Universität Augsburg
Mathematisch-Naturwissenschaftlich-
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Seminar on Physics of Thin Films

SP-STM & MExFM

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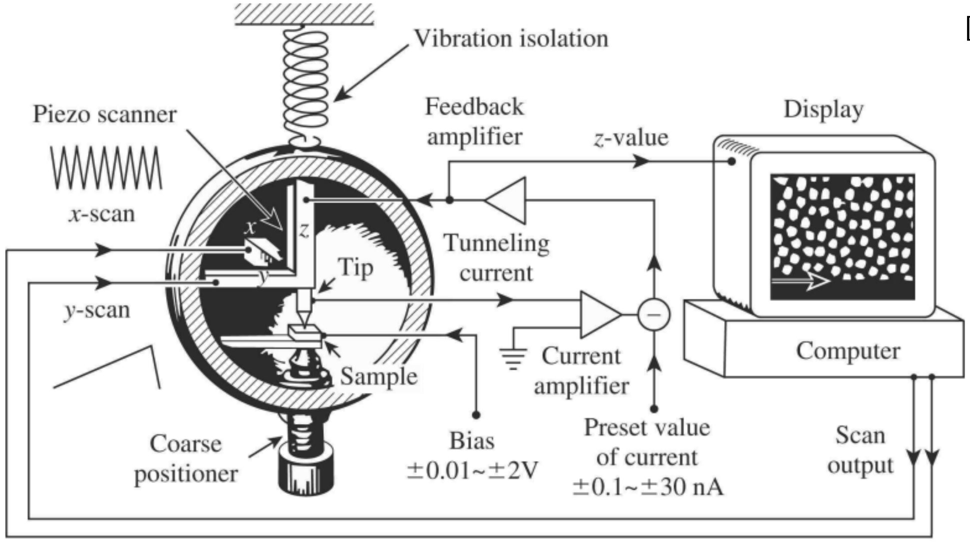
Outline: Spin-Polarized-Scanning-Tunneling-Microscope

Construction & Current Feedback Mechanism

General Functionality & Construction

- Piezo electric crystals allow for very fine control
- Distance sample ↔ tip < 1nm
- Overlapping electron clouds allow for tunneling current to flow between tip/sample
  - Direction reversable, depending on bias voltage sign
- Feedback circuit keeps the perceived tip ↔ sample distance constant
- Combination with different control signals produces different scanning modes
  - A-Scan (dot, often time resolved)
  - B-Scan (line)
  - C-Scan (surface)



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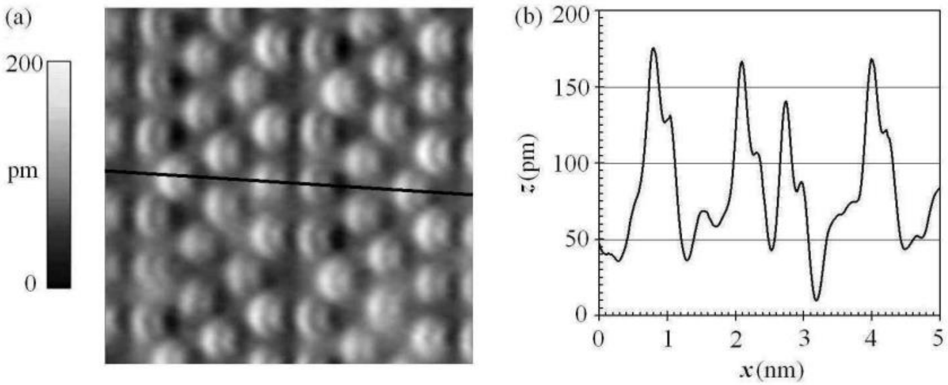

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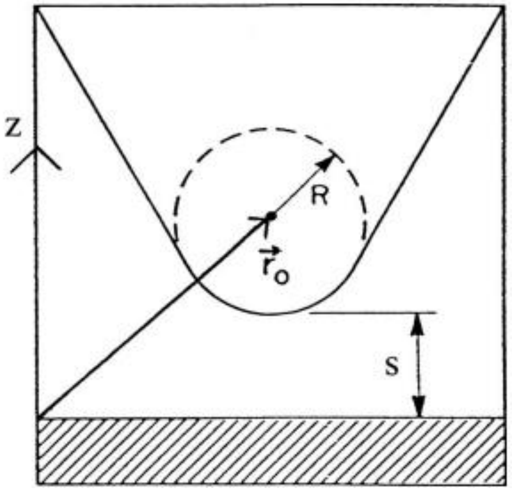
Mathematics of the Tunneling Process

General Functionality & Construction

- The tunneling current depends:
  - On the “local density of states” (LDOS, here $\mathbf{n_S}$)
  - The bias voltage **U**
  - The distance to the sample **S**
    - The exponential dependency is key to the high resolution capability



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$$I = \frac{2\pi e}{\hbar} U \sum_{\mu,\nu} |M_{\mu\nu}|^2 \delta(E_\nu - E_F)\delta(E_\nu - E_F)$$

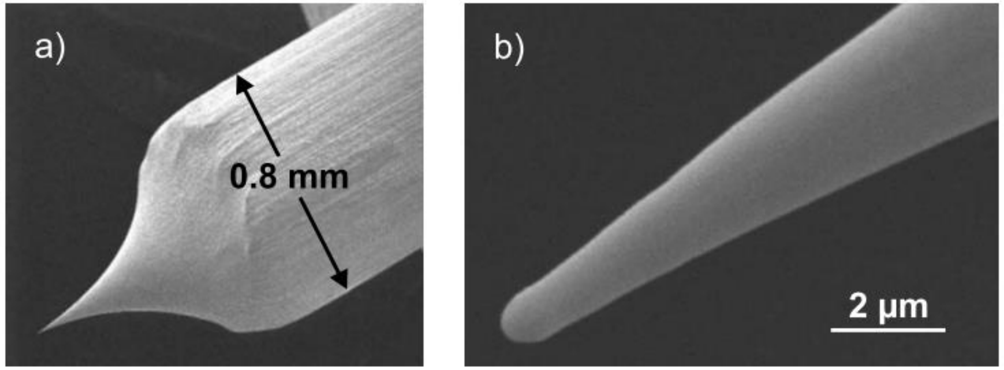
$$M_{\mu\nu} = \frac{-\hbar^2}{2m} \int dS(\Psi_\mu^{\,*} \nabla \Psi_\nu - \Psi_\nu \nabla \Psi_\mu^*) \qquad n_S(E_F, \vec{r}_0) = \sum_\nu |\Psi_\nu(\vec{r}_0)|^2 \delta(E_\nu - E_F)$$

$$\Psi_\mu = \frac{1}{R} e^{-\kappa R} \qquad I \propto \exp(-2\kappa s)$$

Environment & Generating Tips

General Functionality & Construction

- Temperature range generally in the region of mK to some K
  - Too high temperatures cause thermal fluctuations to overshadow measured effects
- Measuring at atom-scale resolution generally requires ultra-high-vacuum (UHV) setups
  - Kinetic energy of gas molecules causes noise through collisions
  - Tips get contaminated with oxides
- Tip preparation
  - Generally performed *in situ* to avoid contaminations
  - Pulling procedures
  - Electrochemical etching methods
  - Cleanup through electron/ion bombardment



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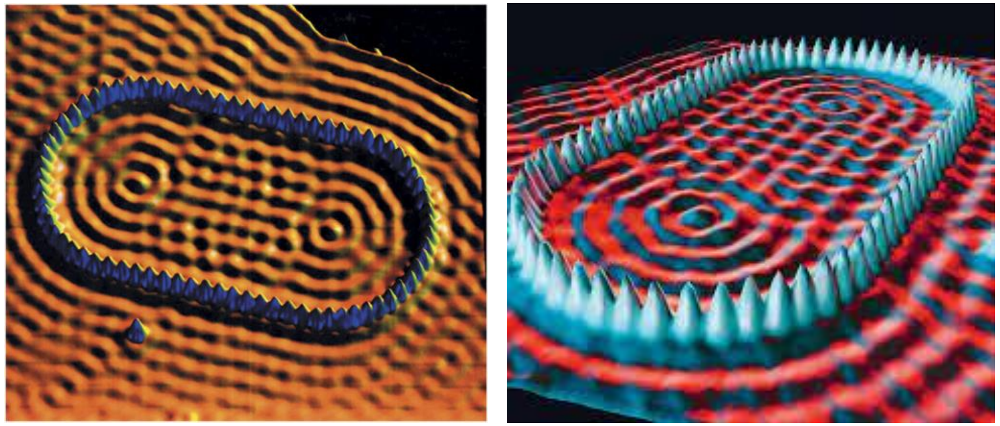
Example: Manipulation of individual atoms

General Functionality & Construction

- Active manipulation of the sample on the per-atom basis
- Constructive process to “drag” atoms into desired locations
- Multiple applications
  - Data storage
  - Sample preparation (for other measurements)
  - Validation of theorized wavefunction behavior

- “Quantum Corrals”



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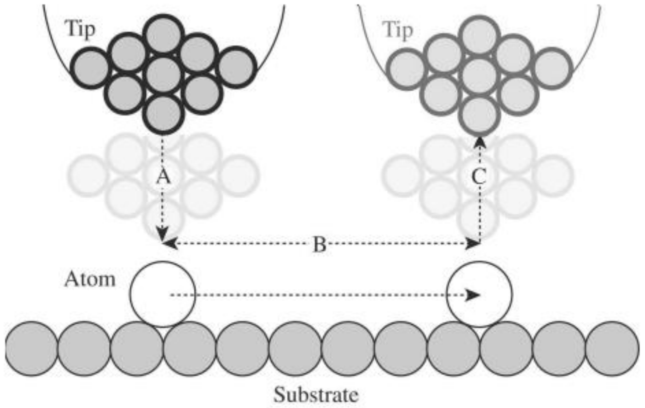

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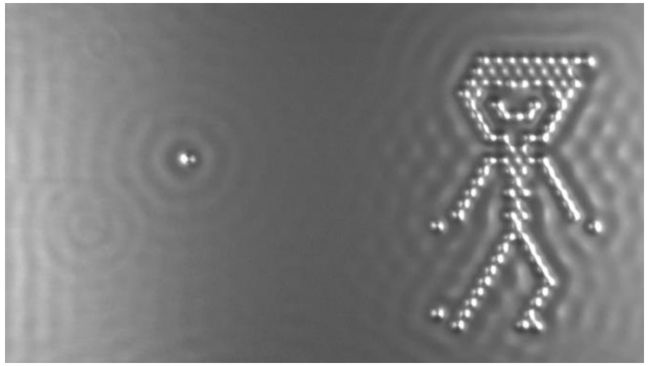
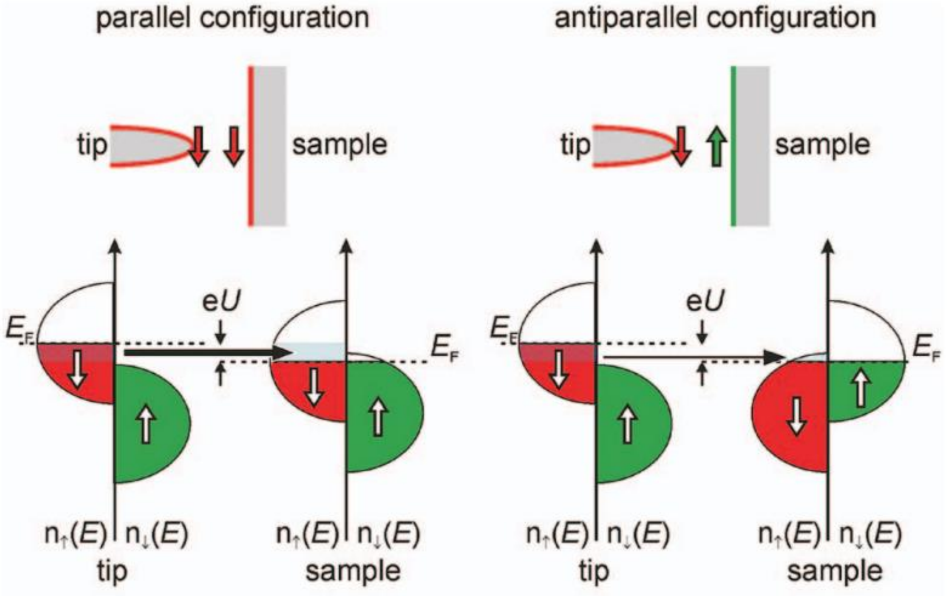


Theory of the Spin Resolved STM

Spin Resolved/Polarized STM (SP-STM)

- The model for a spin-dependent ferromagnet-ferromagnet tunnel junction is applied
- The local densities of states for tip and sample
  - $n_t = n_t^{\uparrow} + n_t^{\downarrow}, \quad n_s = n_s^{\uparrow} + n_s^{\downarrow}$
  - $m_t = n_t^{\uparrow} - n_t^{\downarrow}, \quad m_s = n_s^{\uparrow} - n_s^{\downarrow}$
  - $P_t = m_t / n_t, \quad P_s = m_s / n_s$
- First time experimentally confirmed for stepped antiferromagnetic coordinated, stepped chromium surface



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

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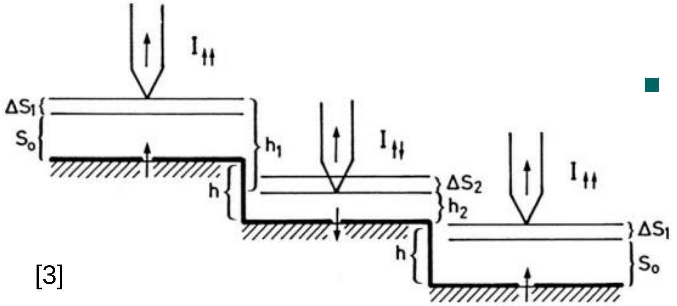


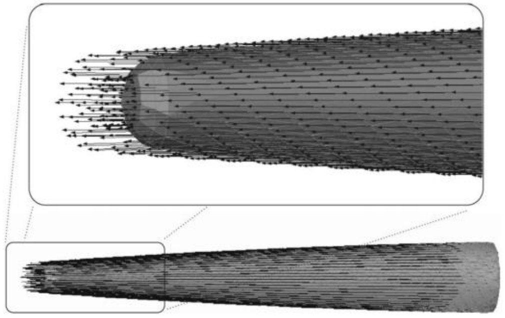
[3]

- Sample composition
  - Cr(001)
  - Steps non-magnetic: 0.144nm
  - Steps magnetic: 0.12nm/0.16nm

Tip ↔ Sample Material Combinations

Spin Resolved/Polarized STM (SP-STM)

- Only the tip or the material are magnetic
  - Equivalent to regular STM, no Spin resolved measurement
- Tip/sample magnetized by optical pumping
- Tip from magnetic material
  - Tip from bulk magnetic material
    - Ferromagnetic tips ↔ Antiferromagnetic tips
  - Non-magnetic tips coated with magnetic thinfilms
    - Easy to handle, versatile and precise
  - Magnetic clusters bonded to the tip
    - Very easy tip generation process



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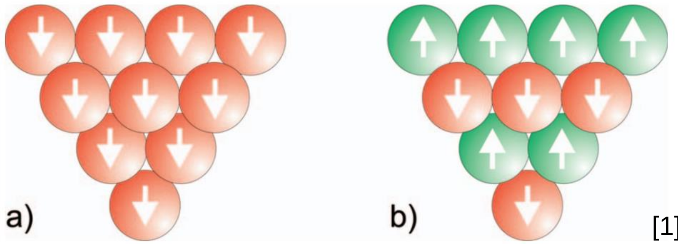

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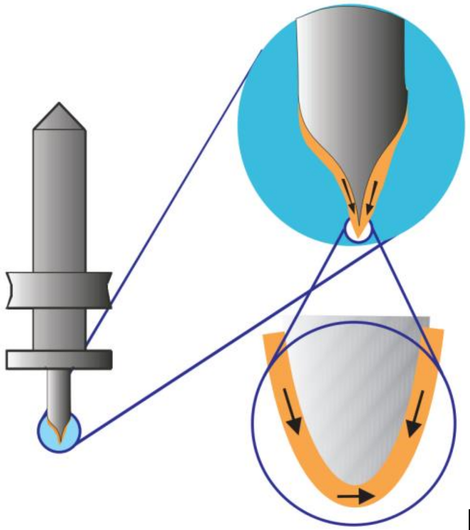

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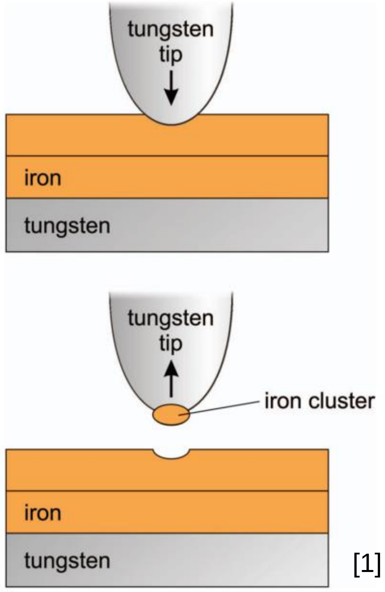

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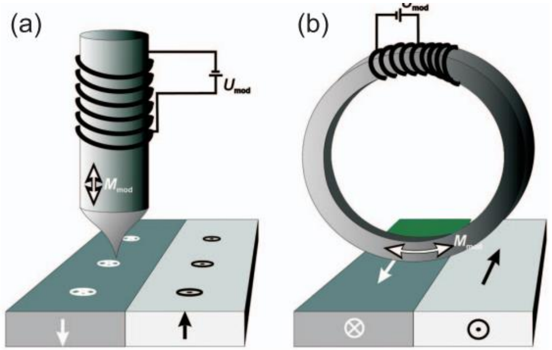
Modes of Operation

Spin Resolved/Polarized STM (SP-STM)

- Constant-current
  - Default imaging mode of STM
  - Feedback circuit makes sure, that the tunneling current is kept constant
  - The smallest magnetic superstructure will be imaged with SP-STM, not necessarily the atomic structure

- SR-spectroscopic
  - Aims to provide separation between topographic structure and electronic structure
  - Probing bias voltage is modulated
  - Extracts energy dependency of the local electron density of states (LDOS)
  - Need to be measured at fixed tip ↔ sample distance (either stationary or secondary ample-and-hold amplifier)

- Modulated tip
  - Aims to provide separation between electronic structure and magnetic structure
  - Magnetization of the tip is modulated periodically
  - Additionally requires bias voltage modulation and tip distance modulation



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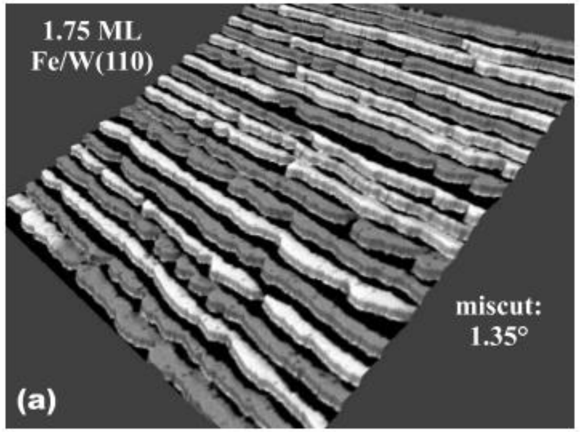
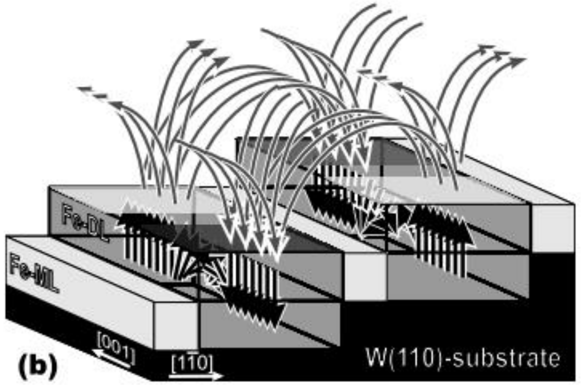
Nanostripes on stepped Surfaces

Experiments & Applications

- Nanostripes get formed when material is deposited on stepped substrate
- Magnetic effects may emerge that depend on the topology
  - Influence of the width?
  - Influence of the height?
  - Influence or the distance between stripes?





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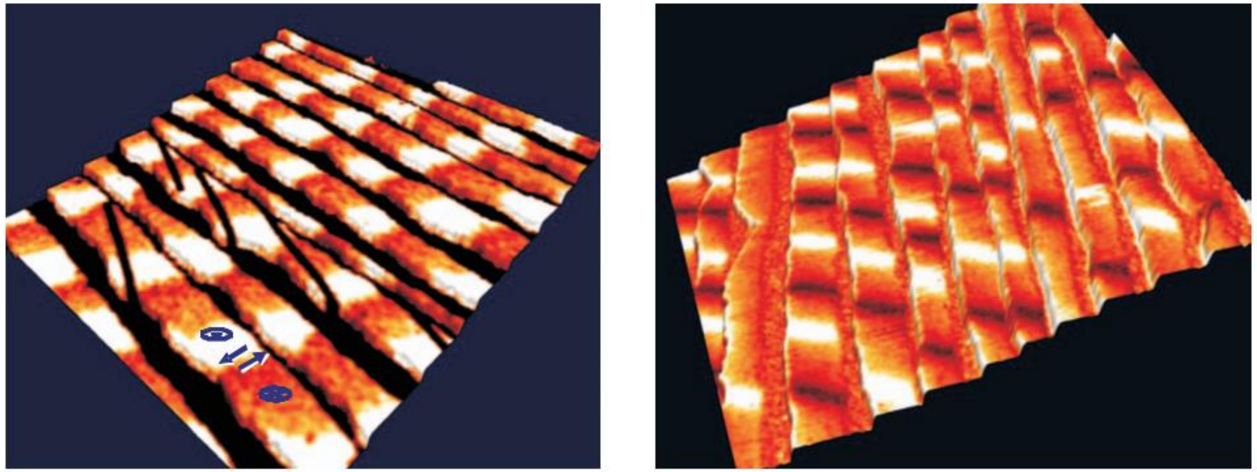

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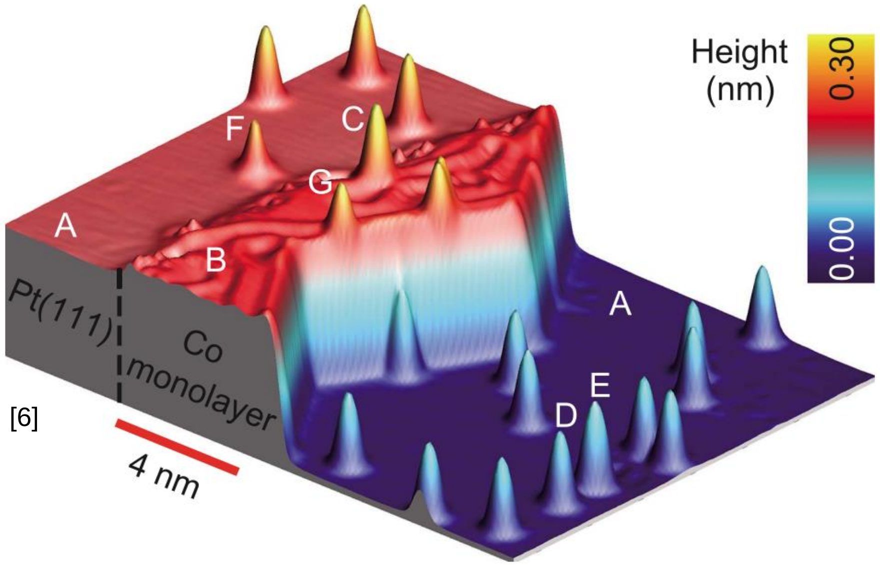
- Sample composition
  - W(110)
  - Fe monolayer
  - Fe doublelayer
  - Left, stripe-width > 10nm, right < 10nm

Measurements on single Adatoms

Experiments & Applications

- Same tip to measure Ir as well as Co locations
  - Spin polarization of tip can be determined
  - Makes arguing about the spin relation surface ↔ adatom possible
- Spin polarization effect of large magnitude when looking at a Co-dimer



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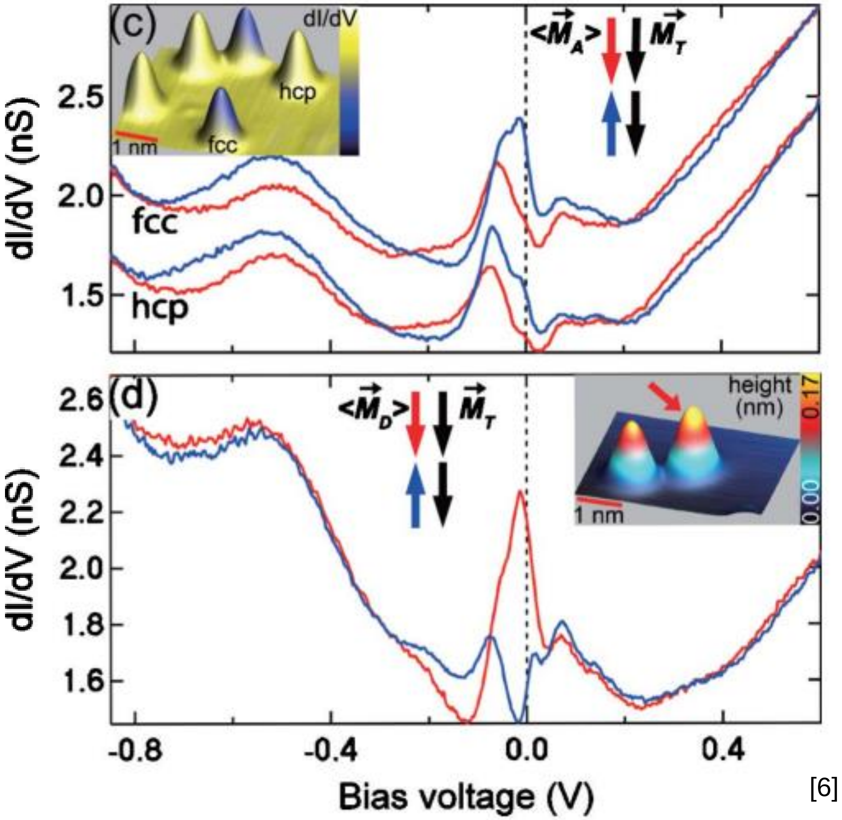


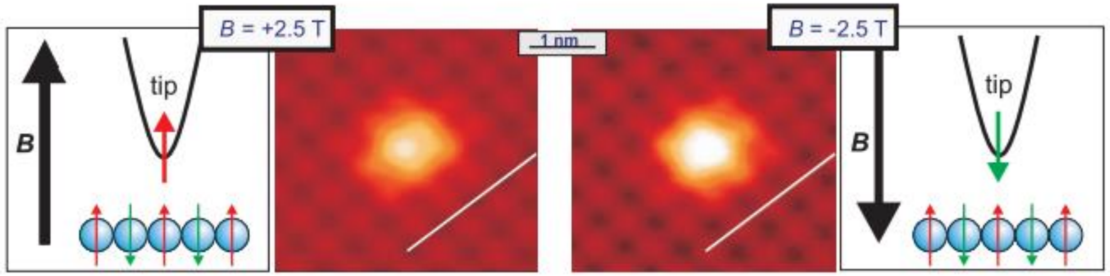
[6]

- Sample composition
  - Pt(111) A
  - Co monolayer B
  - Co adatoms C & D
  - Co dimer E

Antiferromagnetic Arrangements

Experiments & Applications

- Averaging measuring procedures do not allow resolving antiferromagnetic superstructures
  - If magnetic unit cell is smaller than resolution, the magnetic moment is averaged and vanishes
- Topology can be affected by magnetic and non-magnetic contributions



- Sample composition
  - W(001)
  - Fe Monolayer

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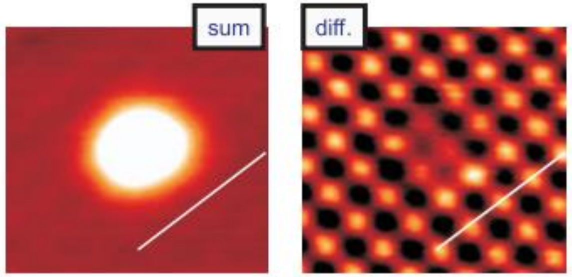
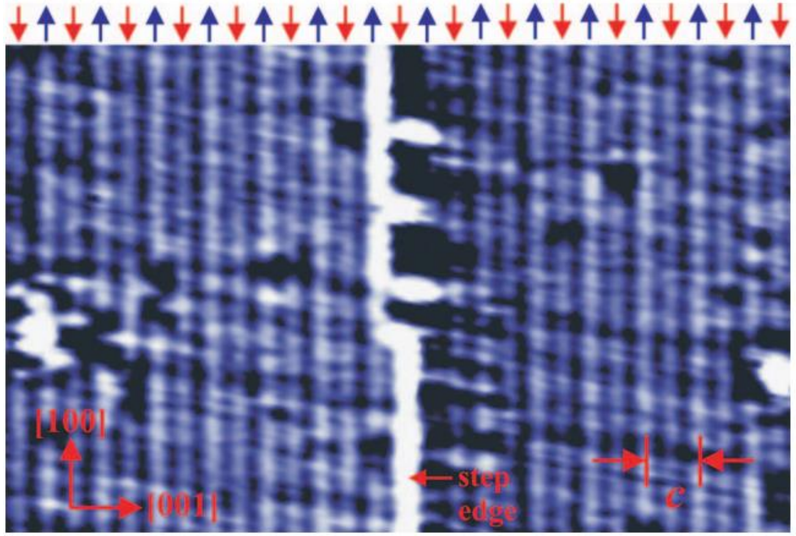
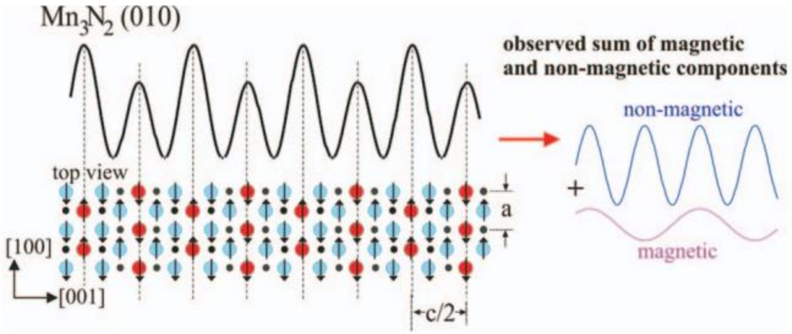






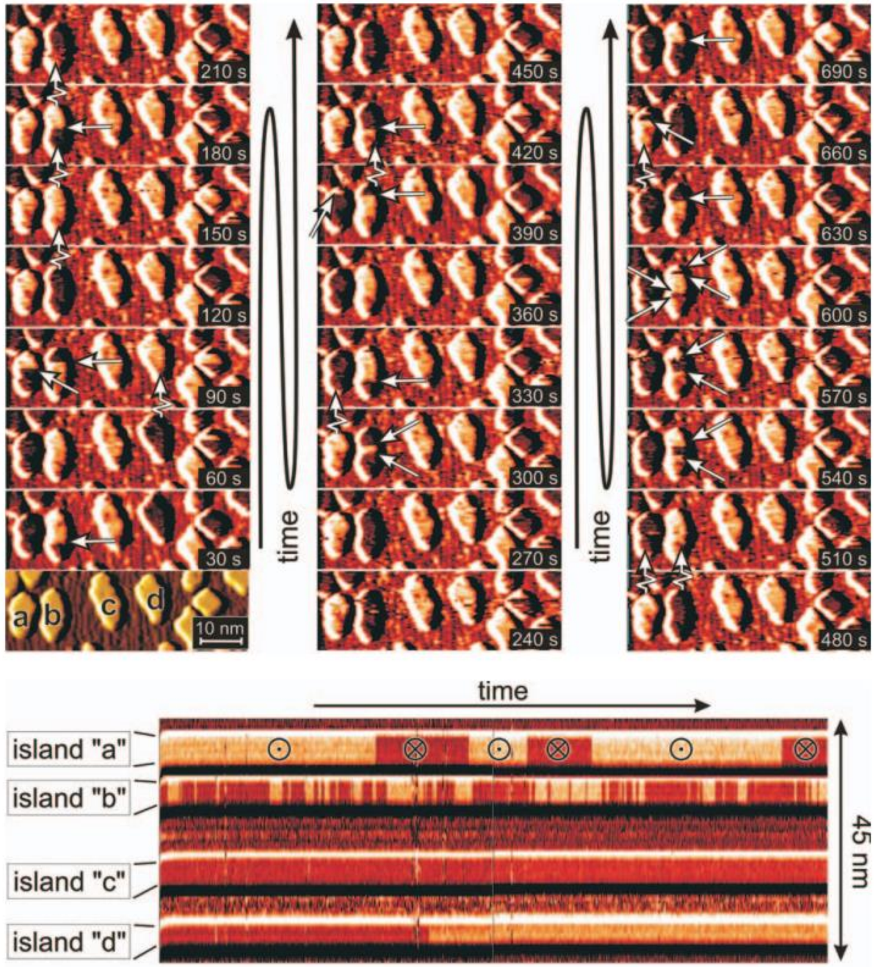
[1]

- Sample composition
  - $Mn_3N_2(010)$

Time Resolved Experiments

Experiments & Applications

- SP-STM does not only image in real-space, but consequently also in the real-time domain
- Time resolution depends on imaging mode and spacial resolution
- Switching events most of the time thermally induced
  - May also be a result of the probe's influence or an external magnetic field

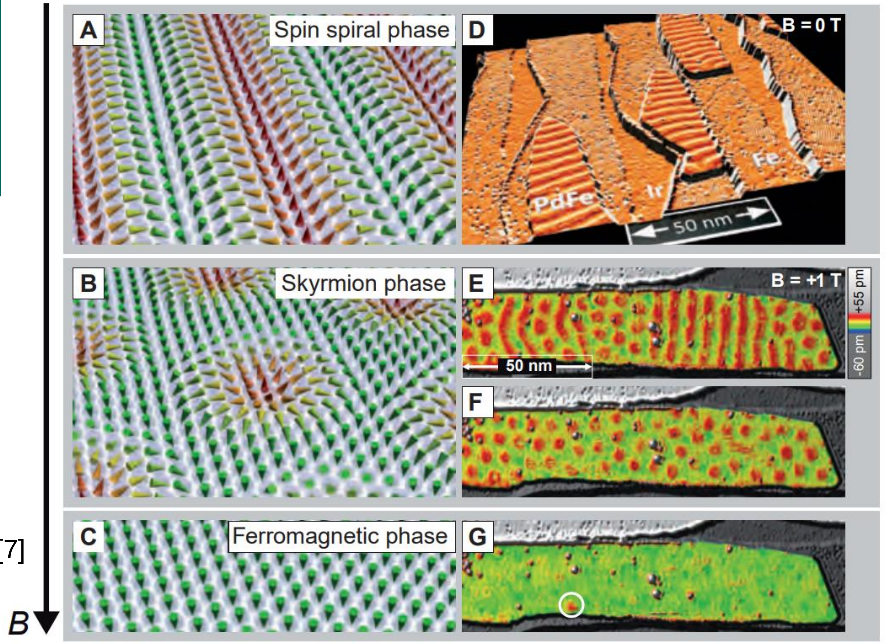


[1]

- Sample composition
  - Mo(110)
  - Fe islands (area < $40 nm^2$)
- Antiferromagnetic tip required
  - Magnetic stray field of a ferromagnetic tip would influence switching behavior

Magnetic RAM through Skyrmion Manipulation

Experiments & Applications



[7]

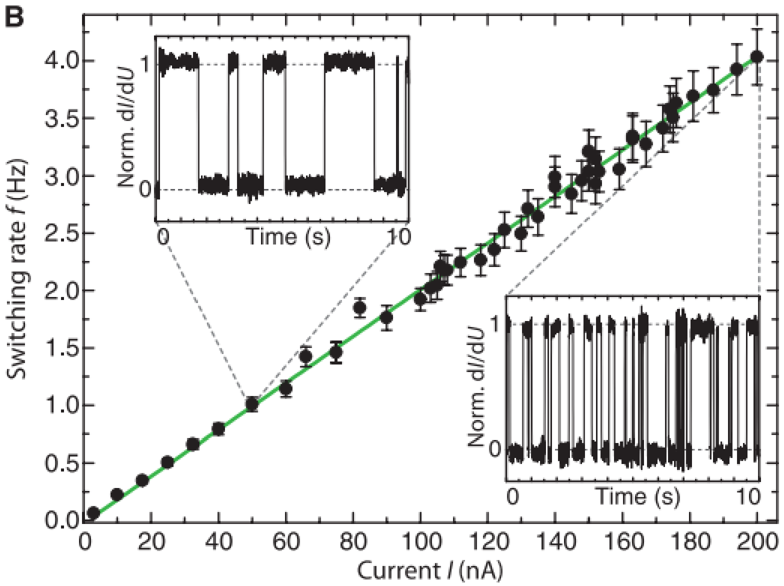
T~8 K

T~4.2 K

- Sample composition
  - Ir(111)
  - PdFe Bilayer

- High temperature (T~8 K)
  - Thermal reordering possible
- Low temperature (T~4.2 K)
  - Only induced reordering possible

[7]



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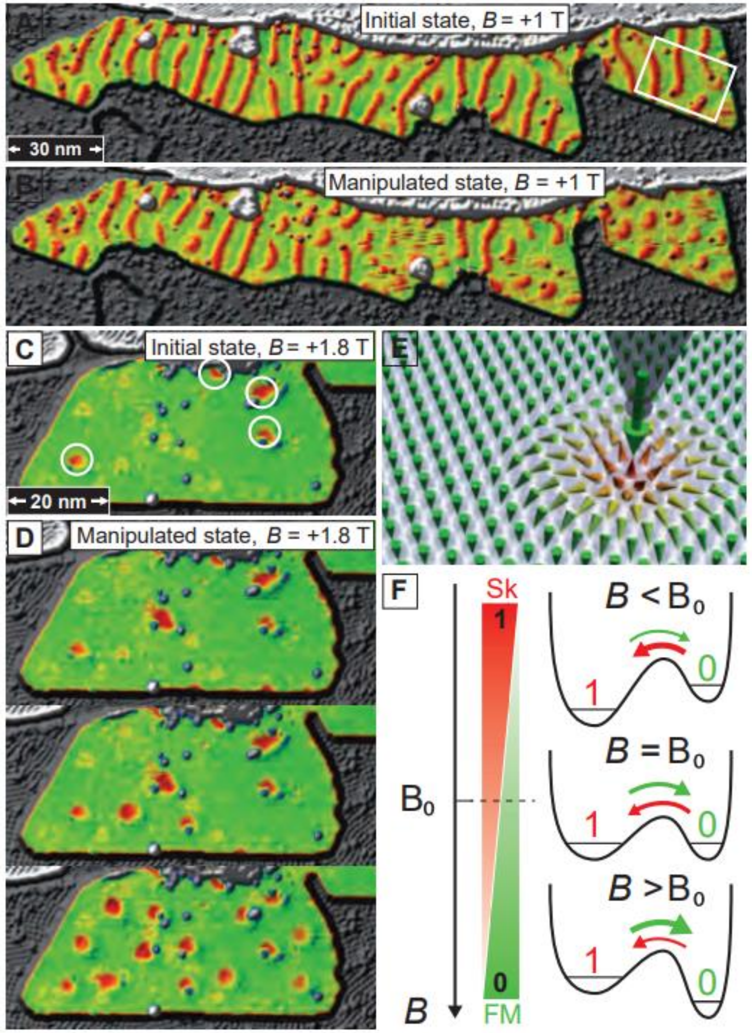
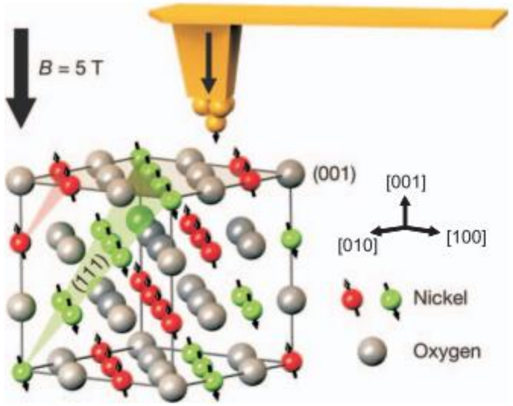


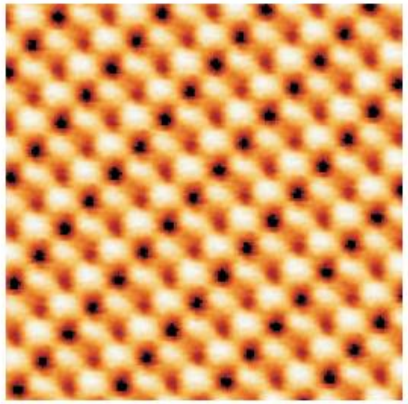
- Switching rate
  - Depends linearly on the tunnel current
  - Also voltage dependent (not shown)

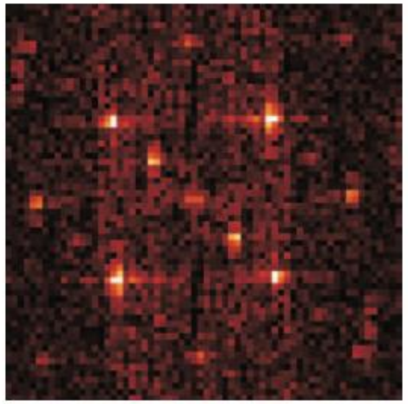
Spin Resolved Microscopy for Insulators?

Outlook: Magnetic Exchange Force Microscopy (MExFM)

- No conductive samples needed
  - Electromagnetic exchange forces are used to deflect a cantilever that carries the probe tip
- Modes of operation
  - "Contact-mode": static mode of operation, tip is dragged along the surface
  - "Tapping-mode": dynamic mode of operation, cantilever is exited to oscillate and bring the tip very close to the sample
  - "Non-contact-mode": dynamic mode of operation, oscillating of the tip near resonant frequency, interaction forces change the resonant frequency
- Magnetized tips may be used to resolve spin dependent interaction forces







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Head-to-head Comparison: MExFM ↔ SP-STM

Outlook: Magnetic Exchange Force Microscopy (MExFM)

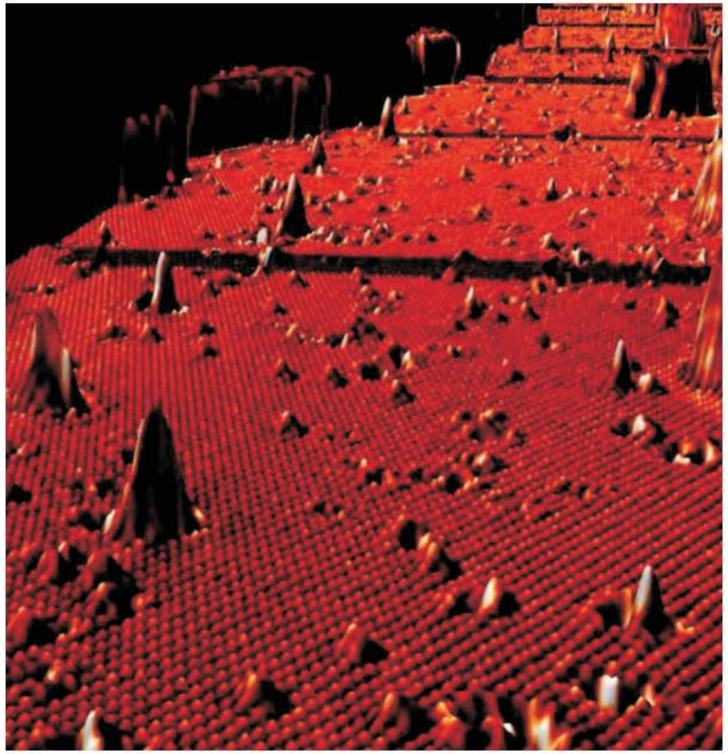
- Sample Conductivity
  - SP-STM: requires electrically conductive samples
  - MExFM: both conductive and non-conductive samples
- Temperature range
  - SP-STM: already applied in the range from 300mK to 350K
  - MExFM: atomic resolution so far only for low temperature experiments
- UHV environment
  - Typically needed, but both can also be performed in liquid (→ immobilizing molecules & combing)
- Supports probing with external magnetic fields
  - High strength fields applicable to both methods
- Precision and complexity
  - Comparable in terms of cost & effort
  - STM is often said to have better resolution however both can achieve atom-scale-resolution
  - SP-STM more applications in research (spin based), while AFM more widespread in the industry

Final Overview

Summary and Conclusion

- Methods allow for probing on atomic scale
  - Measurements are performed in real-space, contrary to most atom-scale measurement methods
- Magnetic moment can be resolved locally
  - Avoids missing substructures with on average neutral magnetic moments
- Possible for metals, as well as insulators
  - SP-STM for metals
  - MExFM for insulators
- Comparably high time-resolution
  - Reducing resolution allows to study the changes of magnetic moments close to real time
- Active manipulation of sample possible (on measurement-scale)
  - Construct custom test environments for wavefunctions
  - Manipulate/create individual molecules for chemical research

Thank you for your kind attention



[1]

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References

Text and Image References

- [1] Spin mapping at the nanoscale and atomic scale (Wiesendanger 2009)
- [2] Introduction to Scanning Tunneling Microscopy (Chen 2007)
- [3] Observation of vacuum tunneling of spin-polarized electrons with the scanning tunneling microscope (Wiesendanger 1990)
- [4] Atomic resolution in scanning force microscopy: Concepts, requirements, contrast mechanisms, and image interpretation (Schwarz 2000)
- [5] Spin polarization of platinum (111) induced by the proximity to cobalt nanostripes (Meier 2011)
- [6] Inversion of spin polarization above individual magnetic adatoms (Zhou 2010)
- [7] Writing and Deleting Single Magnetic Skyrmions (Romming 2013)
- [8] Confinement of Electrons to Quantum Corrals on a Metal Surface (Crommie 1993)
- [9] A Boy And His Atom: The World's Smallest Movie (IBM 2013)