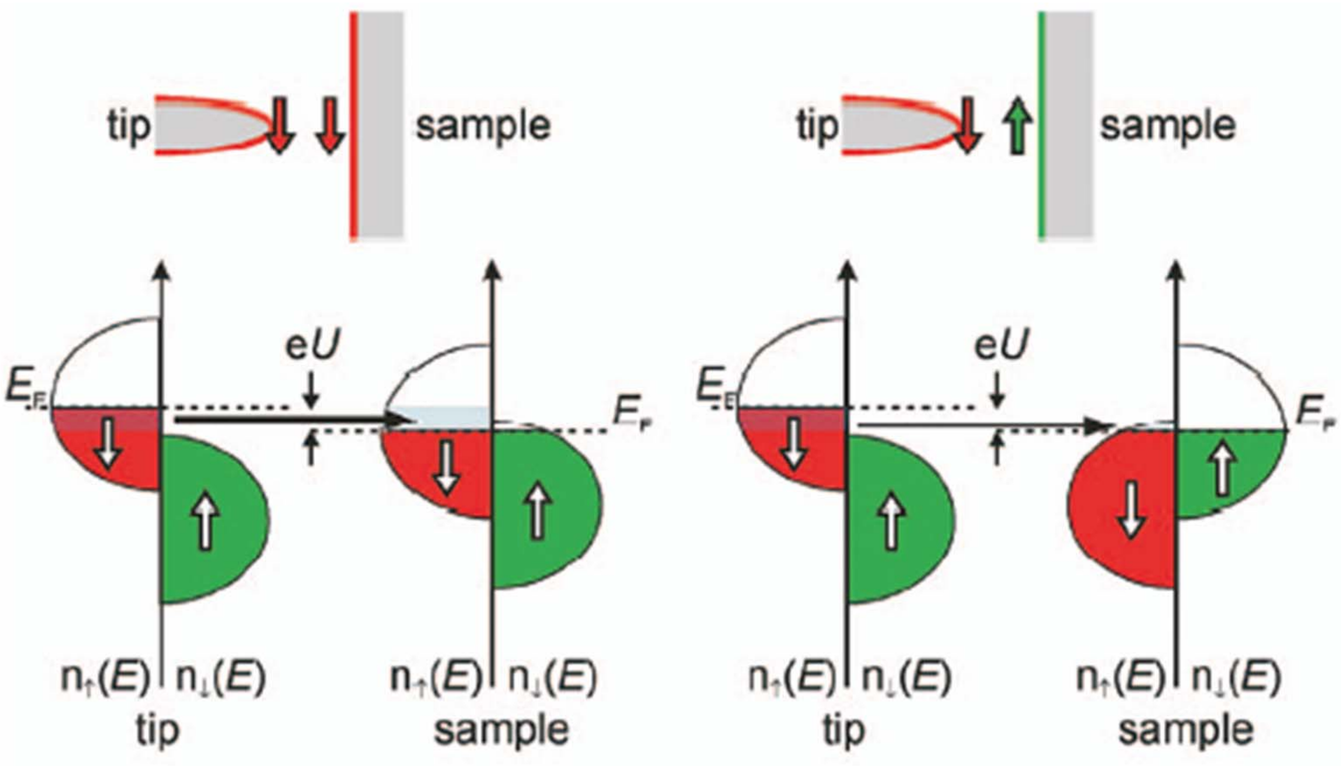


Nature 430, 329 (2004).

Spin Polarized Scanning Tunneling Microscopy

- **Basic Theory**
- **Spin Polarized Tip**
- **Operation Modes**
- **Applications**

Basic Theory



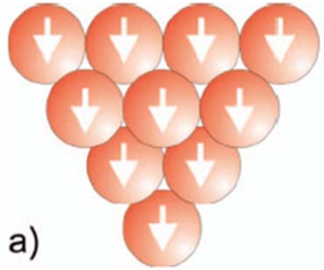
$$I_{SP}(U_0) \propto I_0 \cdot [1 + P_{tip} \cdot P_{sample} \cdot \cos(\vec{m}_{tip}, \vec{m}_{sample})]$$

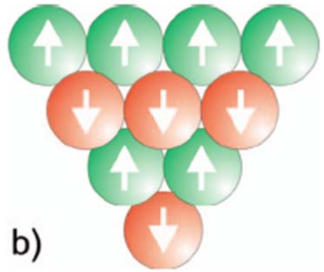
Spin Polarized Tip

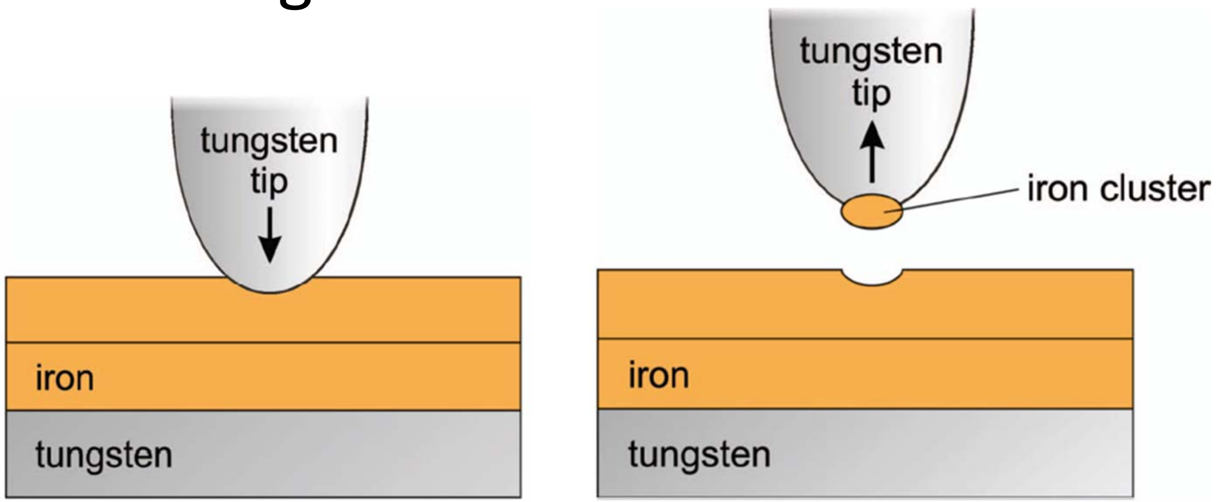
- Bulk magnetic material:
  Iron, CoFeNiSiB, Cr, MnNi, CrO_2, Fe_3O_4

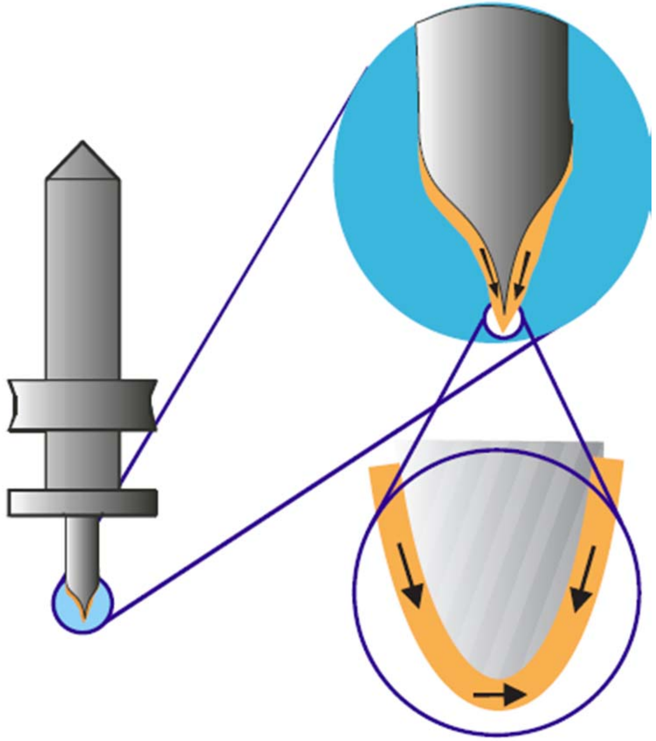
- Magnetic Film

- Magnetic Cluster







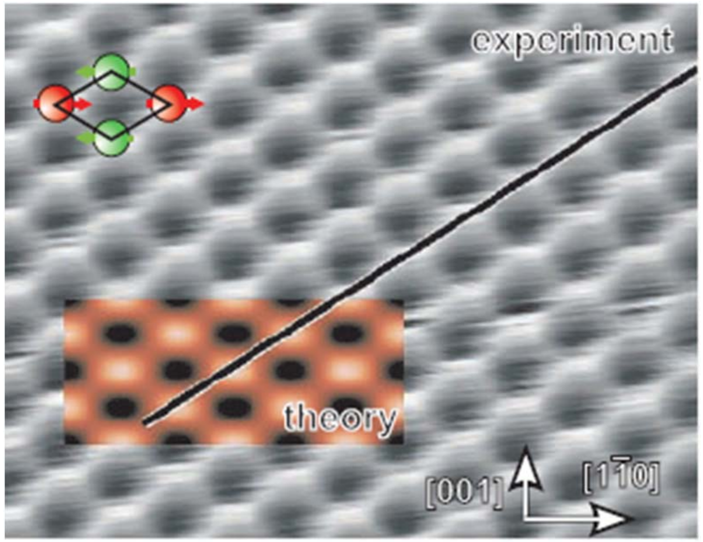


Operation Modes of SP-STM

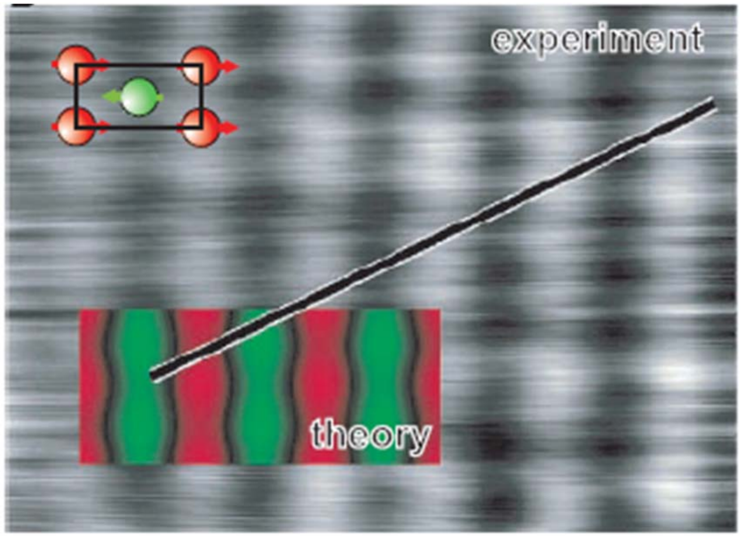
- Constant Current Mode
- Spin-resolved spectroscopic mode
- Modulated tip magnetization mode

Constant Current Mode

$$\Delta I(\vec{r}_{\|}, z, U, \theta) = \sum_{n \neq 0} \Delta I_{\vec{q}^{\mathrm{n}}}(z, U, \theta) e^{i\vec{q}^{\mathrm{n}} \cdot \vec{r}}$$



With nonmagnetic W tip

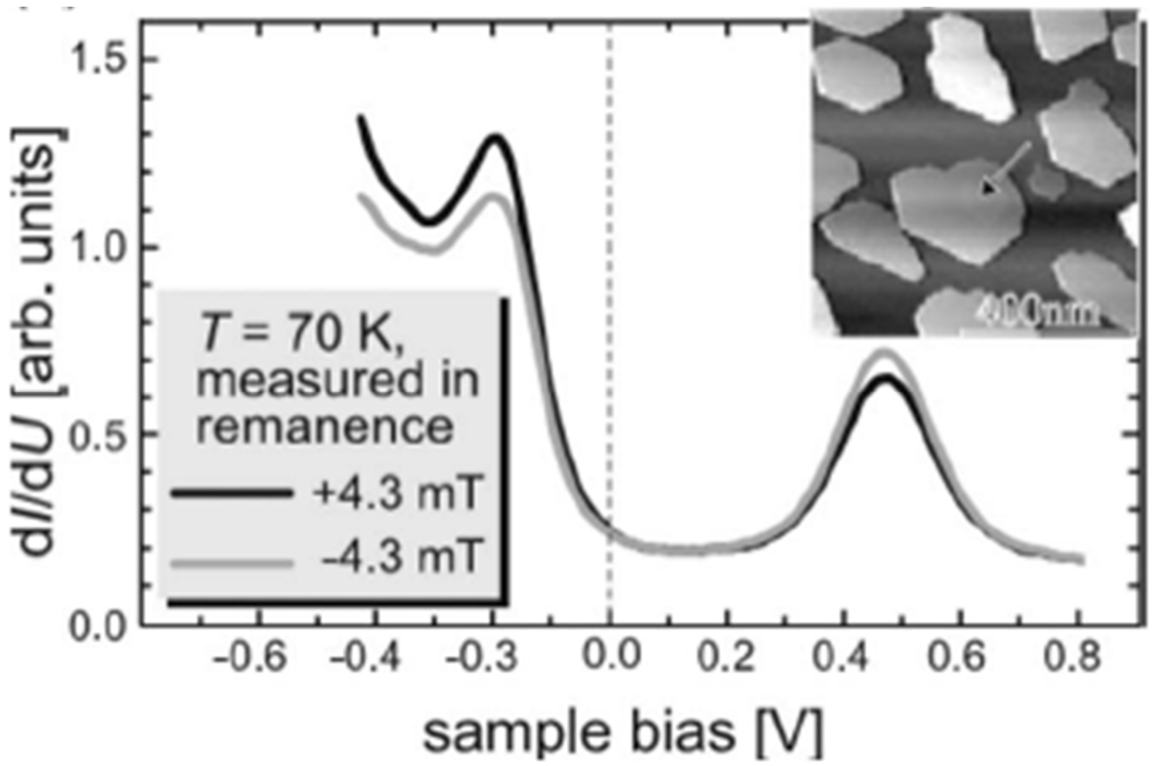


With magnetic Fe tip

Mn monolayer on W(110)

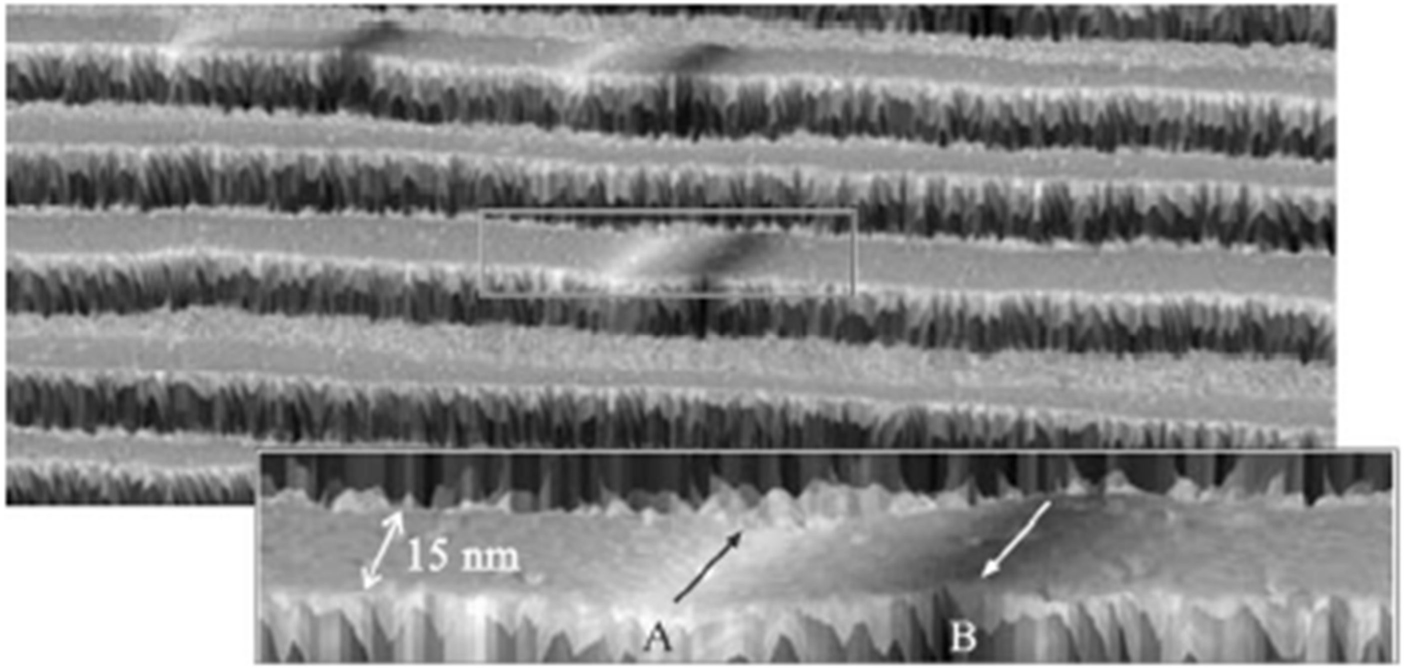
Spin-resolved spectroscopic mode

$$\frac{dI}{dU}(R_t,U) \propto n_t n_s(R_t,E_F+eU) + \vec{m}_t \cdot \vec{m}_s(R_t,E_F+eU)$$



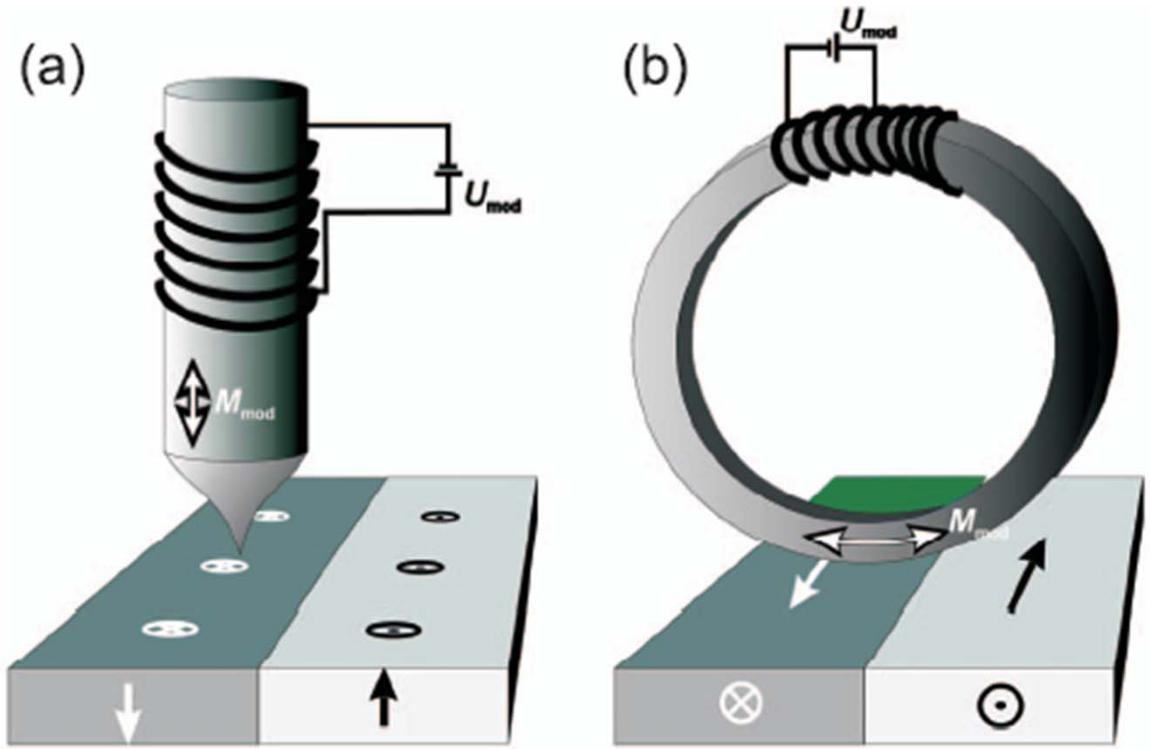
Gd(0001) island, Fe coated tip

Spin-resolved spectroscopic mode



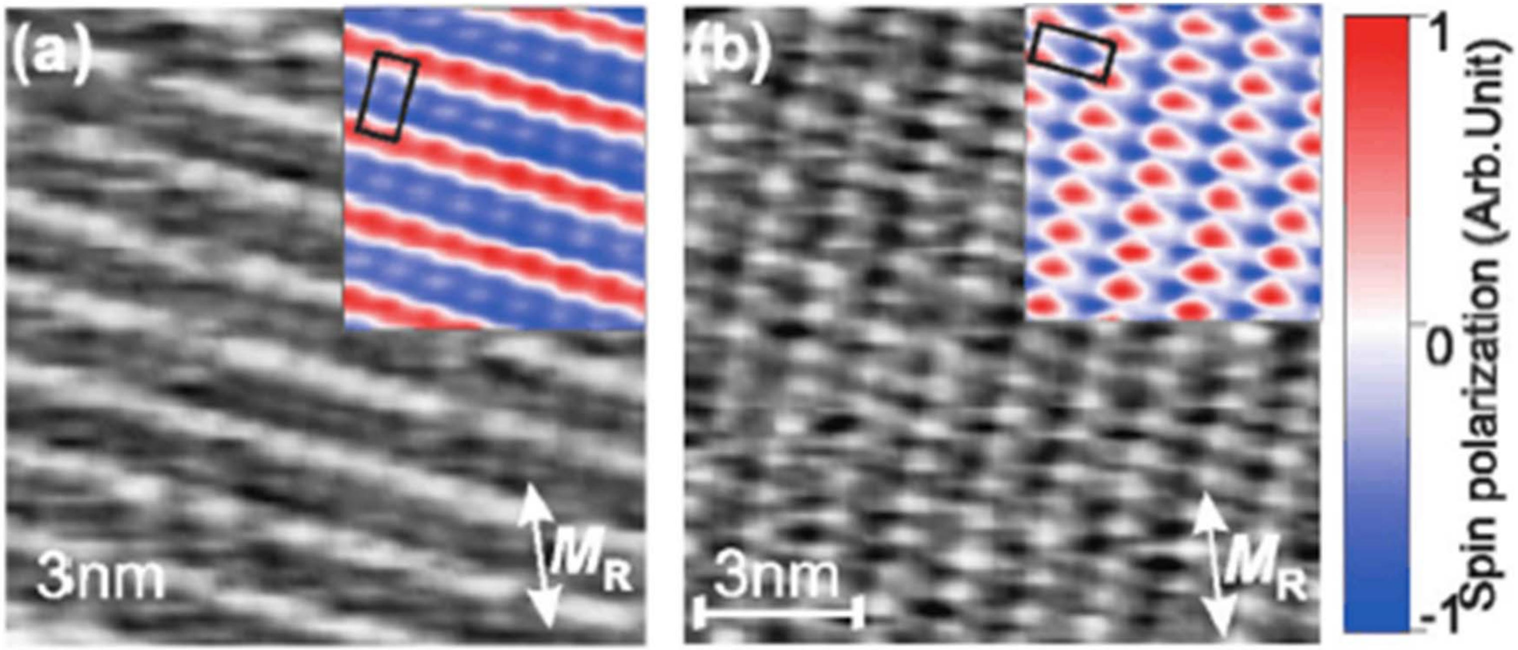
Fe double layer on W(110)

Modulated tip magnetization mode



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

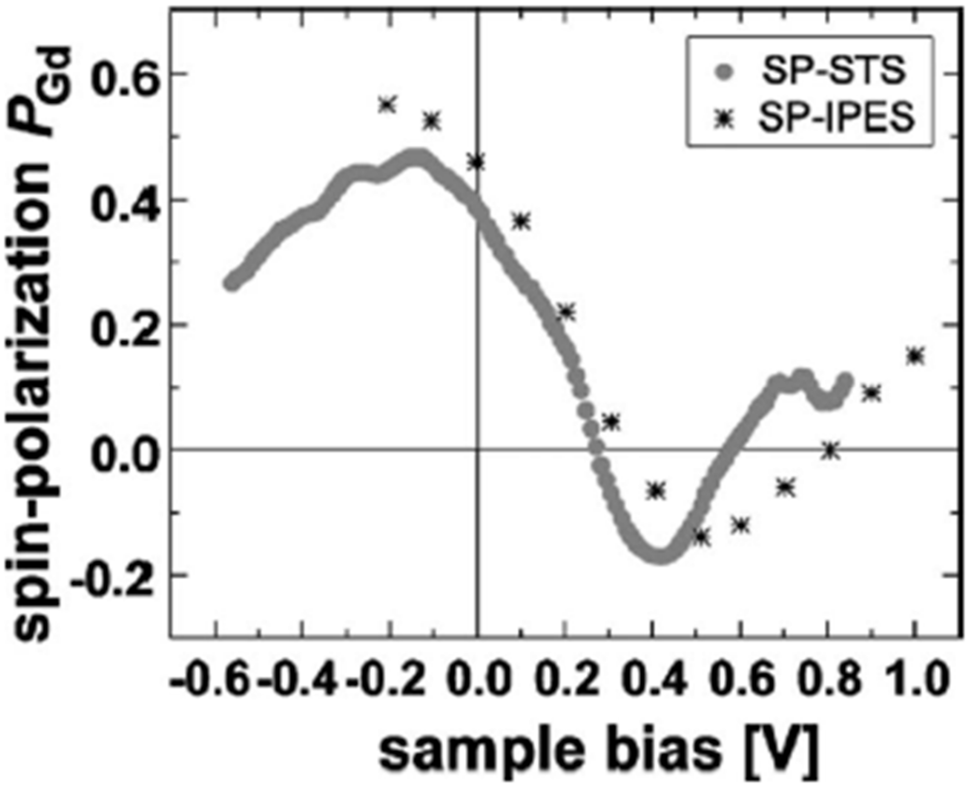
Modulated tip magnetization mode



Mn on Fe(001)

Spin polarization

$$P(eU) = \frac{dI/dU_{\uparrow\uparrow}(U) - dI/dU_{\uparrow\downarrow}(U)}{dI/dU_{\uparrow\uparrow}(U) + dI/dU_{\uparrow\downarrow}(U)}$$

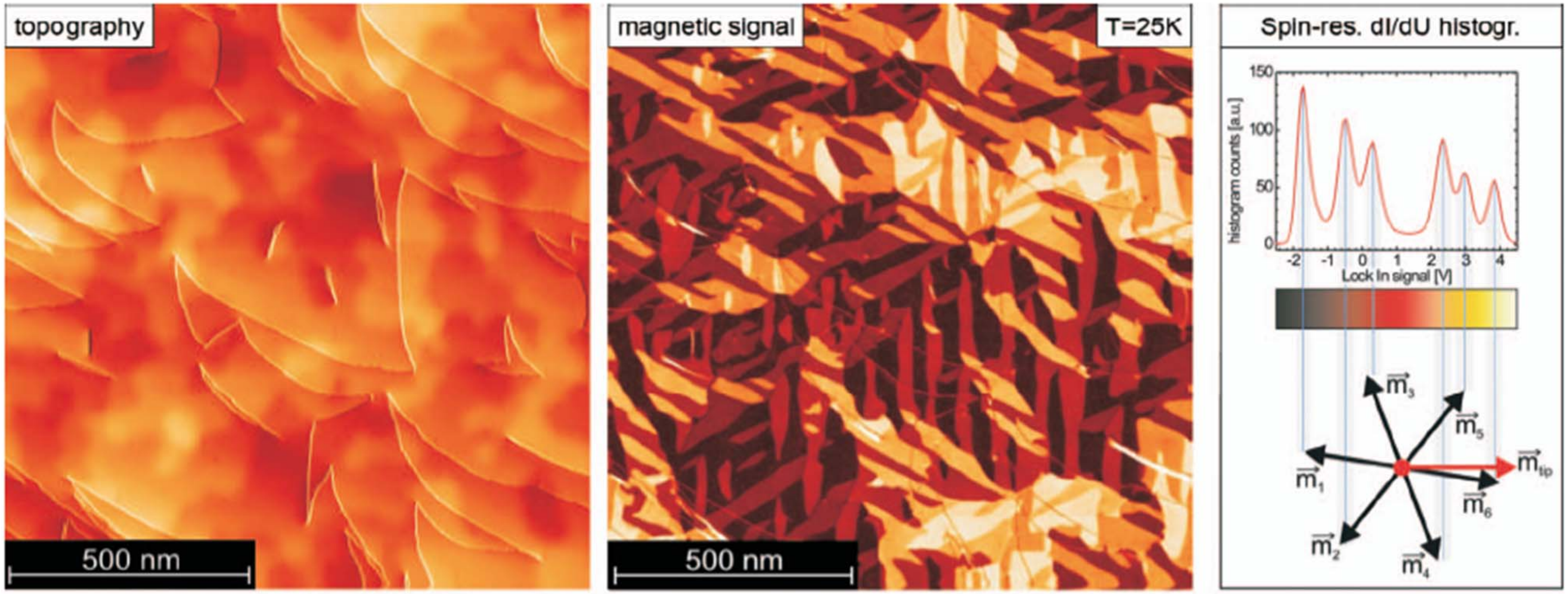


Application:

- Magnetic domain and domain wall structure
- Nanostrip and nanowires
- Nanoisland and nanoparticle
- Atomic resolution spin mapping
- Individual adatoms
- Magnetization dynamics and spin transport

Magnetic domain and domain wall structure

Ferromagnetic rare-earth metal films

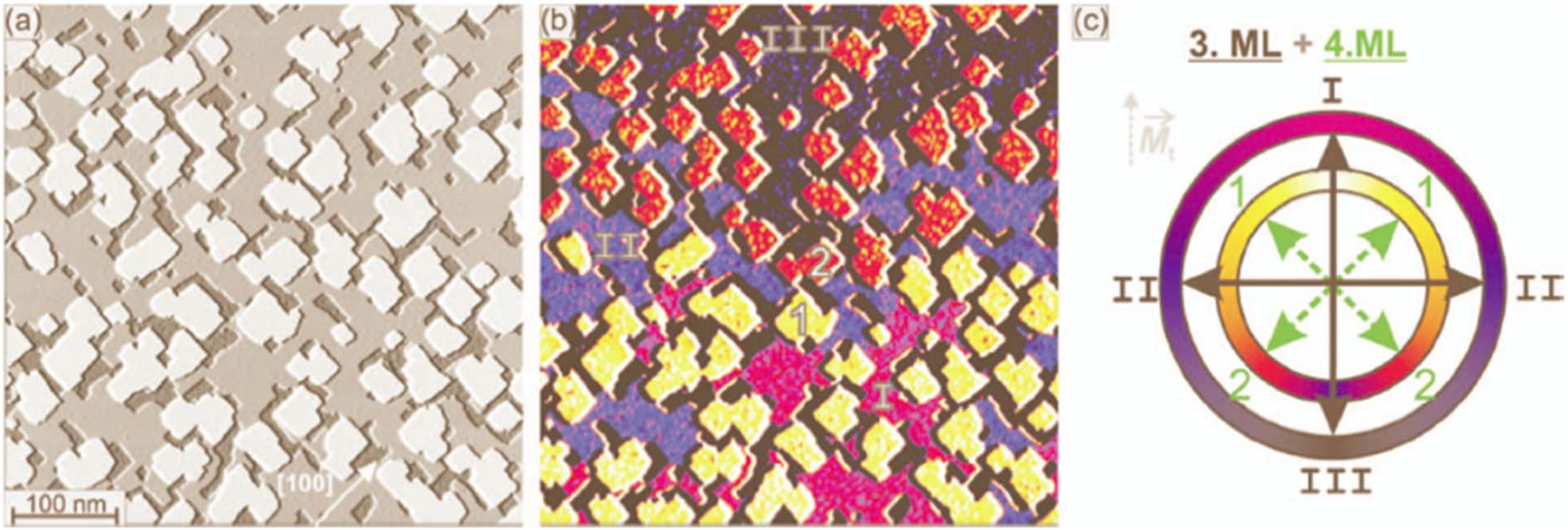


a) b) c)

Dy(0001) film (90ML) on W(110), Dy probe tip

Magnetic domain and domain wall structure

Ferromagnetic transition-metal single crystal and thin films



Fe film (3.2ML) on W(001)

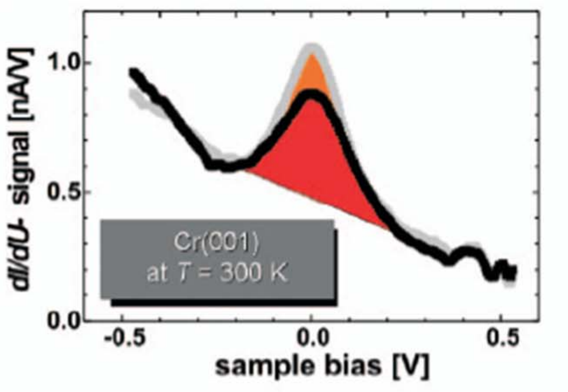
1st layer: out-of-plane anisotropy, AF

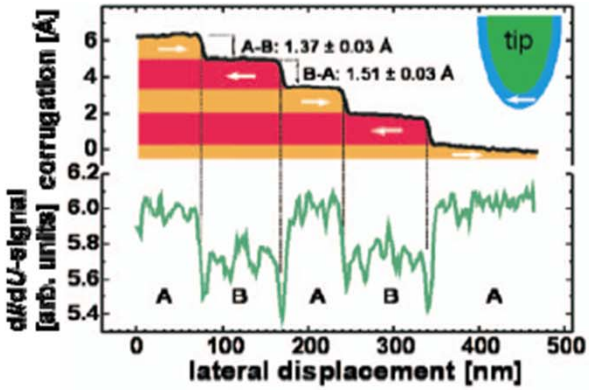
2nd and 3rd layer: easy direction on [110]

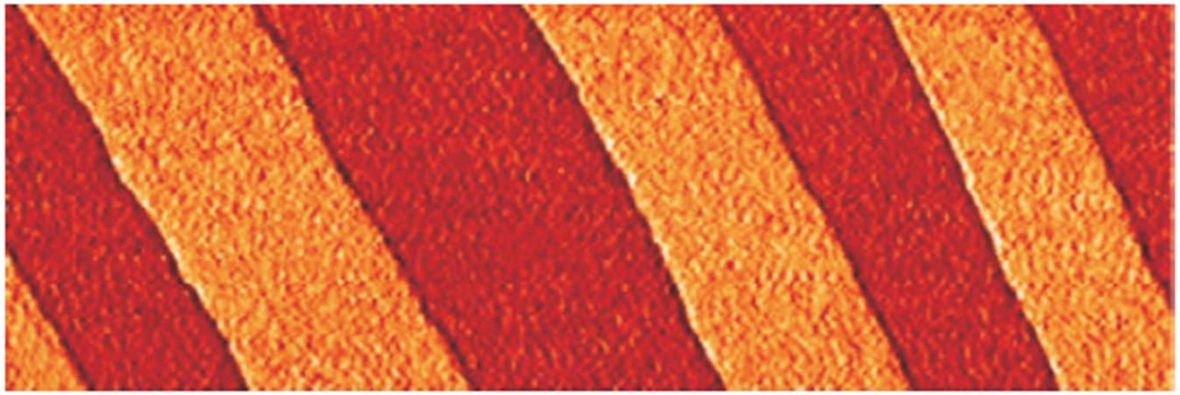
4th layer: easy direction on [100]

Magnetic domain and domain wall structure

Antiferromagnetic single crystals and thin films



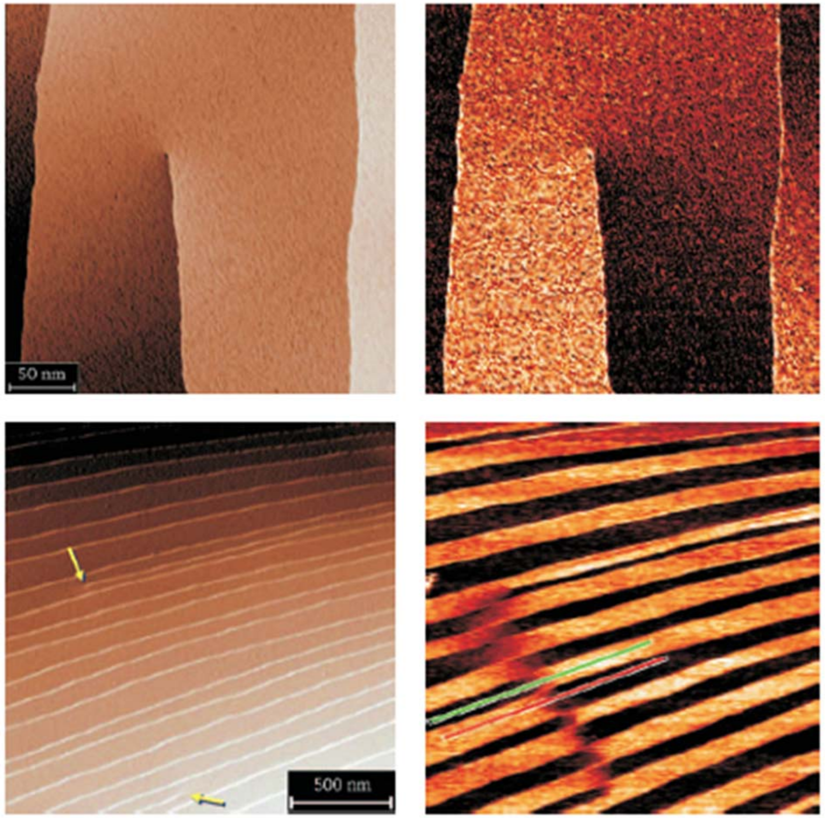




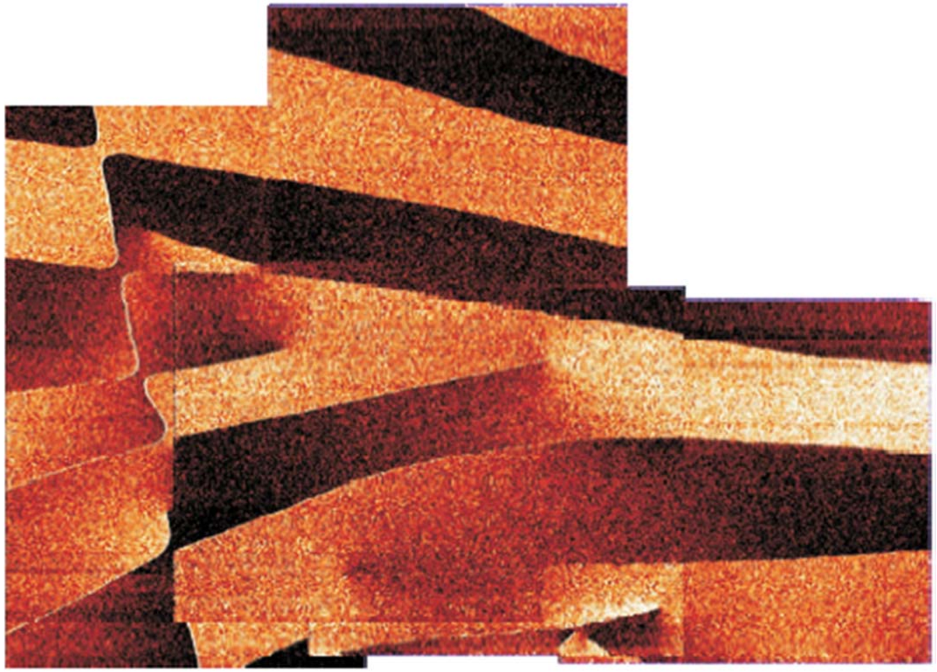
Cr(001), with Fe coated W tip

Magnetic domain and domain wall structure

Screw and edge dislocation

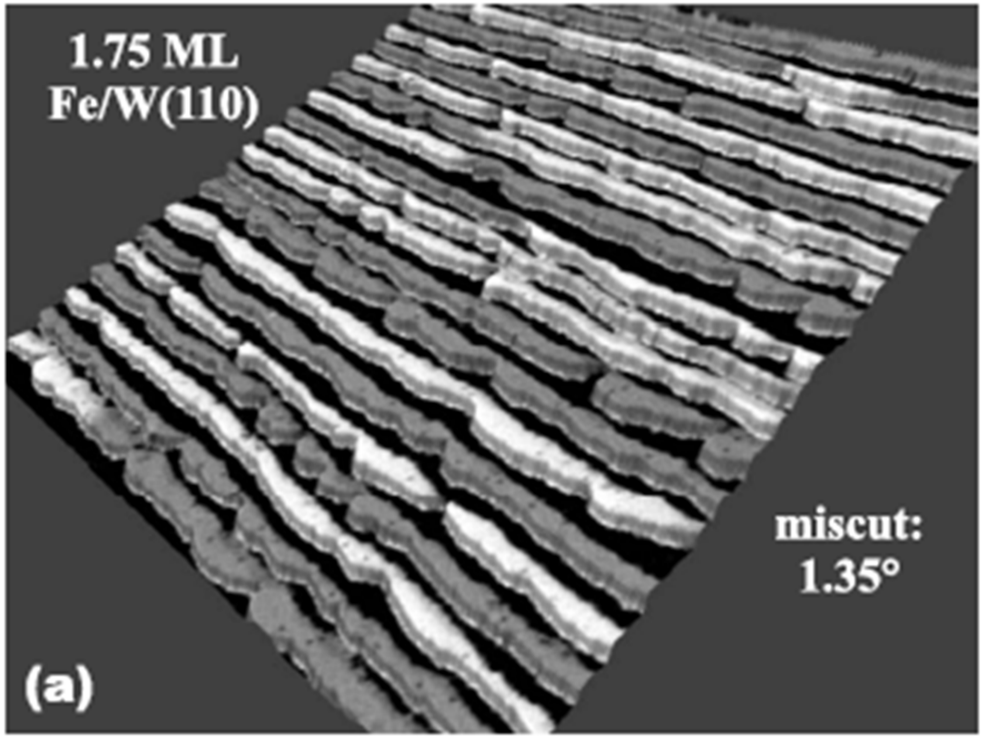


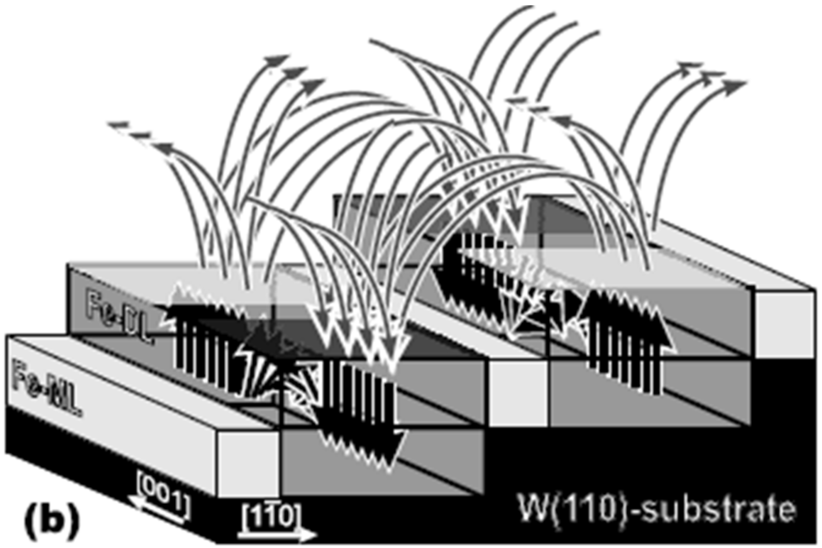
Topo **SP-STS**



Cr(001), with Fe coated W tip

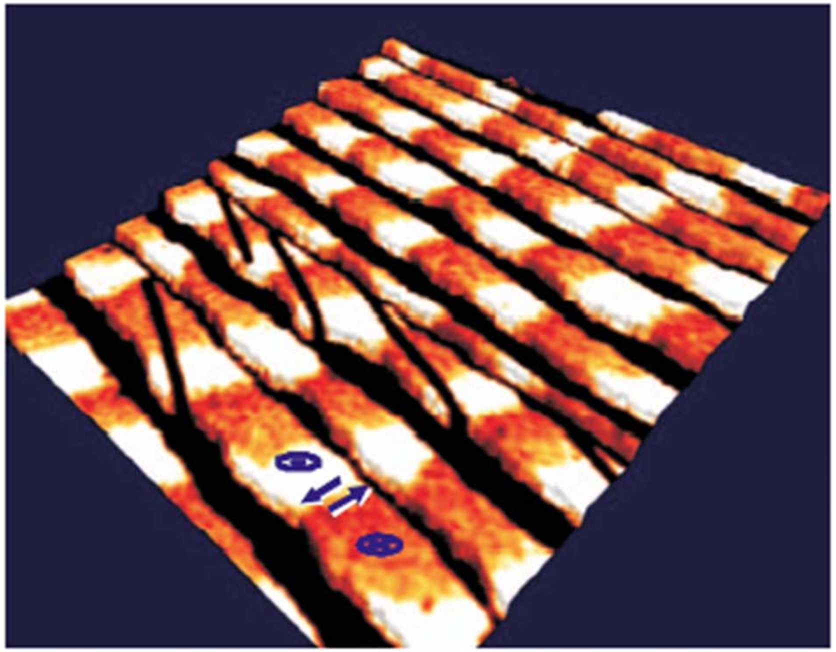
Nanostrip and nanowires

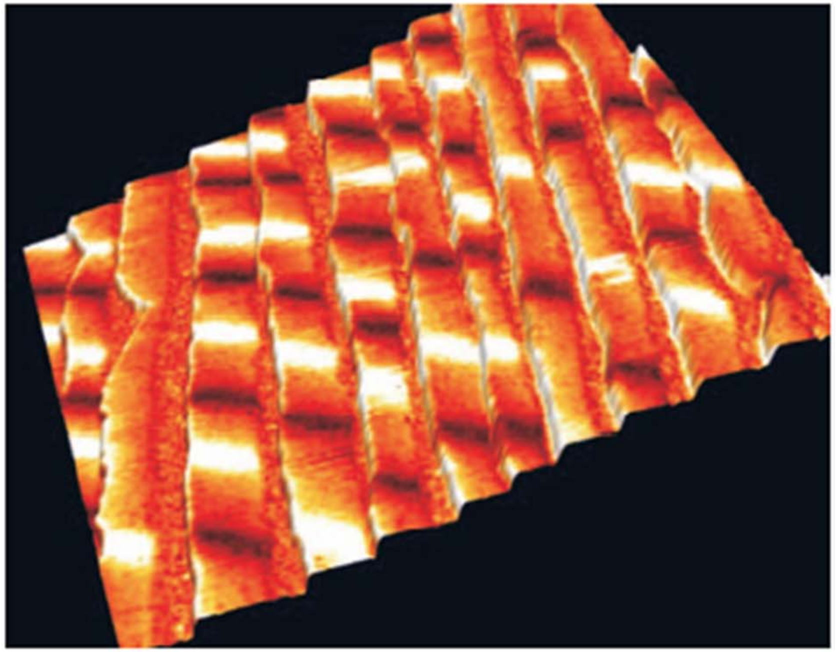




With Gd coated tip

Nanostrip and nanowires



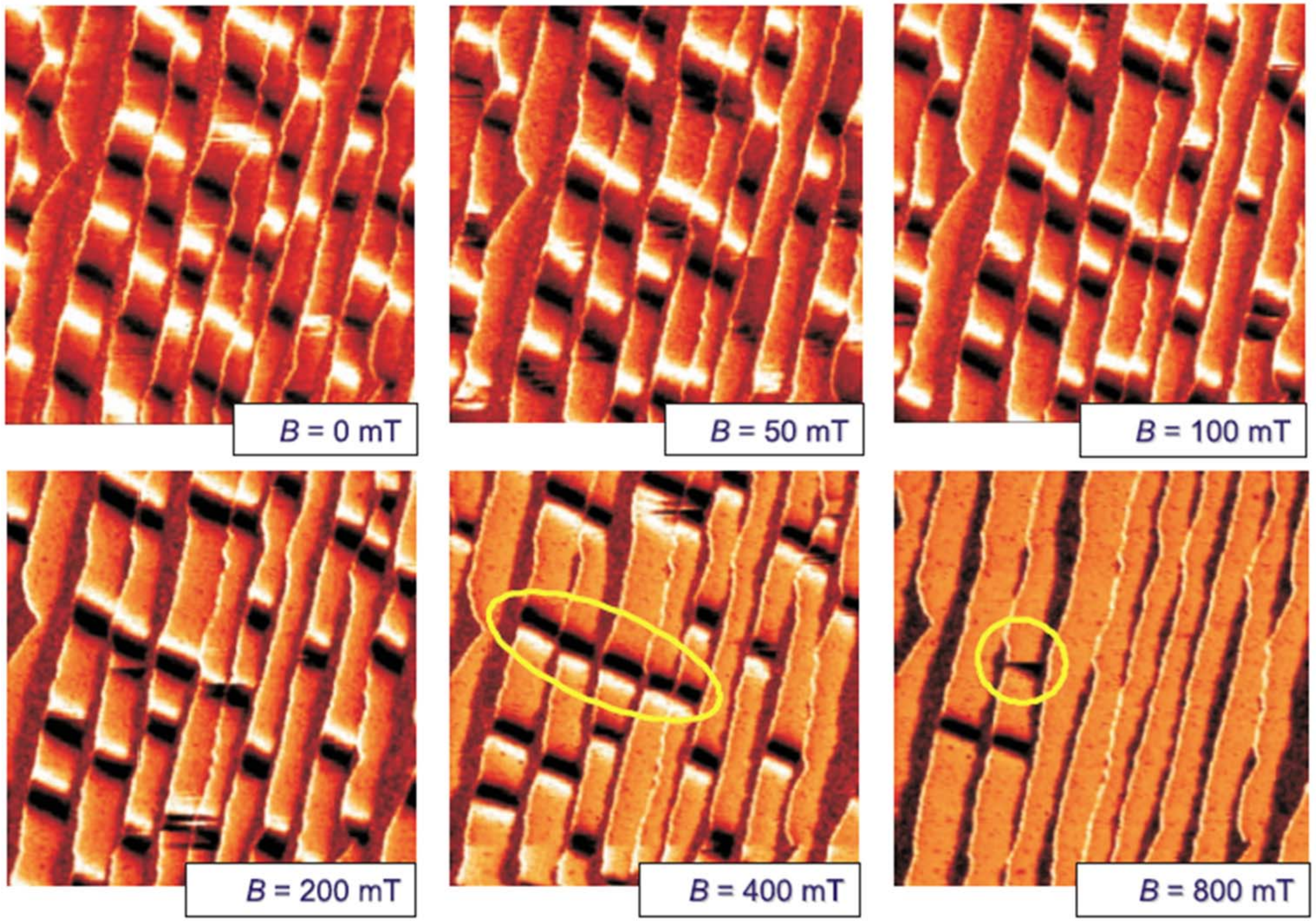


Gd coated tip: out of plane

Fe coated tip: in plane

Nanostrip and nanowires

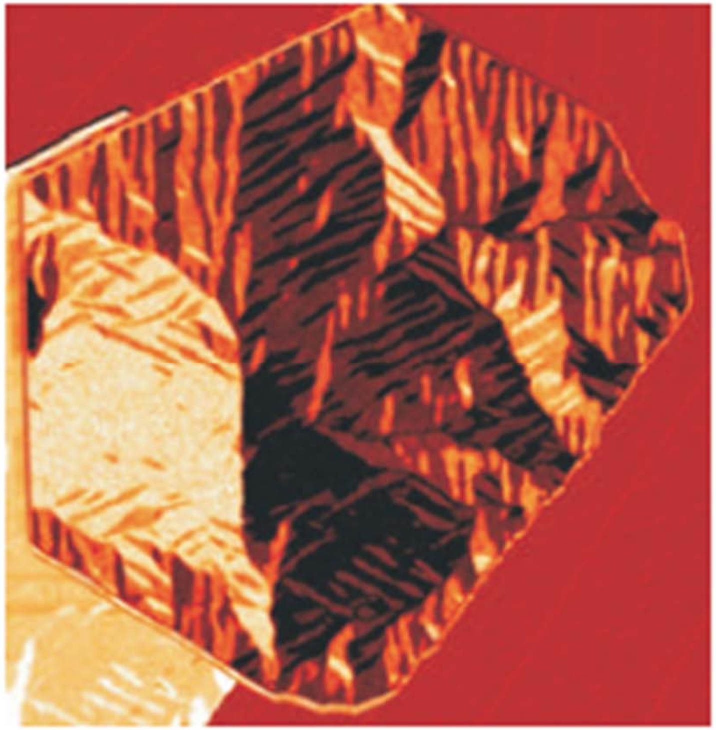
Domain wall dynamics under magnetic field

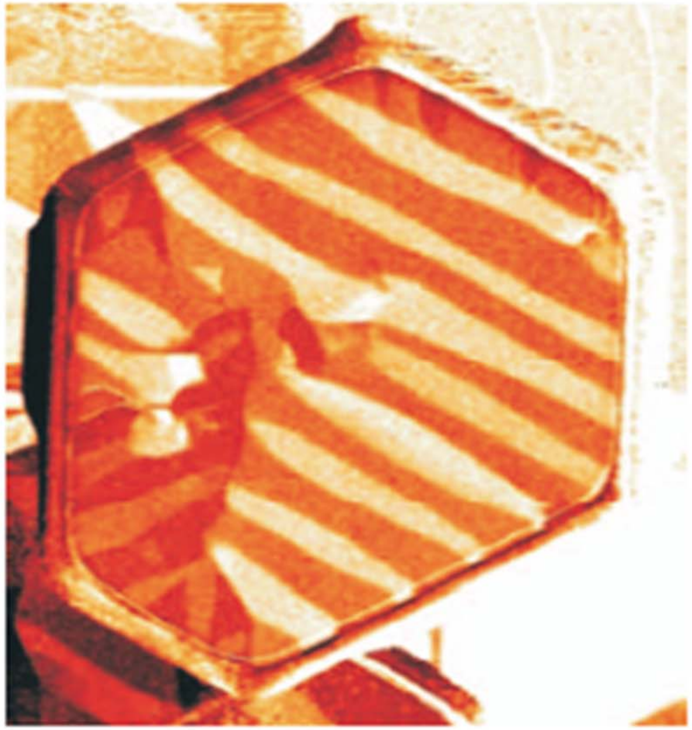


Fe thin film. With Fe coated tip

Nanoisland and nanoparticle

Multidomain States





Dy nanoislands on W(110), 800nm and 400nm

Nanoisland and nanoparticle

Science AAAS A. Wachowiak, *et al.*
Science **298**, 577 (2002);

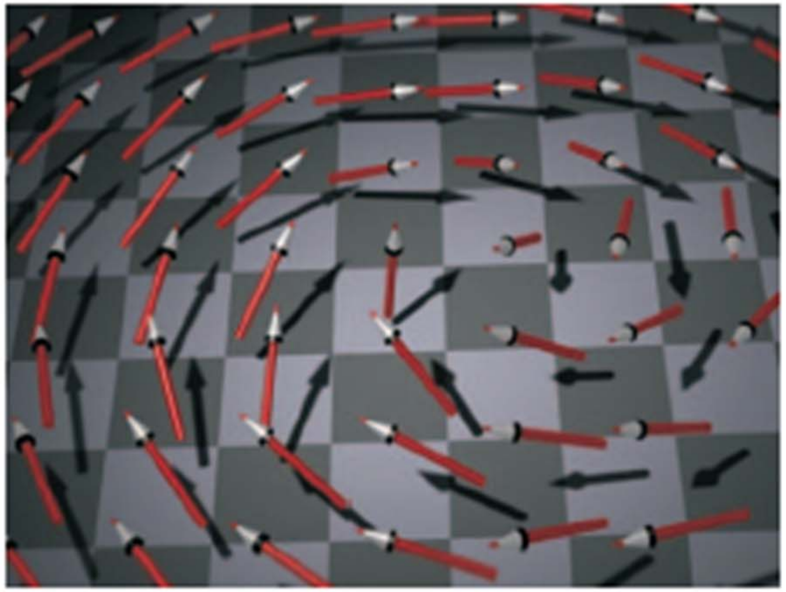
Direct Observation of Internal Spin Structure of Magnetic Vortex Cores

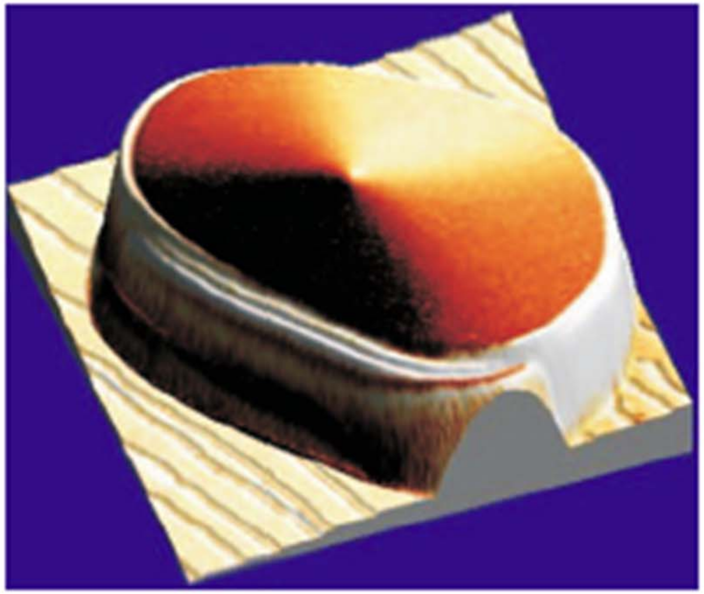
A. Wachowiak, J. Wiebe, M. Bode,* O. Pietzsch,
M. Morgenstern, R. Wiesendanger

Thin film nanoscale elements with a curling magnetic structure (vortex) are a promising candidate for future nonvolatile data storage devices. Their properties are strongly influenced by the spin structure in the vortex core. We have used spin-polarized scanning tunneling microscopy on nanoscale iron islands to probe for the first time the internal spin structure of magnetic vortex cores. Using tips coated with a layer of antiferromagnetic chromium, we obtained images of the curling in-plane magnetization around and of the out-of-plane magnetization inside the core region. The experimental data are compared with micromagnetic simulations. The results confirm theoretical predictions that the size and the shape of the vortex core as well as its magnetic field dependence are governed by only two material parameters, the exchange stiffness and the saturation magnetization that determines the stray field energy.

Nanoisland and nanoparticle

Magnetic Vortex States

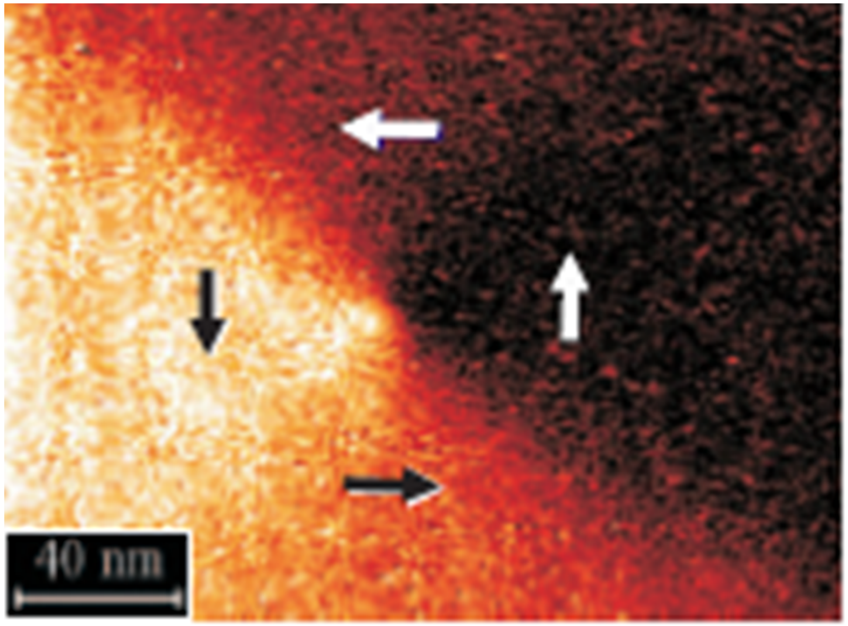




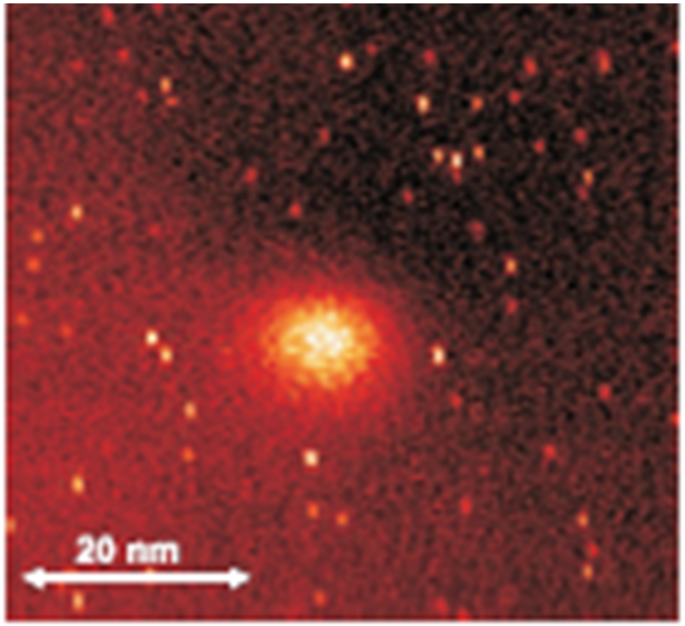
Fe islands, 200nm, 8nm thick
with Cr coated W tip: in plane sensitive

Nanoisland and nanoparticle

Magnetic Vortex States



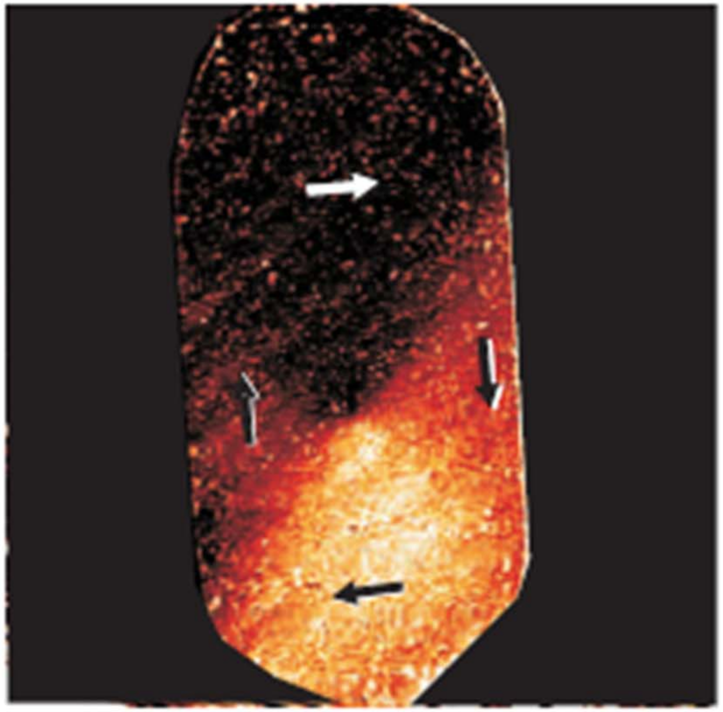
in plane sensitive



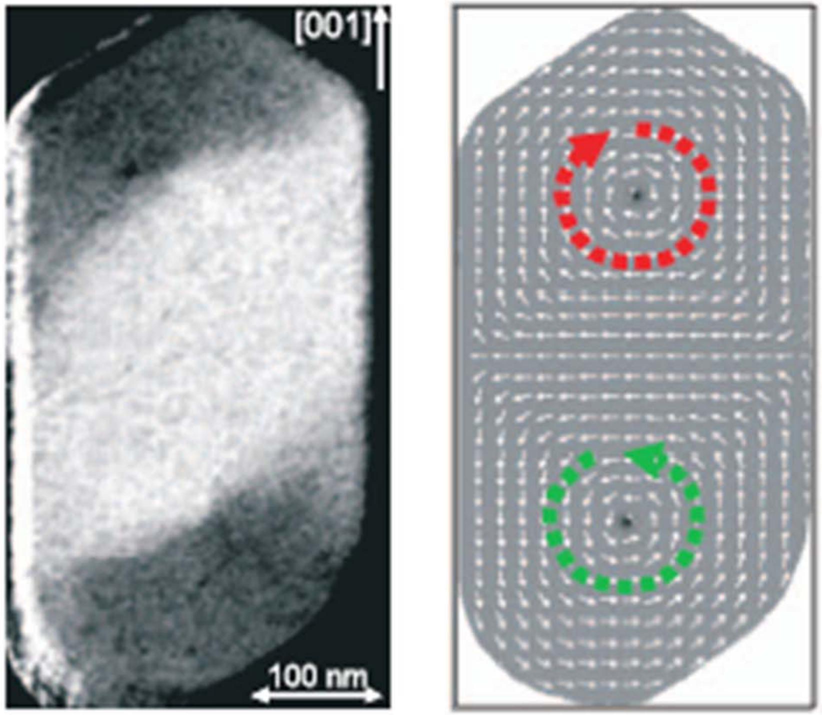
Out of plane sensitive

Nanoisland and nanoparticle

Magnetic Vortex States



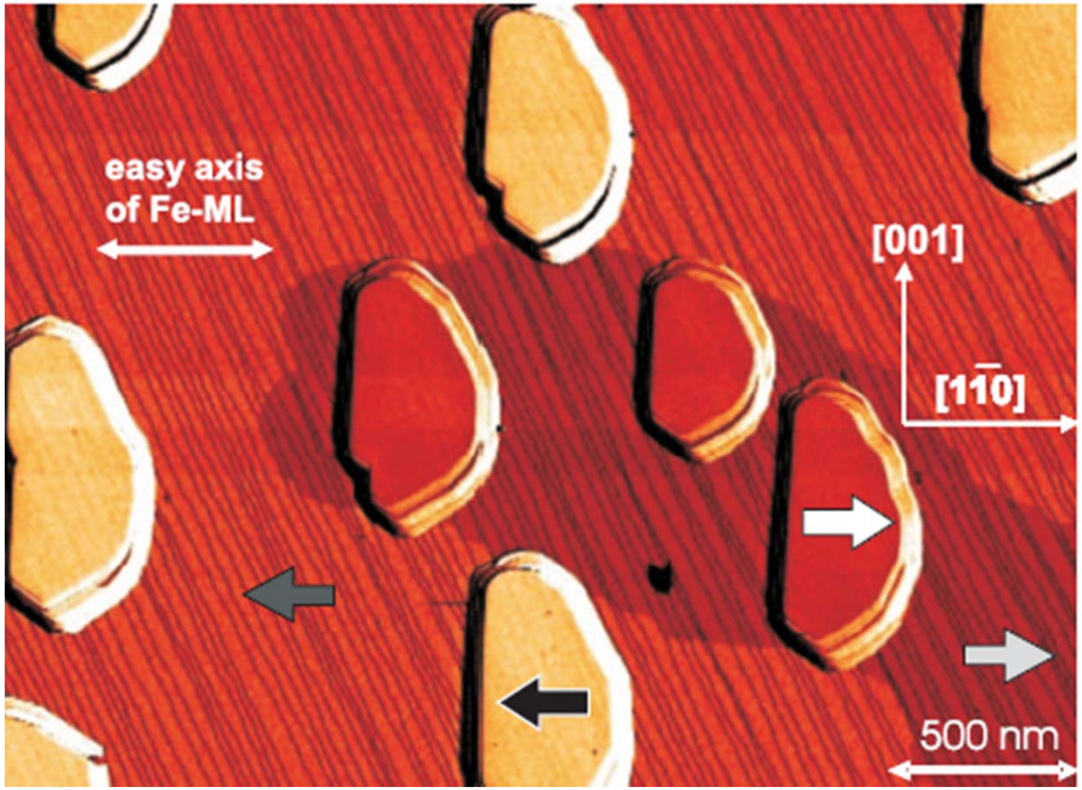
Fe island, 7.5nm thick



Fe island, 8.5nm thick

Nanoisland and nanoparticle

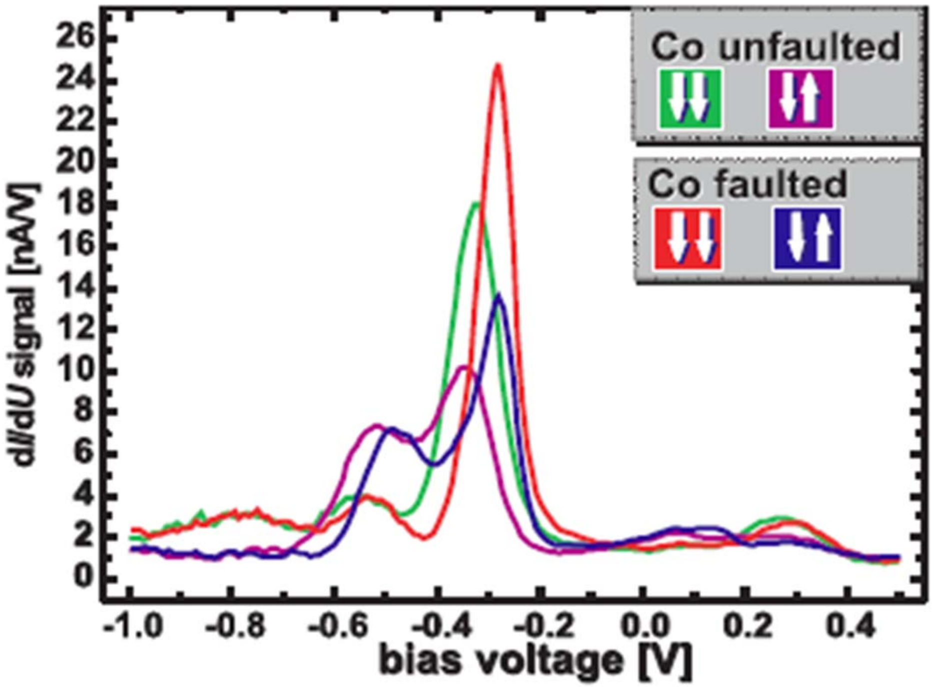
Single Domain States: favorable for small size and thickness

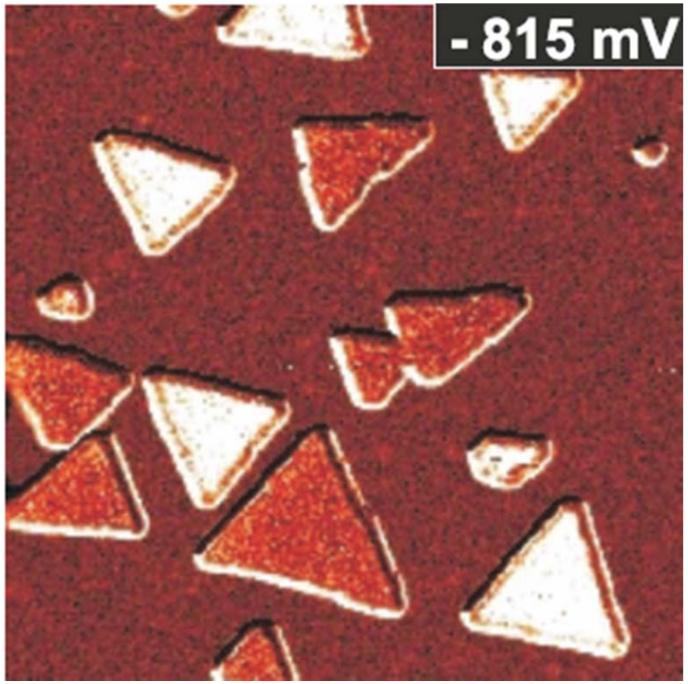


Fe monolayer and islands on W(110)

Nanoisland and nanoparticle

Single Domain States: favorable for small size and thickness

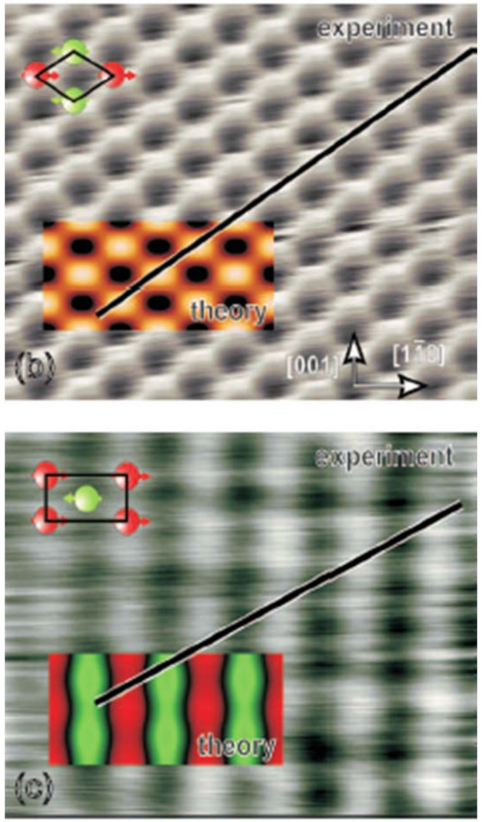


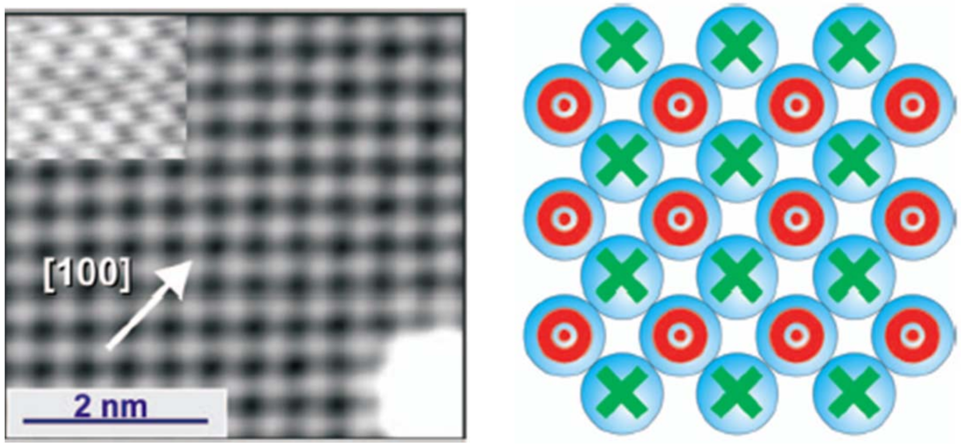


Co islands on Cu(111)

Atomic resolution spin mapping

Antiferromagnetic transition metal films



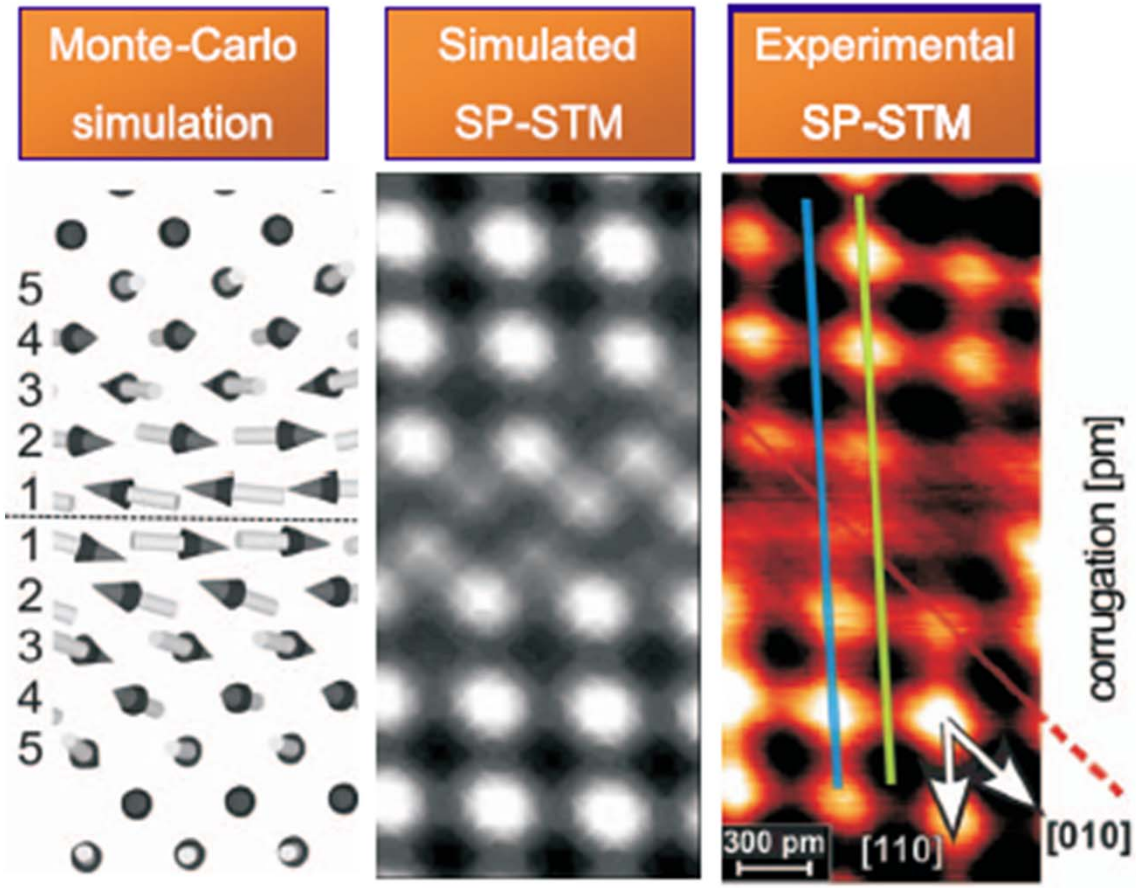


Fe ML on W(001), with Fe coated Tip

Mn ML on W(110), with Fe coated Tip

Atomic resolution spin mapping

Antiferromagnet domain wall



Fe ML on W(001)

Individual adatoms

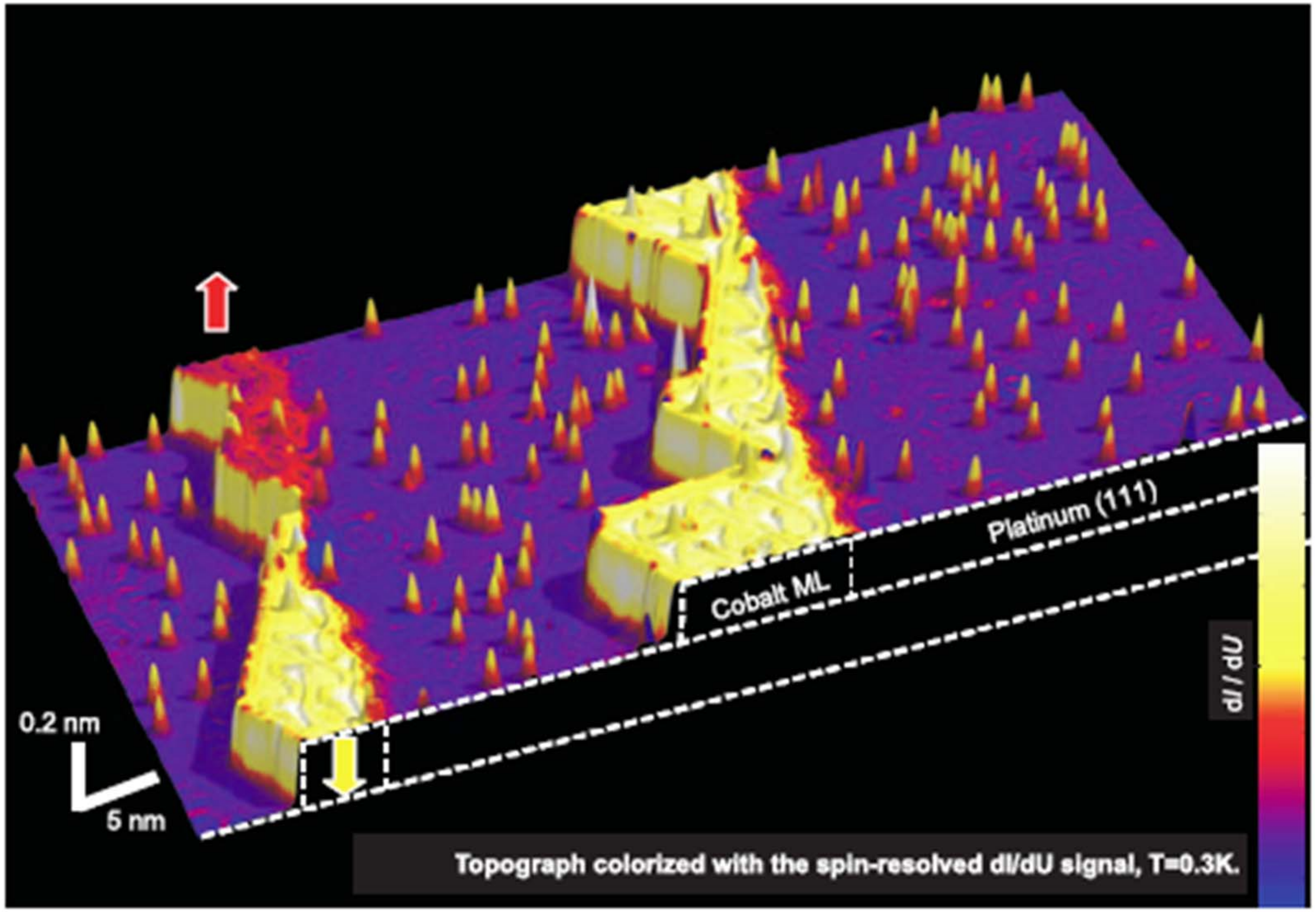
Focko Meier, *et al.*
Science **320**, 82 (2008);

Revealing Magnetic Interactions from Single-Atom Magnetization Curves

Focko Meier,* Lihui Zhou, Jens Wiebe,† Roland Wiesendanger

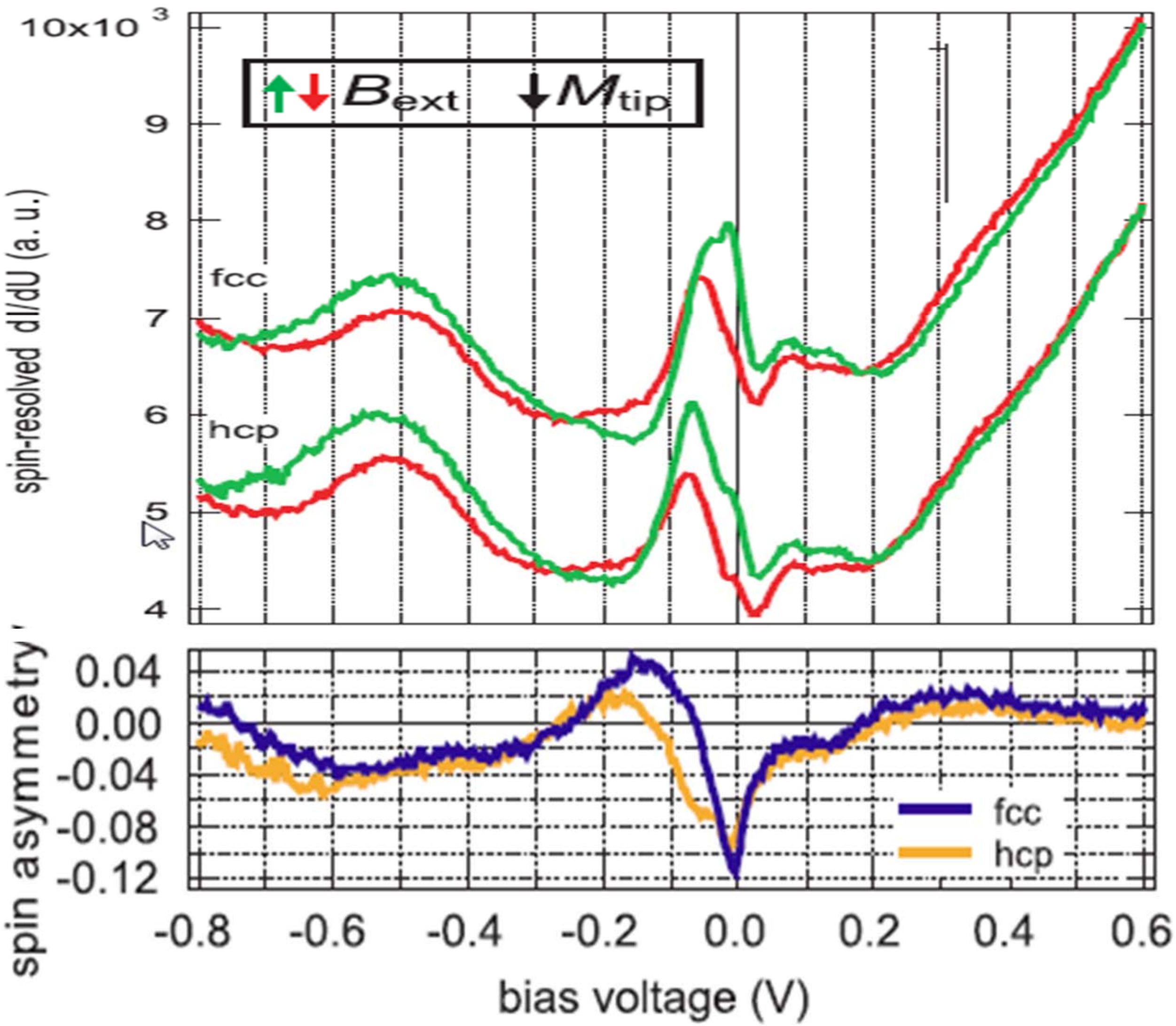
The miniaturization of magnetic devices toward the limit of single atoms calls for appropriate tools to study their magnetic properties. We demonstrate the ability to measure magnetization curves of individual magnetic atoms adsorbed on a nonmagnetic metallic substrate with use of a scanning tunneling microscope with a spin-polarized tip. We can map out low-energy magnetic interactions on the atomic scale as evidenced by the oscillating indirect exchange between a Co adatom and a nanowire on Pt(111). These results are important for the understanding of variations that are found in the magnetic properties of apparently identical adatoms because of different local environments.

Individual adatoms



Co on Pt(111), With Cr coated W tip

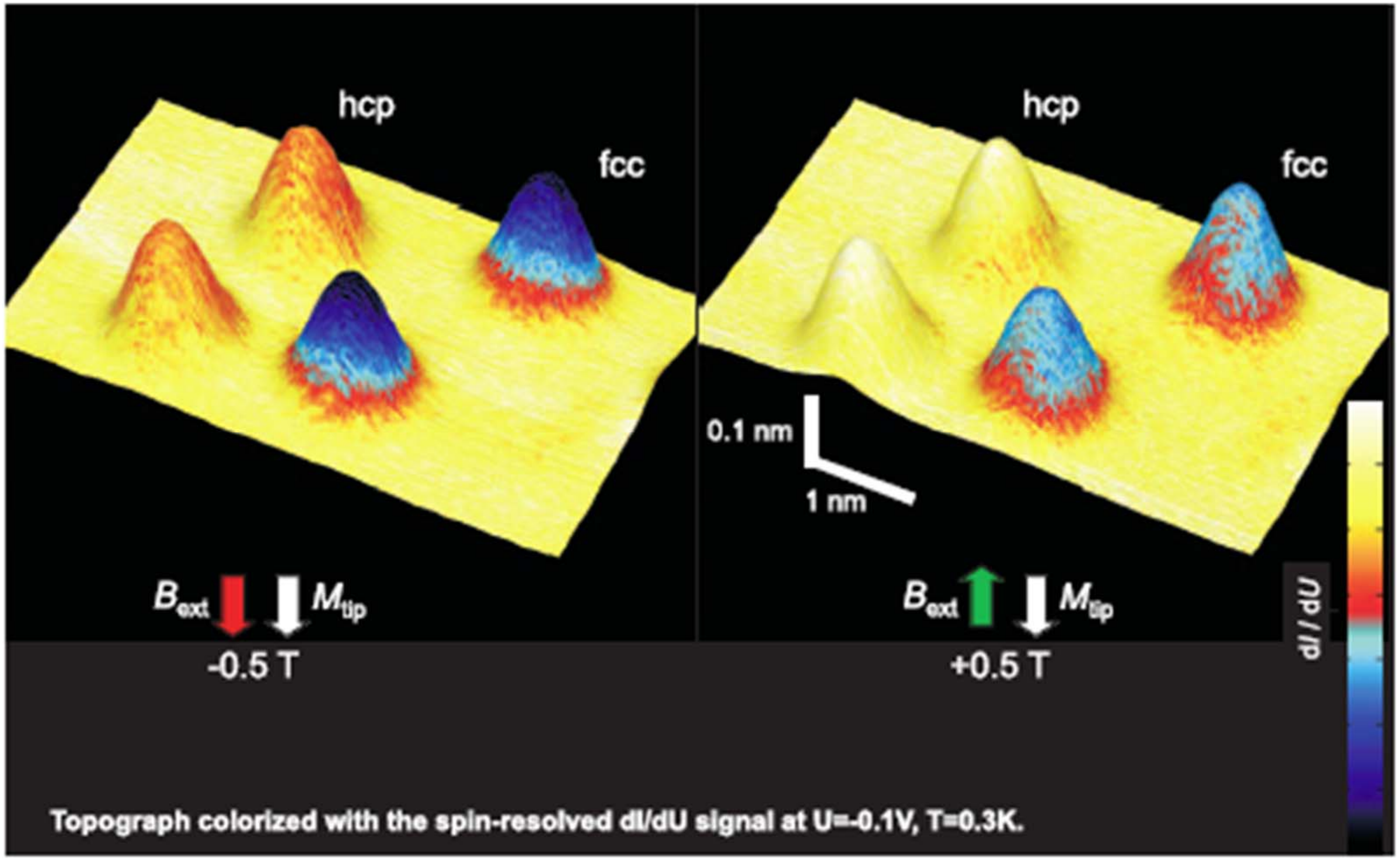
Individual adatoms



Co on Pt(111), With Cr coated W tip

Individual adatoms

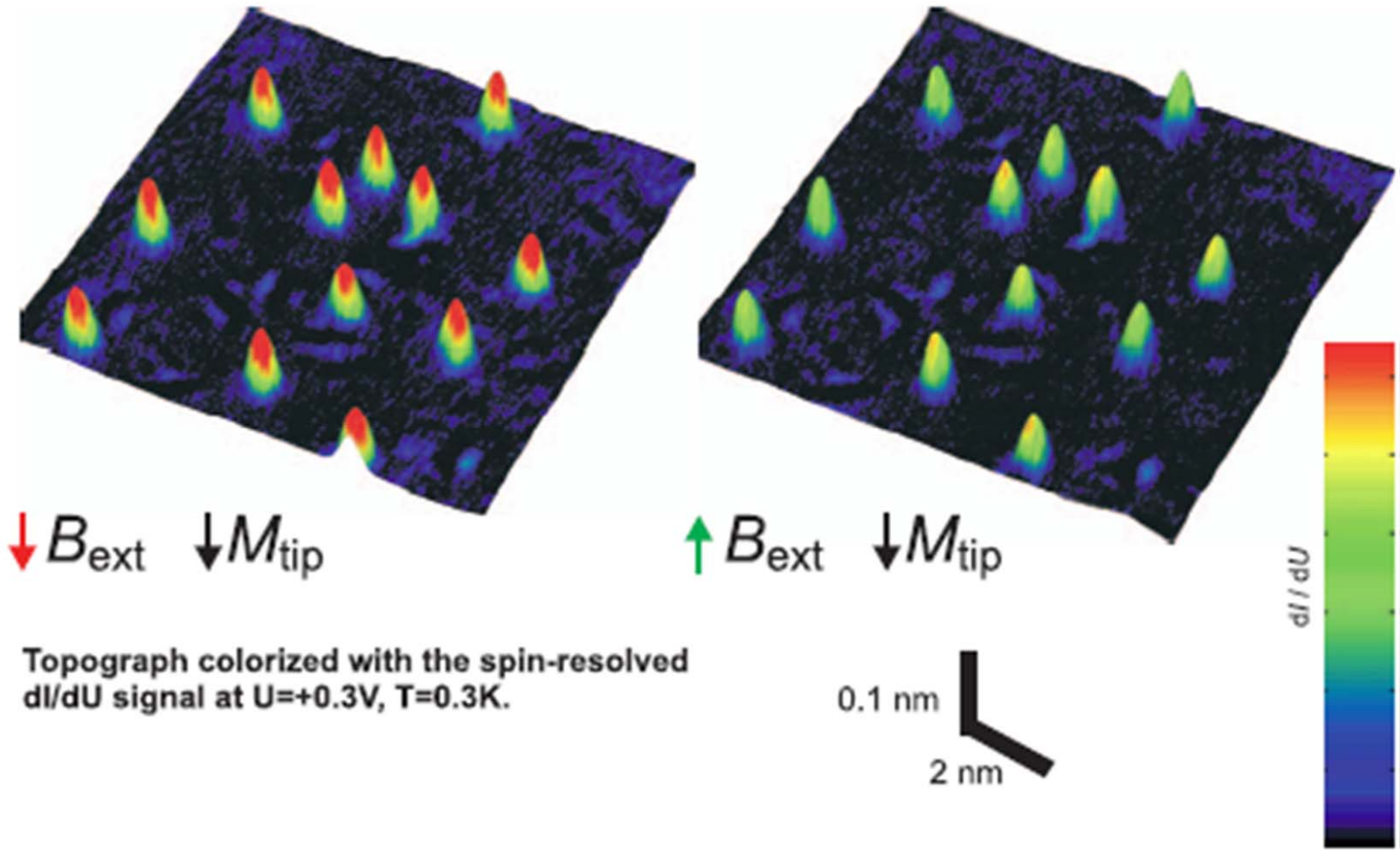
Bias Voltage: -0.1V



Co on Pt(111), With Cr coated W tip

Individual adatoms

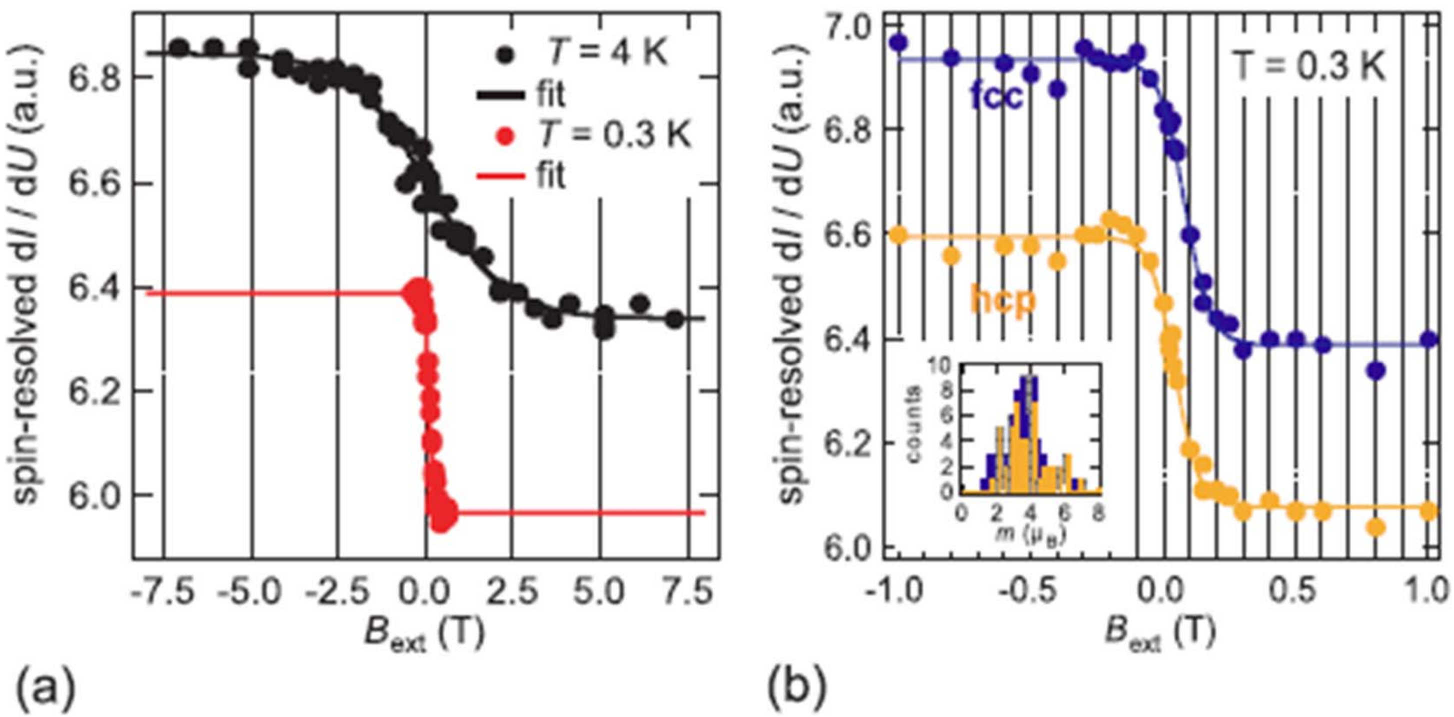
Bias Voltage: +0.3V



Co on Pt(111), With Cr coated W tip

Magnetization dynamics and spin transport

$$\langle M_A \rangle = M_{\text{sat}} \frac{\int_0^{2\pi} d\phi \int_0^{\pi} d\theta \sin\theta \cos\theta e^{-E(\theta,B_{\text{ext}})/k_B T}}{\int_0^{2\pi} d\phi \int_0^{\pi} d\theta \sin\theta e^{-E(\theta,B_{\text{ext}})/k_B T}},$$

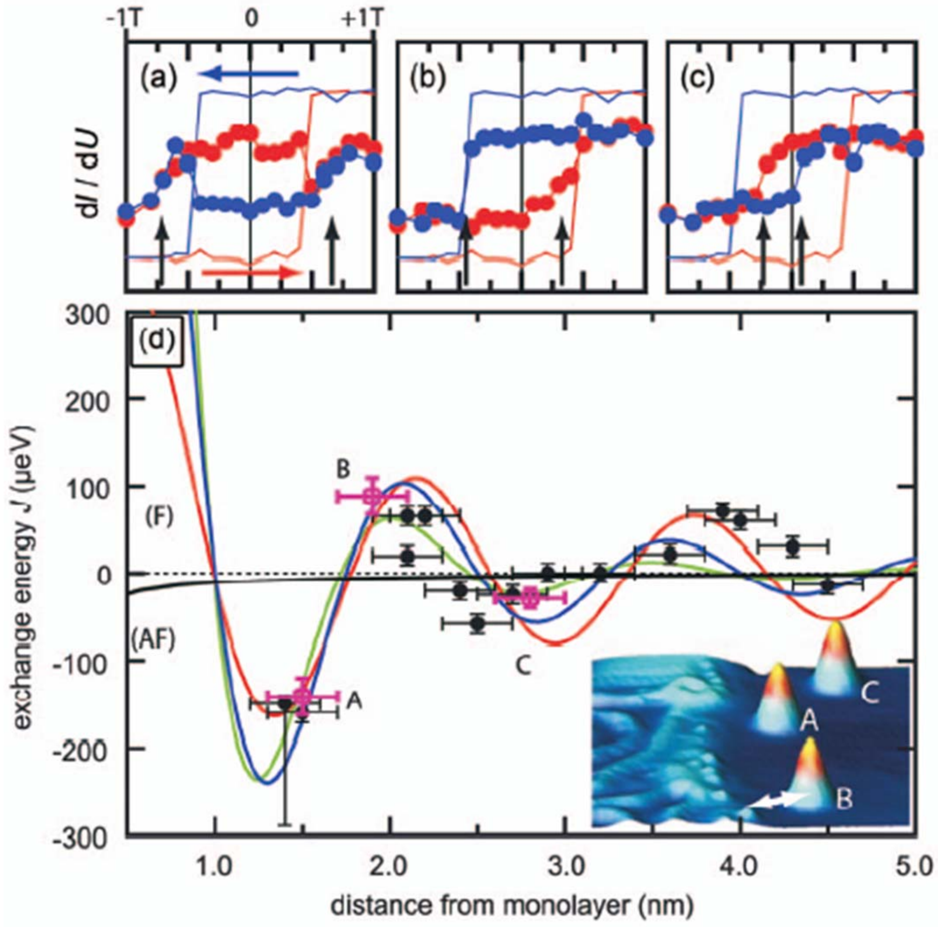


Co on Pt(111), With Cr coated W tip

Magnetization dynamics and spin transport

Exchange Interaction

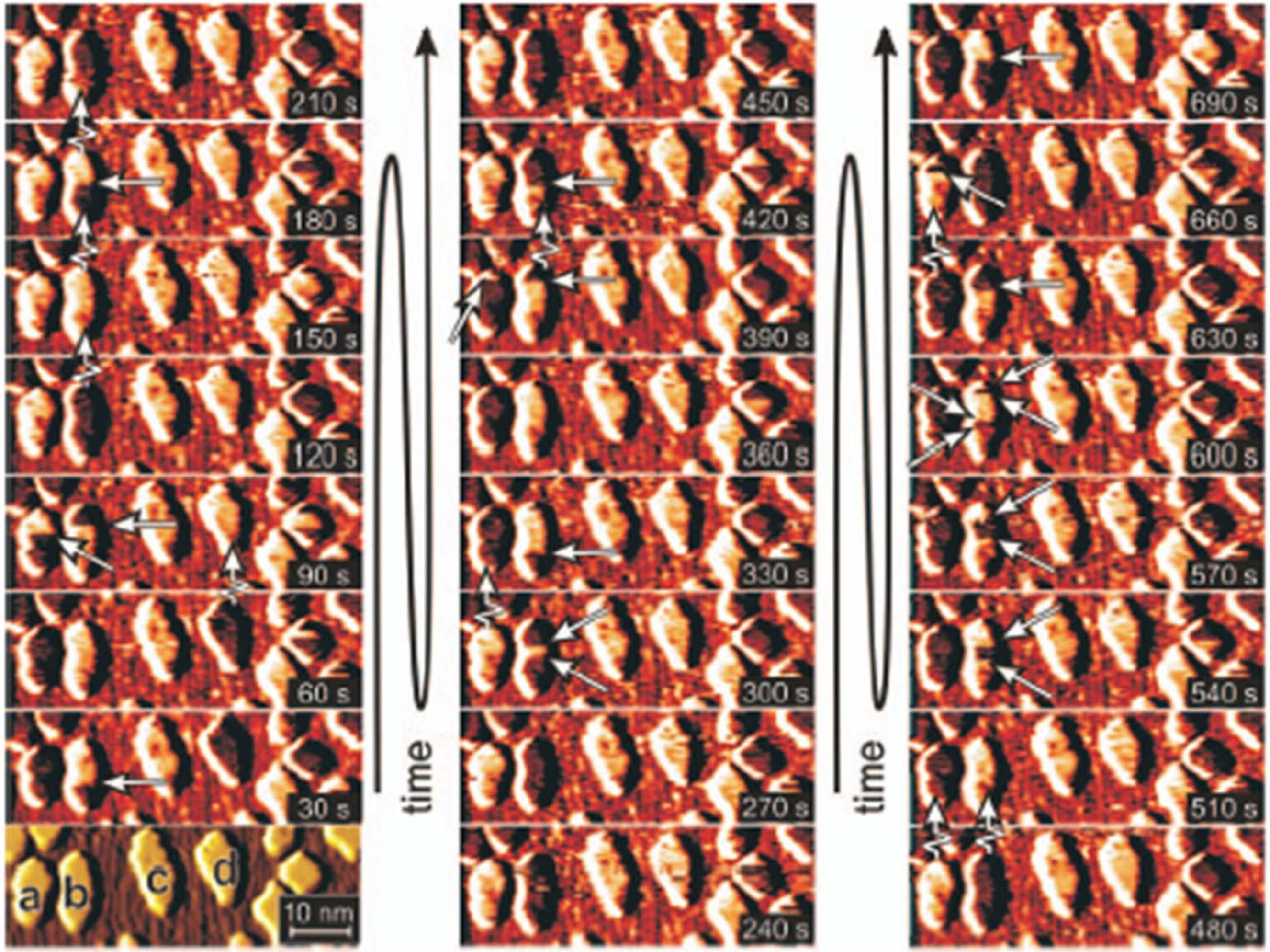
$$J_{\mathrm{RKKY}}(d) \propto \frac{\cos(2k_F d)}{(2k_F d)^D}.$$



Co on Pt(111), With Cr coated W tip

Magnetization dynamics and spin transport

Magnetic Swtiching



Fe on Mo(110)

Magnetization dynamics and spin transport

Science AAAS

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

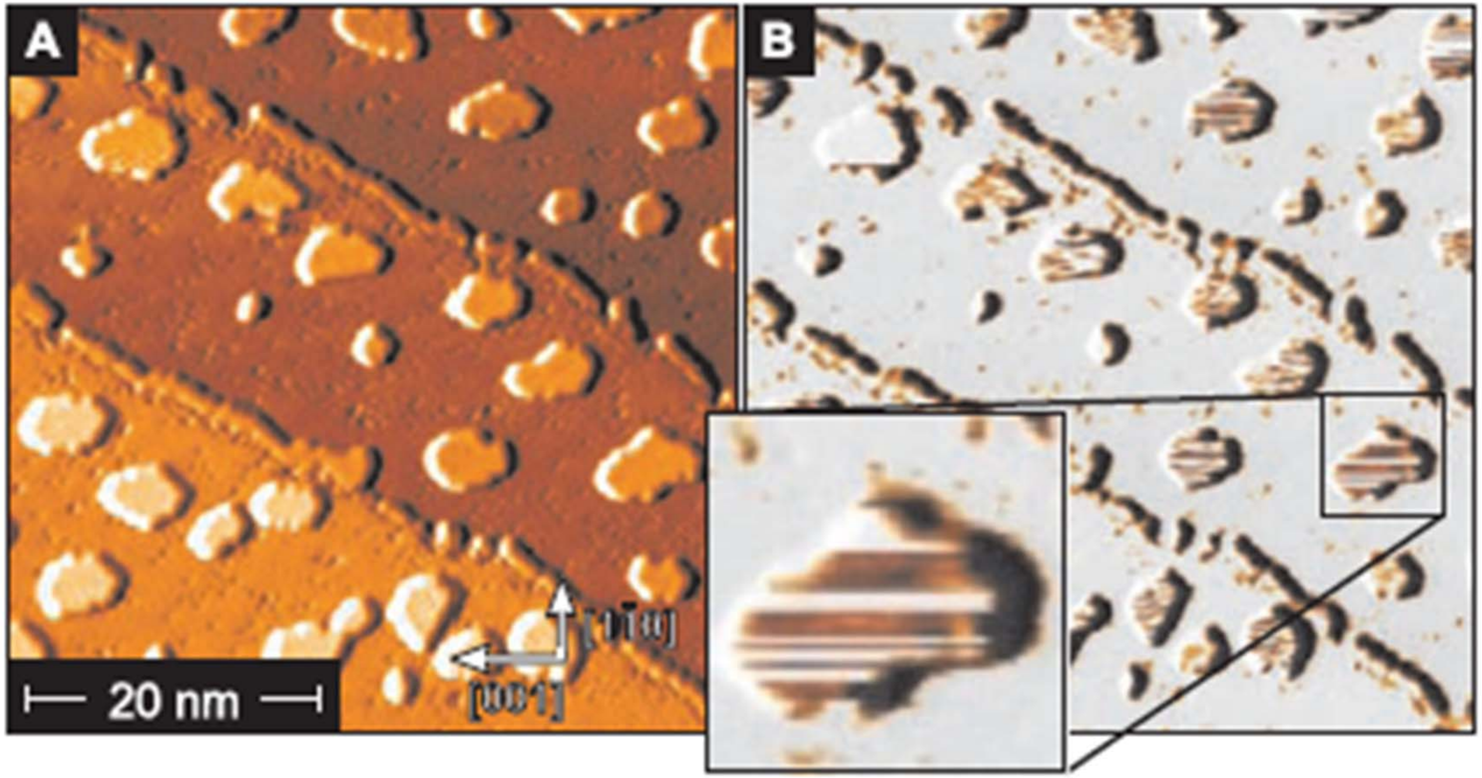
Current-Induced Magnetization Switching with a Spin-Polarized Scanning Tunneling Microscope

S. Krause,*§ L. Berbil-Bautista,*† G. Herzog, M. Bode,‡ R. Wiesendanger

Switching the magnetization of a magnetic bit by injection of a spin-polarized current offers the possibility for the development of innovative high-density data storage technologies. We show how individual superparamagnetic iron nanoislands with typical sizes of 100 atoms can be addressed and locally switched using a magnetic scanning probe tip, thus demonstrating current-induced magnetization reversal across a vacuum barrier combined with the ultimate resolution of spin-polarized scanning tunneling microscopy. Our technique allows us to separate and quantify three fundamental contributions involved in magnetization switching (i.e., current-induced spin torque, heating the island by the tunneling current, and Oersted field effects), thereby providing an improved understanding of the switching mechanism.

Magnetization dynamics and spin transport

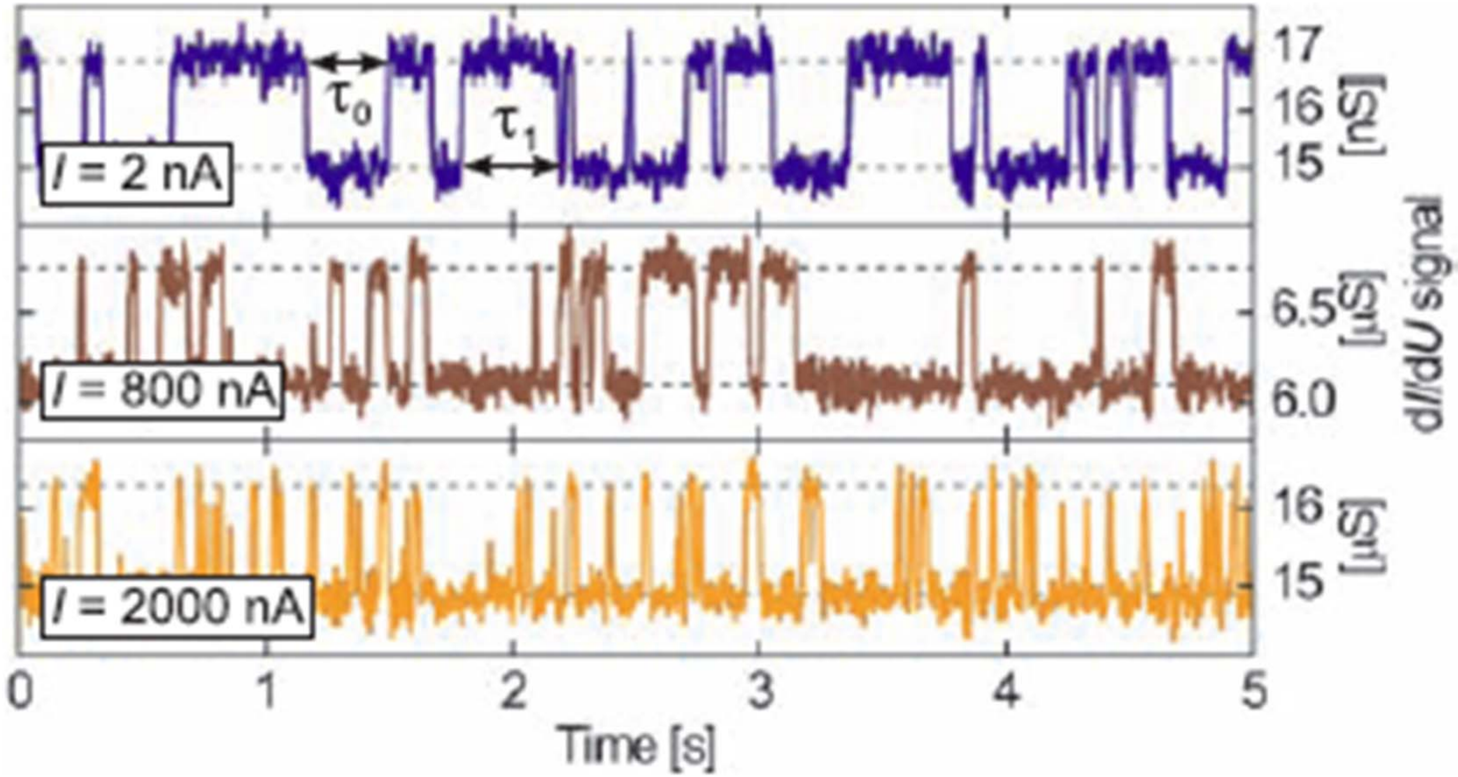
Magnetic Swtiching



Fe on W(110)

Magnetization dynamics and spin transport

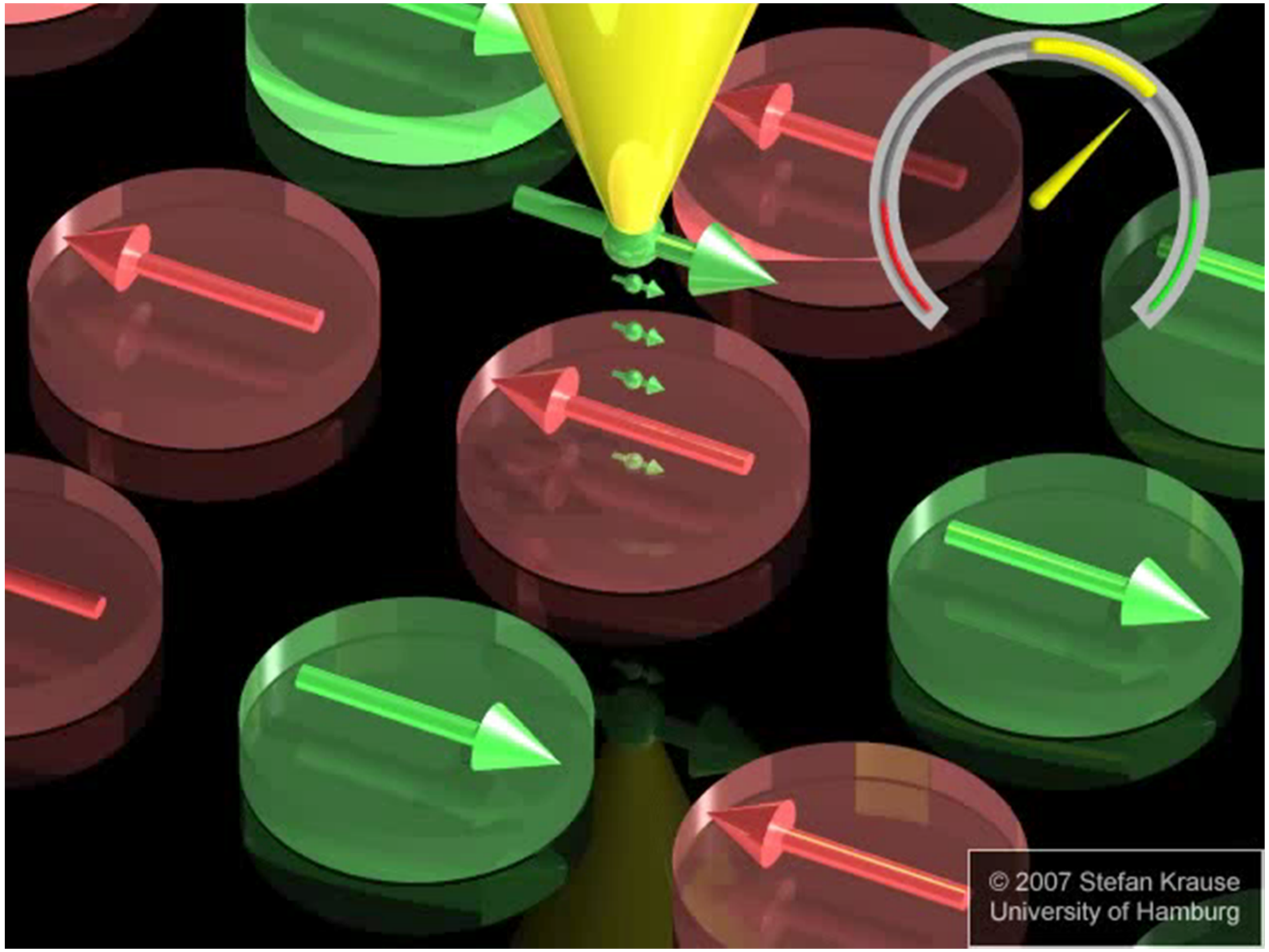
Magnetic Swtiching



Fe on W(110)

Magnetization dynamics and spin transport

Video: Spin Polarized Current Induced Spin Switch



Magnetization dynamics and spin transport

Science AAAS

Alexander Ako Khajetoorians, *et al.*
Science **332**, 1062 (2011);

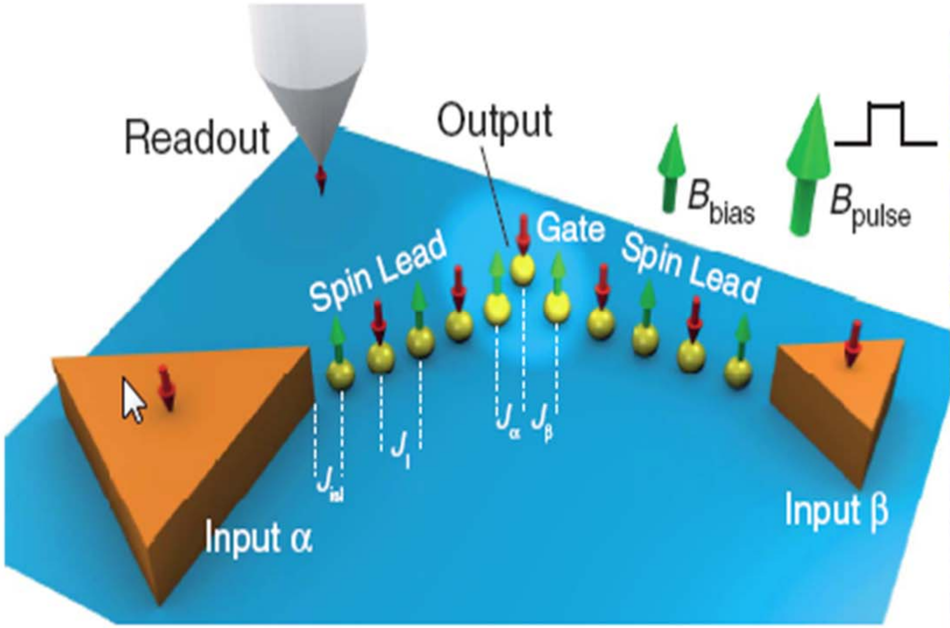
Realizing All-Spin–Based Logic Operations Atom by Atom

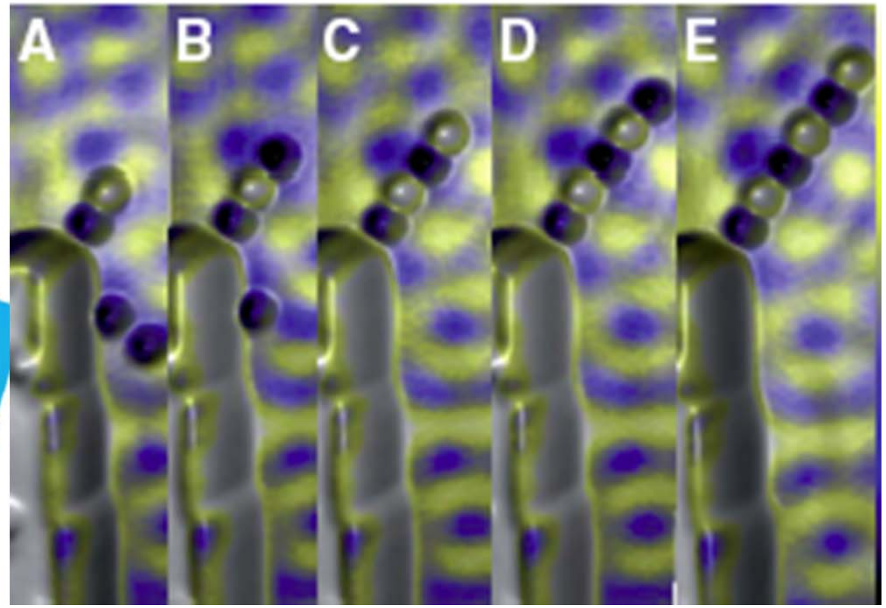
Alexander Ako Khajetoorians, Jens Wiebe,* Bruno Chilian, Roland Wiesendanger

An ultimate goal of spintronic research is the realization of concepts for atomic-scale all-spin–based devices. We combined bottom-up atomic fabrication with spin-resolved scanning tunneling microscopy to construct and read out atomic-scale model systems performing logic operations. Our concept uses substrate-mediated indirect exchange coupling to achieve logical interconnection between individual atomic spins. Combined with spin frustration, this concept enables various logical operations between inputs, such as NOT and OR.

Magnetization dynamics and spin transport

Spin Logic Circuit

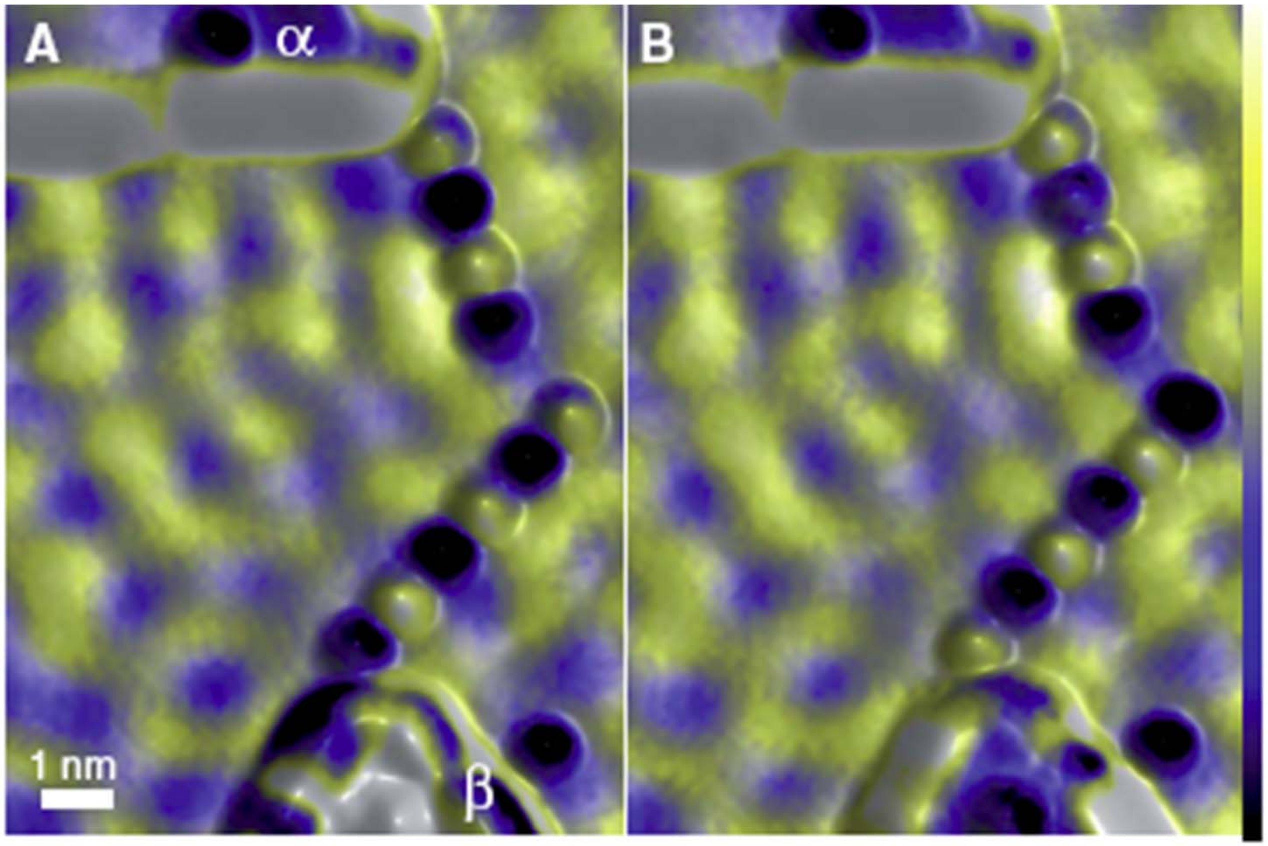




Fe on Cu(111)

Magnetization dynamics and spin transport

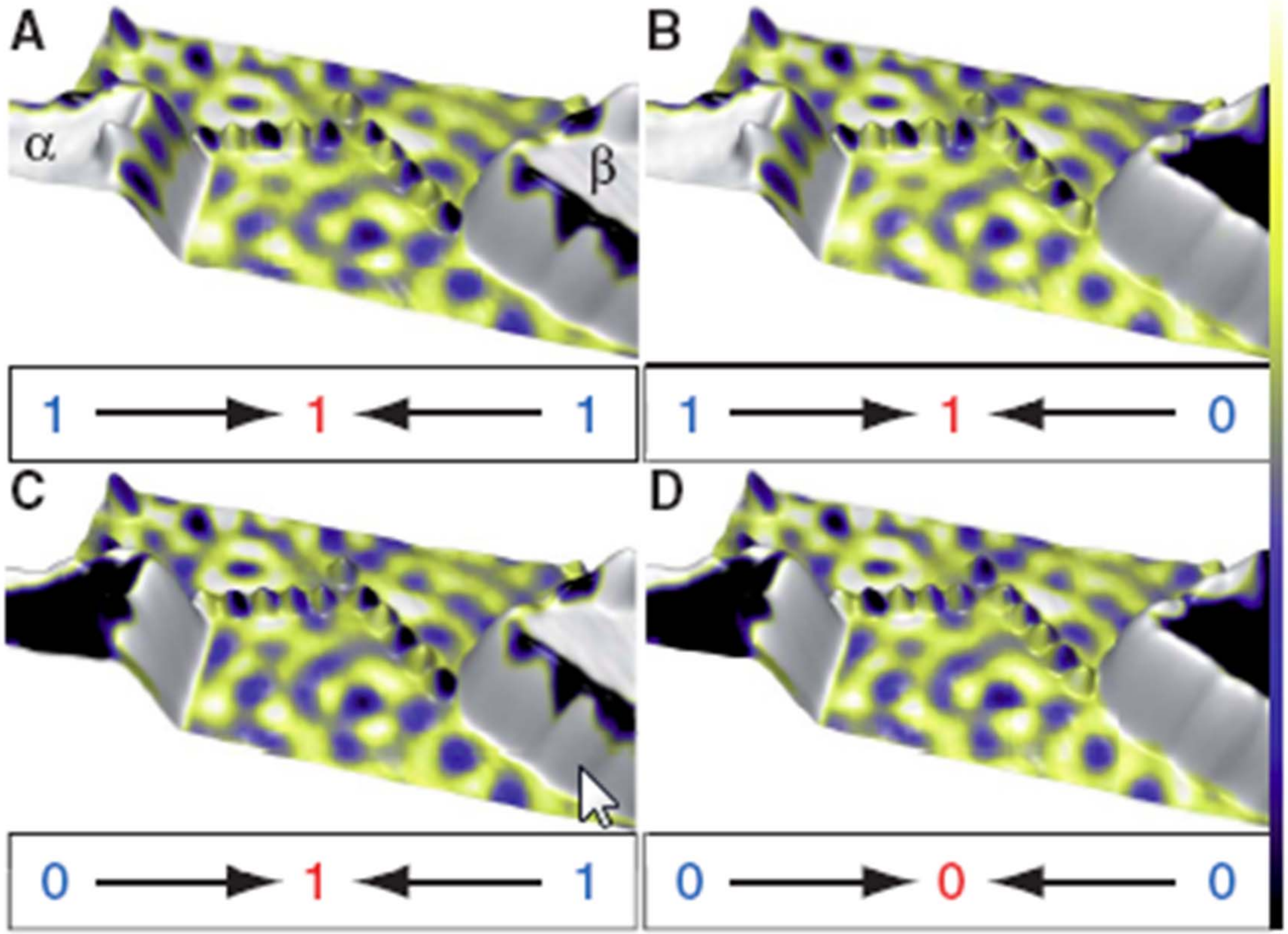
Spin Logic Circuit



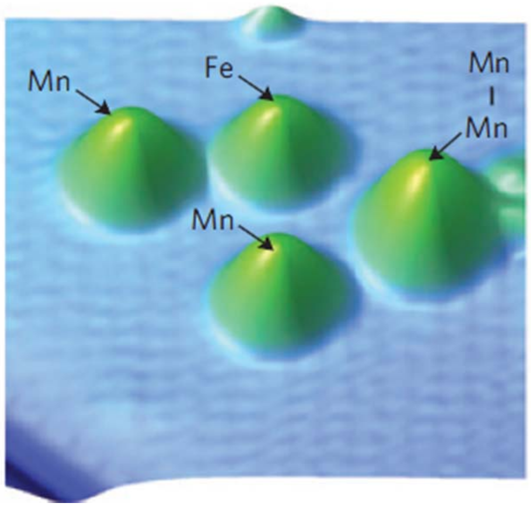
Fe on Cu(111)

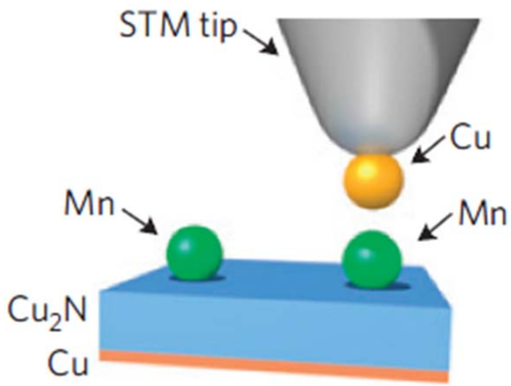
Magnetization dynamics and spin transport

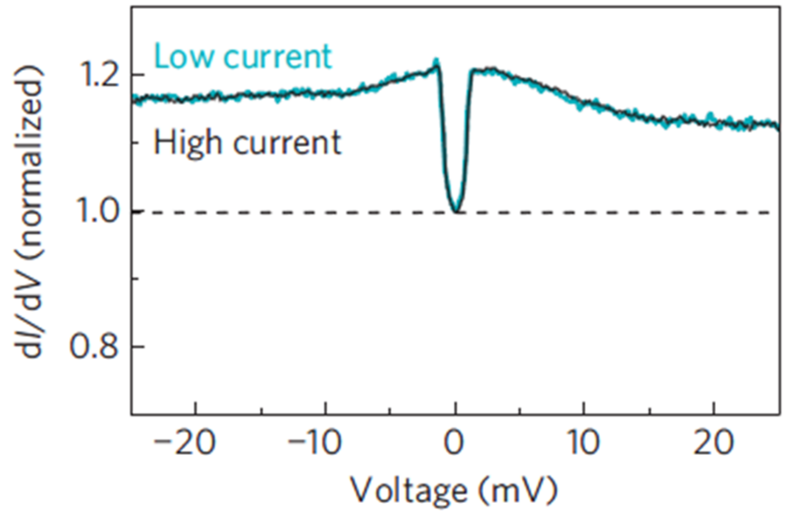
OR Logic Circuit



Controlling quantum spin states with currents







Non-SP STM tip
Spin flip IETS
B = 7 T
T = 0.5 K
Vex = 0.7 meV

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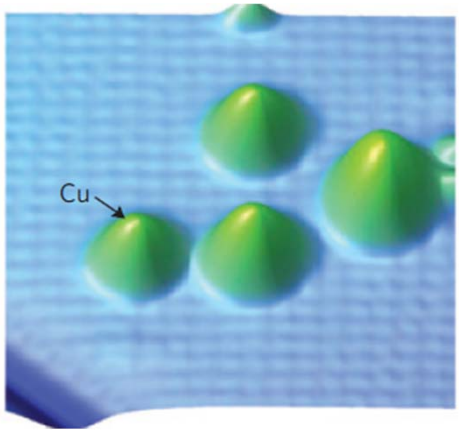
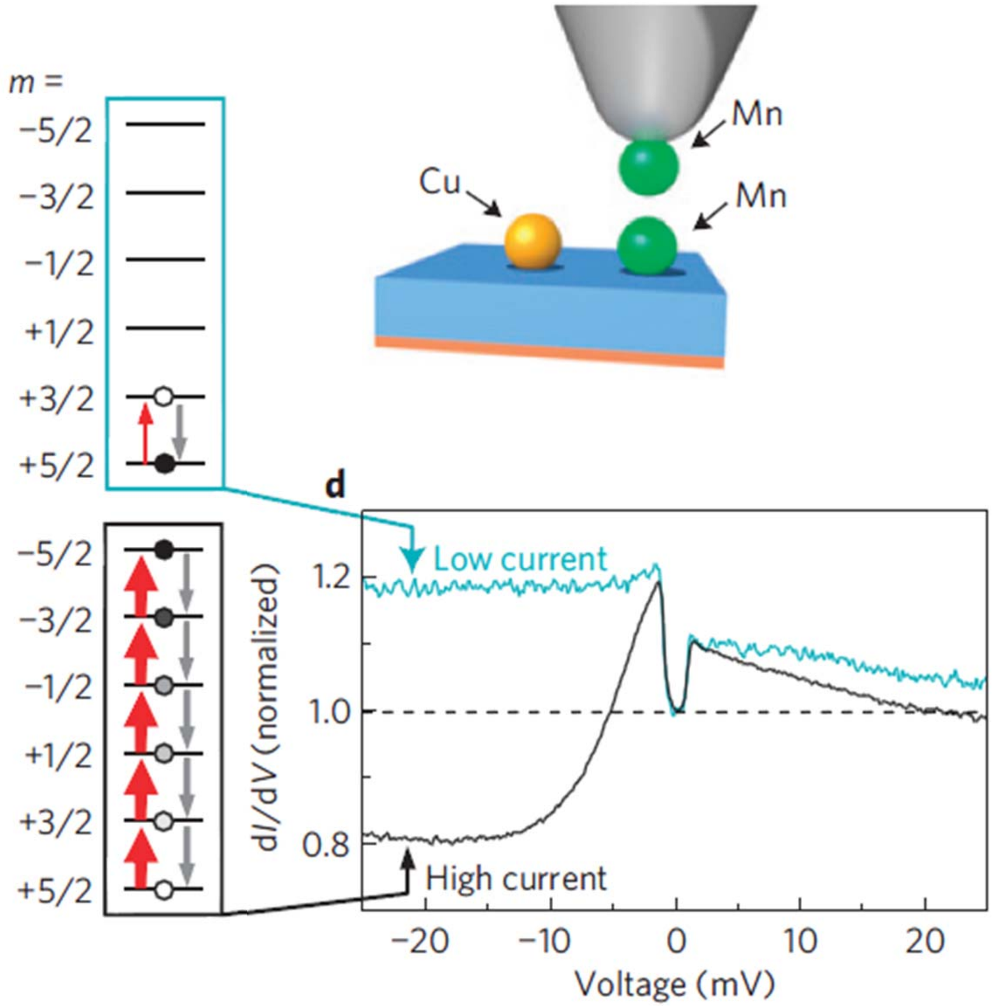
Controlling quantum spin states with currents

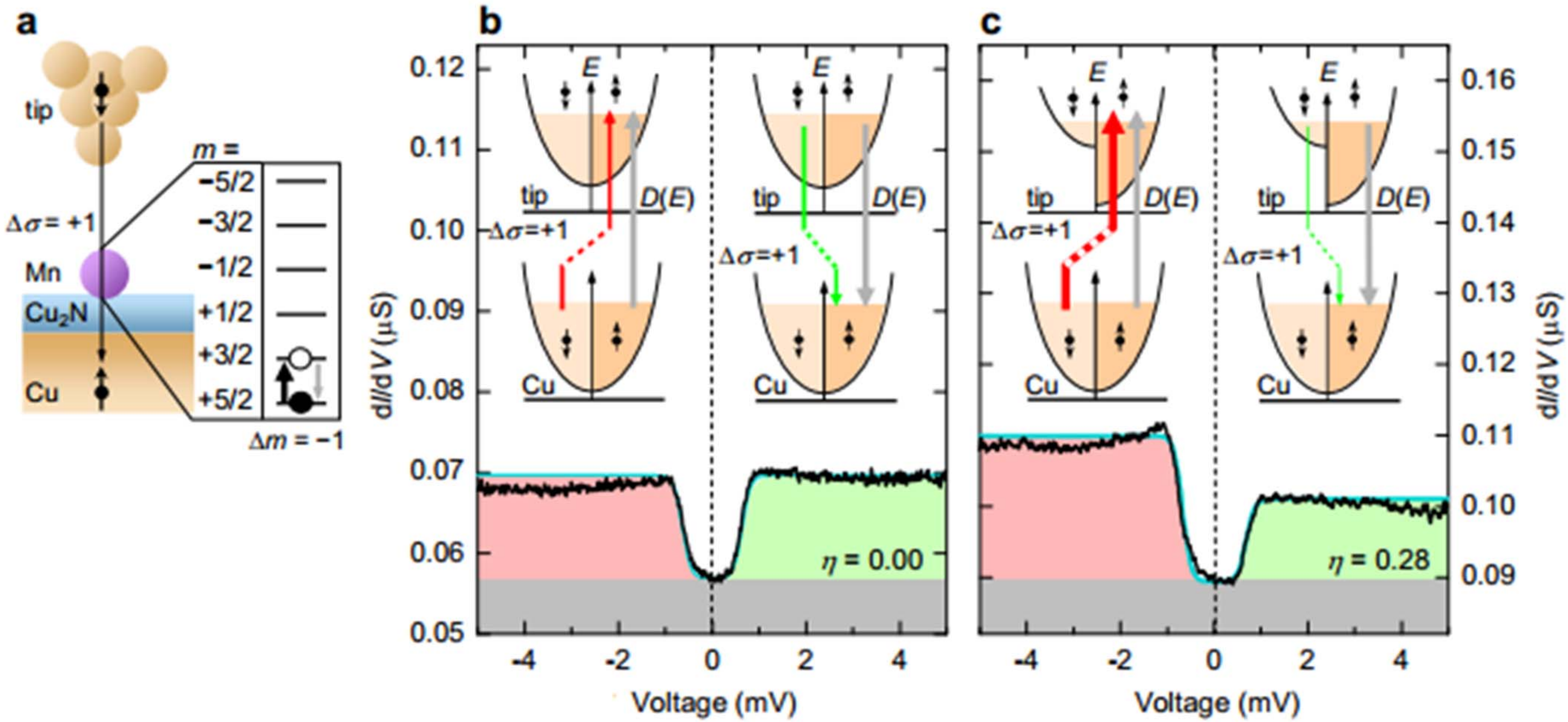




SP STM tip
Spin flip IETS
B = 7 T
T = 0.5 K
Vex = 0.7 meV

Controlling quantum spin states with currents

Origin of asymmetrical IETS: tip spin polarization



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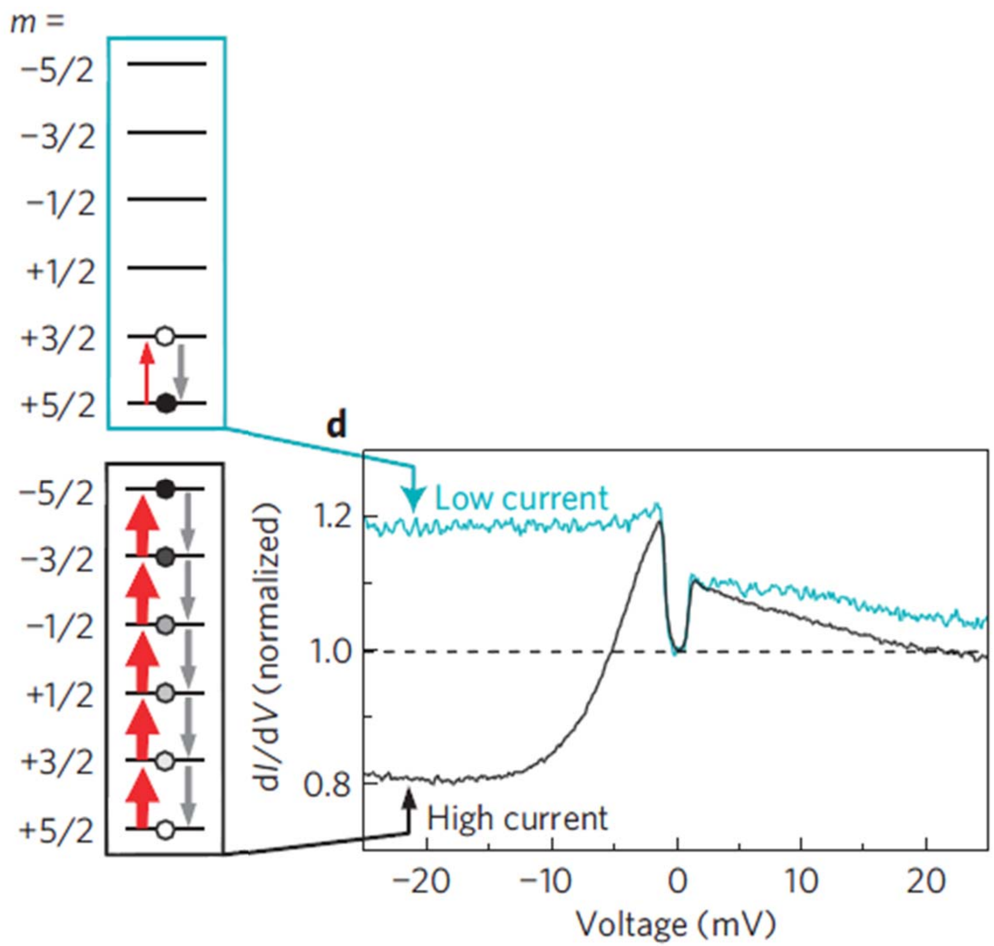
Controlling quantum spin states with currents

Current dependence of IETS: spin state population



Life time information!

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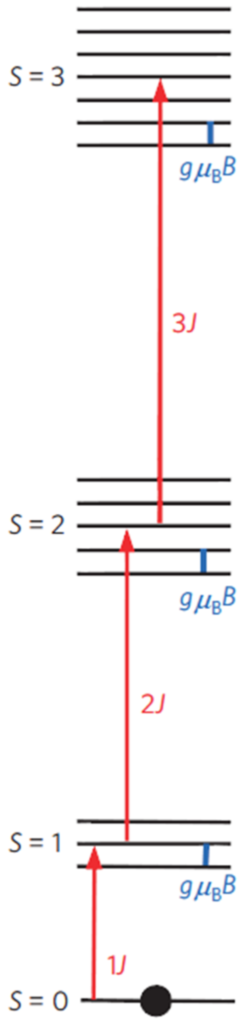
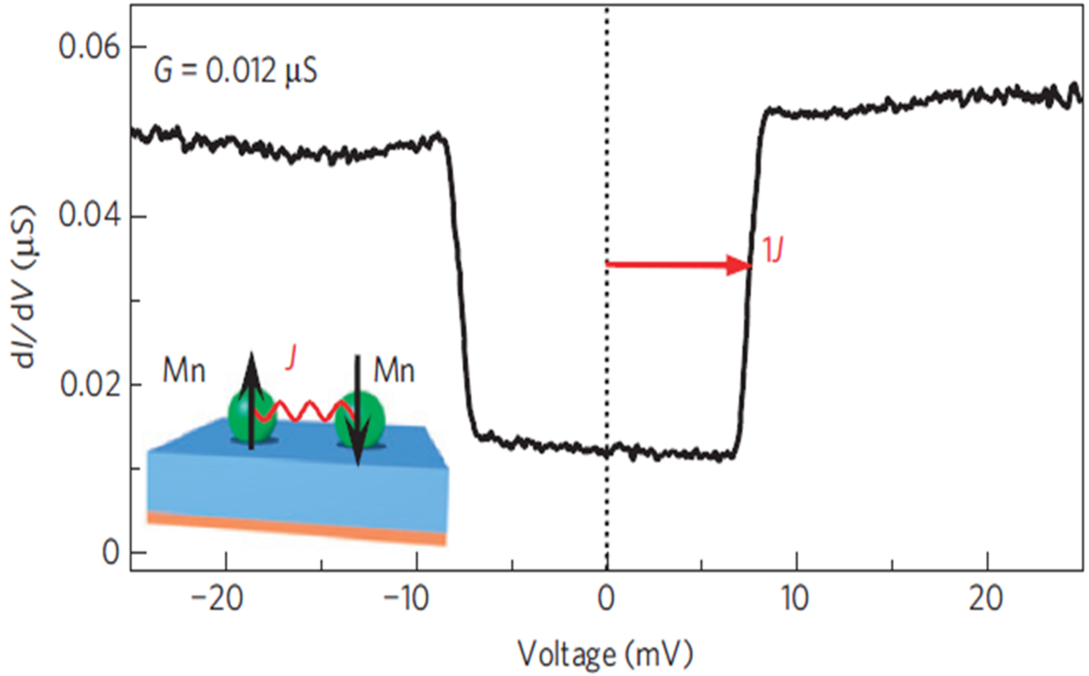
Controlling quantum spin states with currents

Excitation from excited state: evidence on dimer





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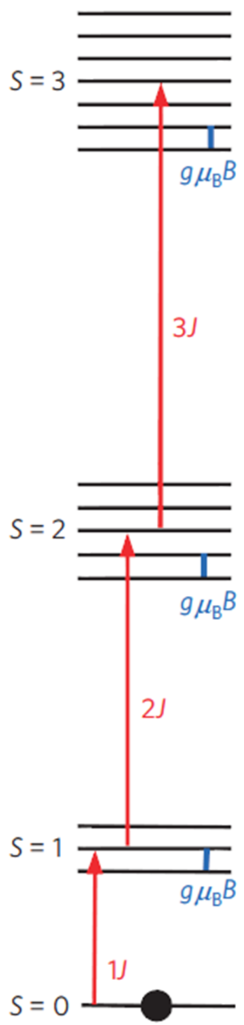
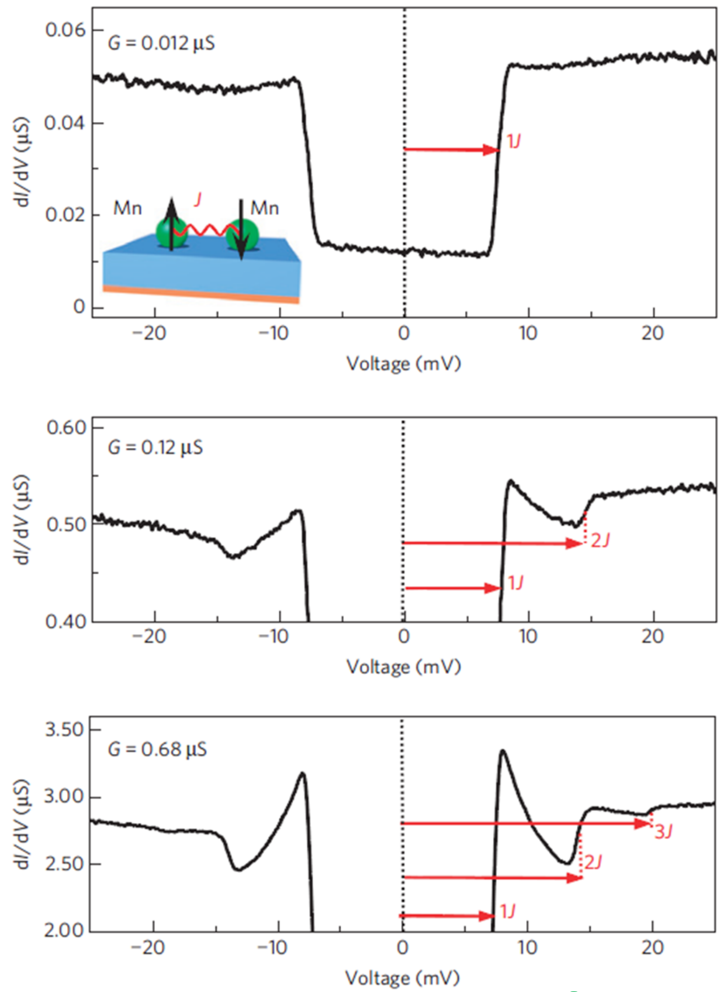
Controlling quantum spin states with currents

Excitation from excited state: evidence on dimer





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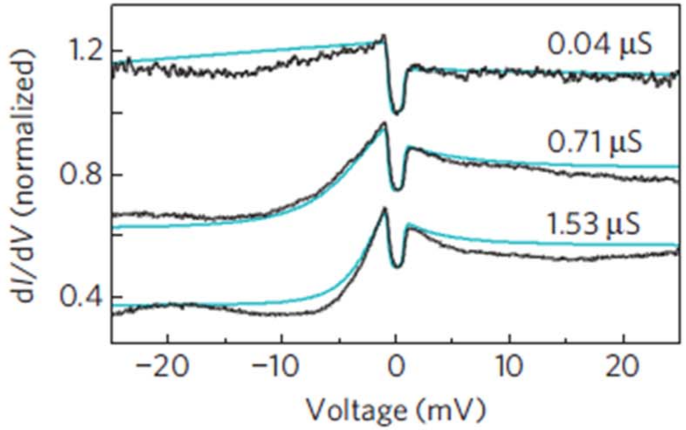
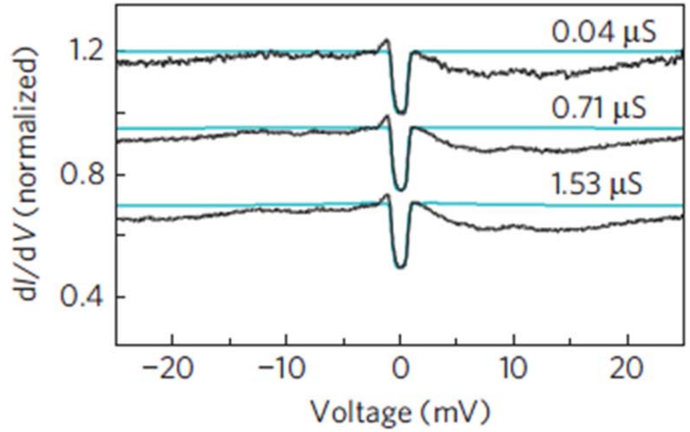
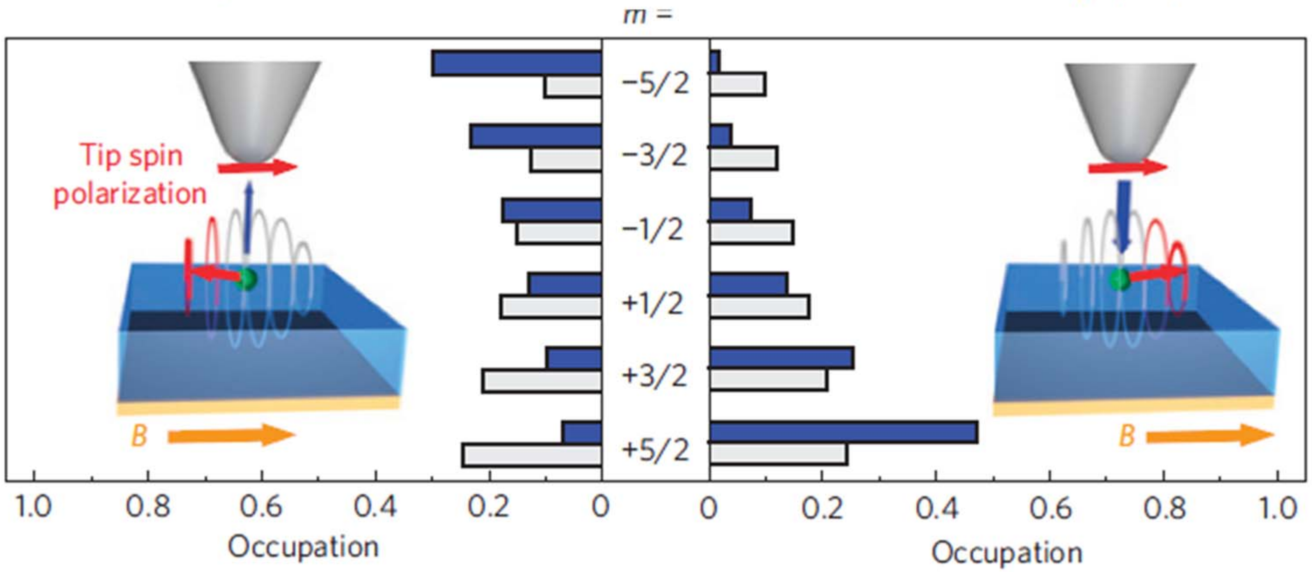
Controlling quantum spin states with currents

Excited state population: SP v.s. Non-SP





Bias effect



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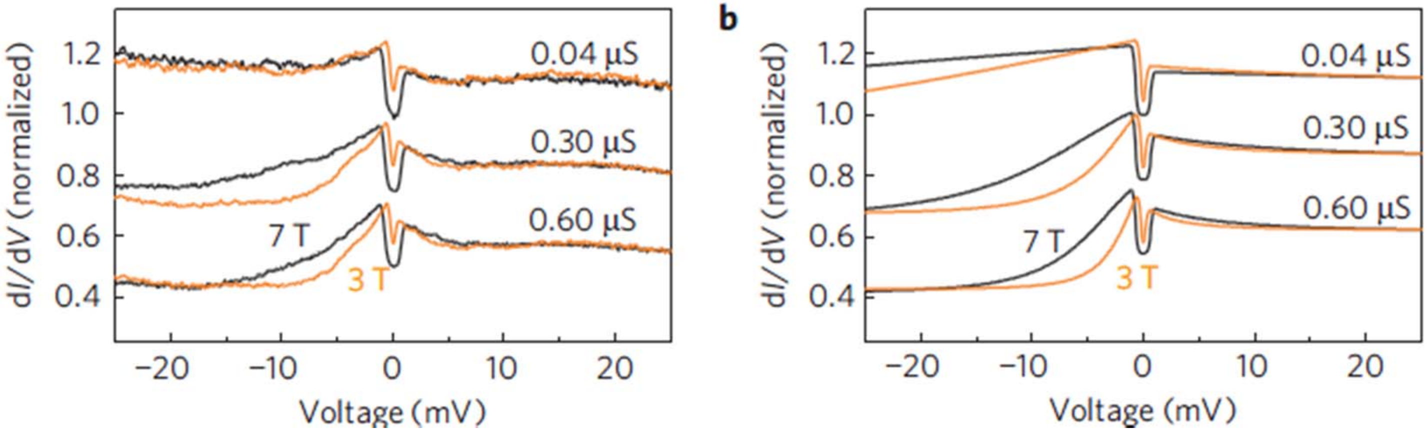
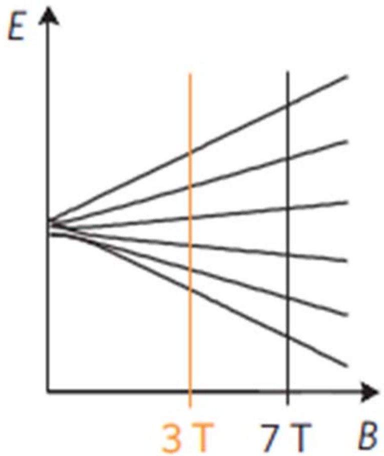
Controlling quantum spin states with currents

Spin lifetime and B field effect



B field effect



m	τ_i(3 T)	τ_i(7 T)
−5/2	0.35 ns	0.18 ns
−3/2	0.25 ns	0.12 ns
−1/2	0.26 ns	0.12 ns
+1/2	0.35 ns	0.14 ns
+3/2	0.73 ns	0.25 ns
+5/2	——	——

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Electron Spin Relaxation Times

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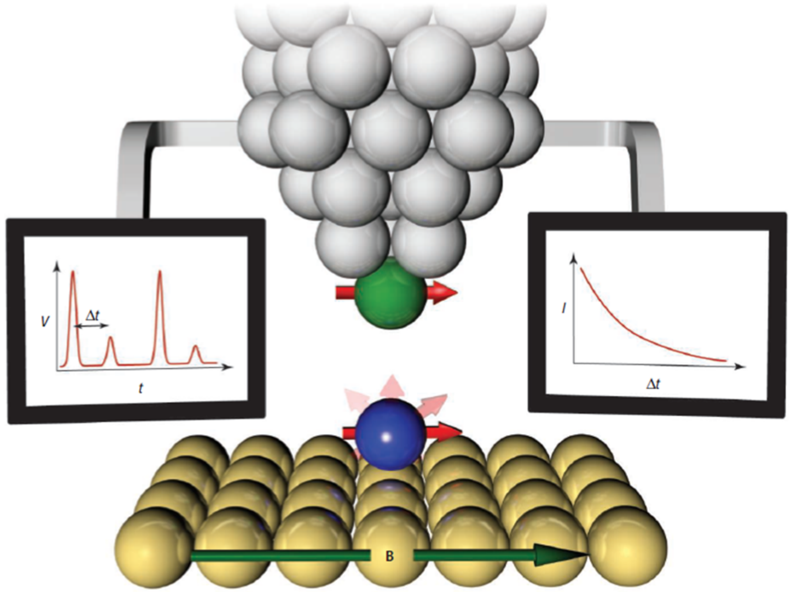


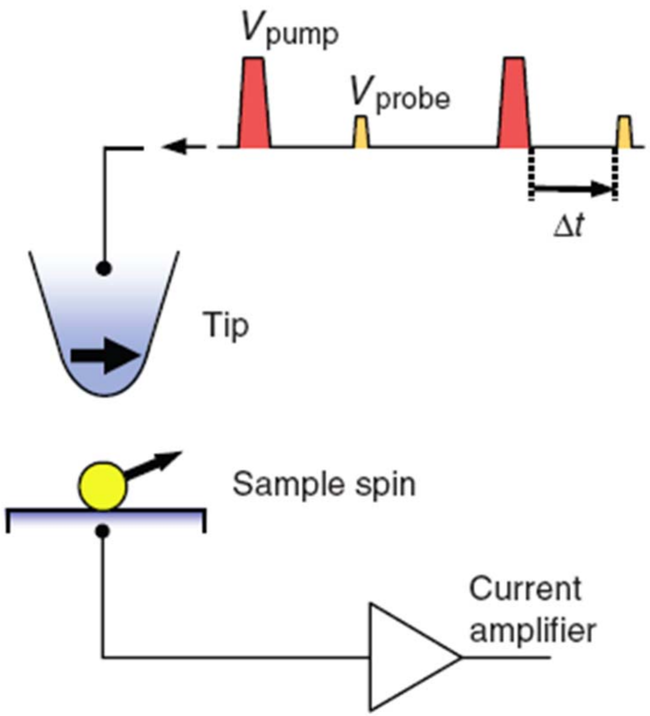
Measurement of Fast Electron Spin Relaxation Times with Atomic Resolution

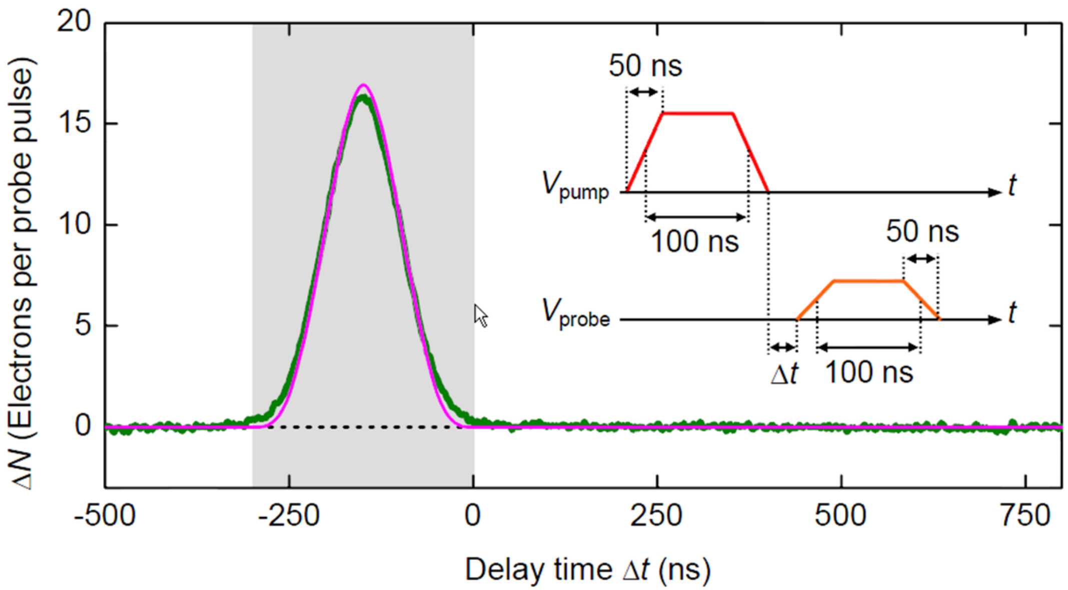
Sebastian Loth,[1*] Markus Etzkorn,[2] Christopher P. Lutz,[1] D. M. Eigler,[1] Andreas J. Heinrich[1*]

Single spins in solid-state systems are often considered prime candidates for the storage of quantum information, and their interaction with the environment the main limiting factor for the realization of such schemes. The lifetime of an excited spin state is a sensitive measure of this interaction, but extending the spatial resolution of spin relaxation measurements to the atomic scale has been a challenge. We show how a scanning tunneling microscope can measure electron spin relaxation times of individual atoms adsorbed on a surface using an all-electronic pump-probe measurement scheme. The spin relaxation times of individual Fe-Cu dimers were found to vary between 50 and 250 nanoseconds. Our method can in principle be generalized to monitor the temporal evolution of other dynamical systems.

Electron Spin Relaxation Times

Spin sensitive pump-probe measurement scheme





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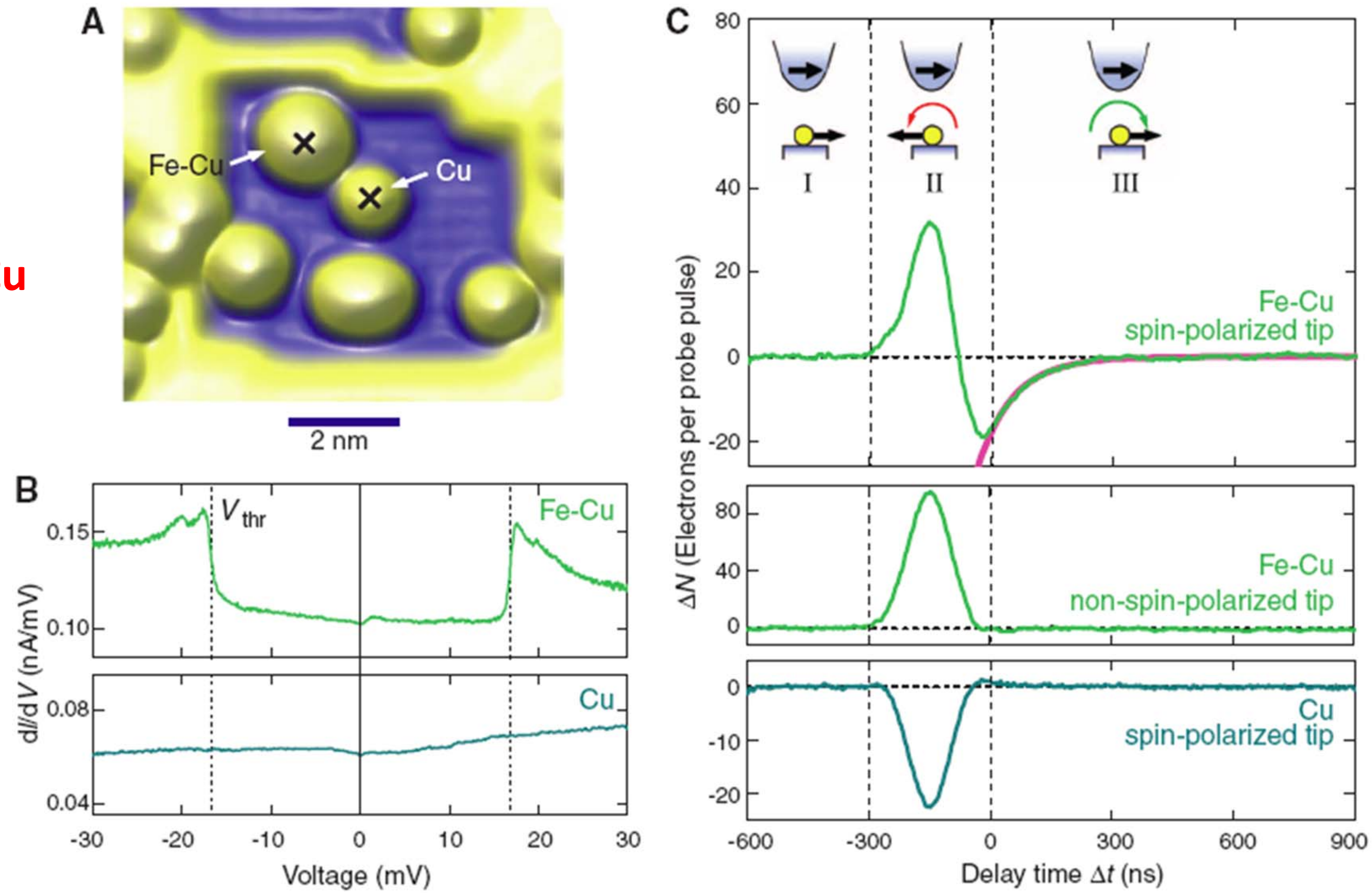
Electron Spin Relaxation Times

Spin sensitive pump-probe measurement

B = 7T
S = 2 for Fe-Cu
SP: Mn /tip



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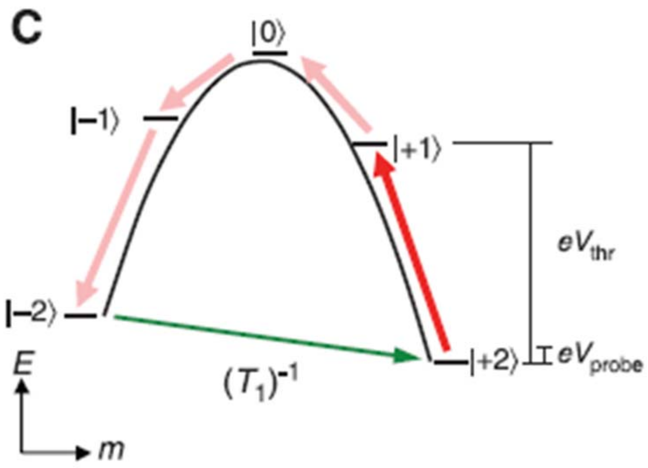
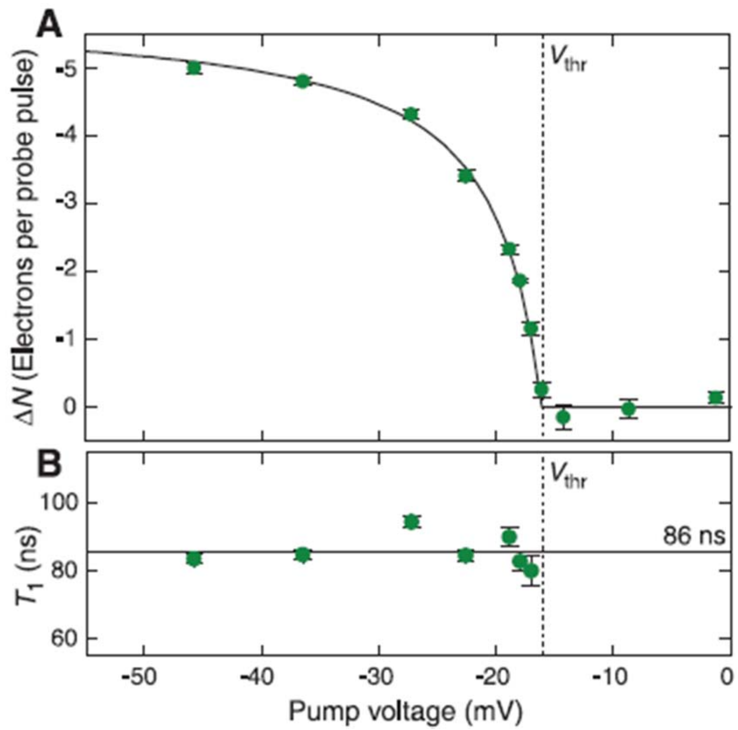
Electron Spin Relaxation Times

Spin sensitive pump-probe threshold

Why Fe-Cu: large anisotropy





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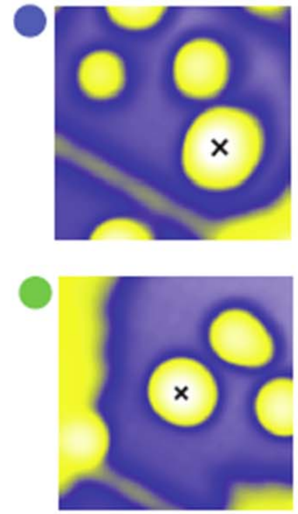
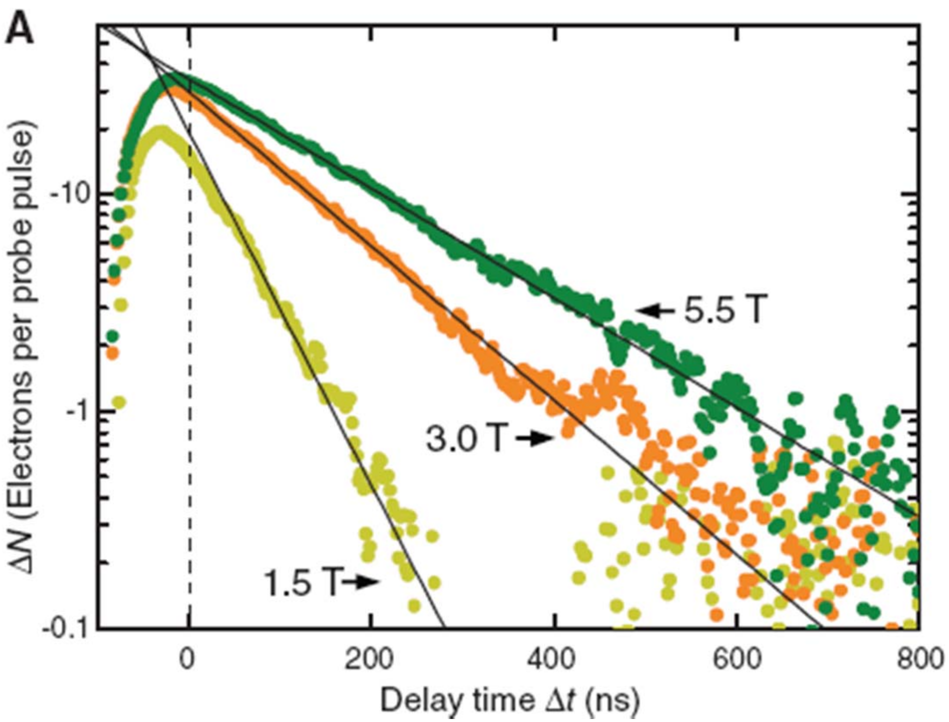
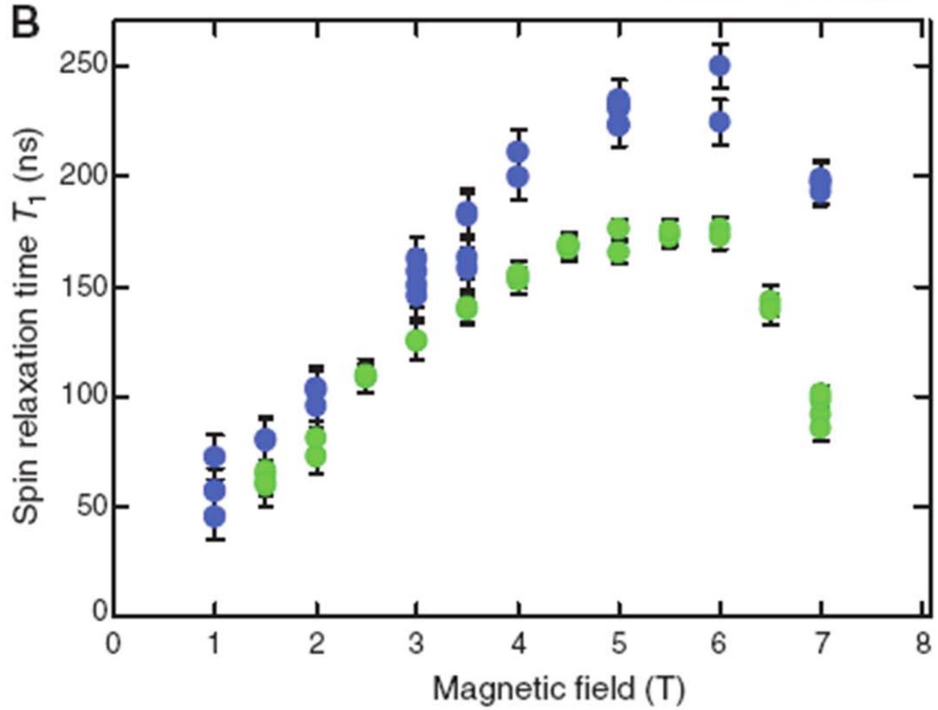
Electron Spin Relaxation Times



Spin relaxation time





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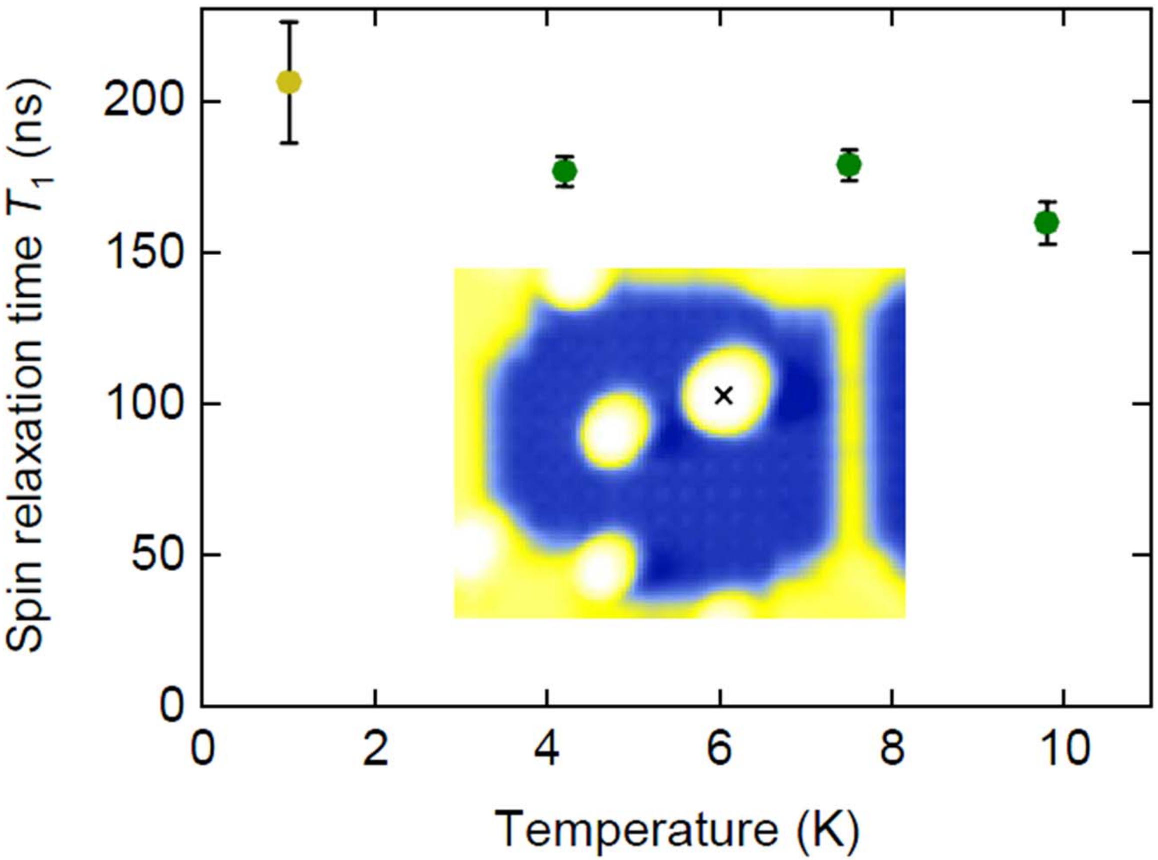
Electron Spin Relaxation Times

Temperature dependence



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Electron Spin Relaxation Times

Atomic spatial resolution: Movie

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Question:

Faster dynamics (ps - fs)?

More methods?