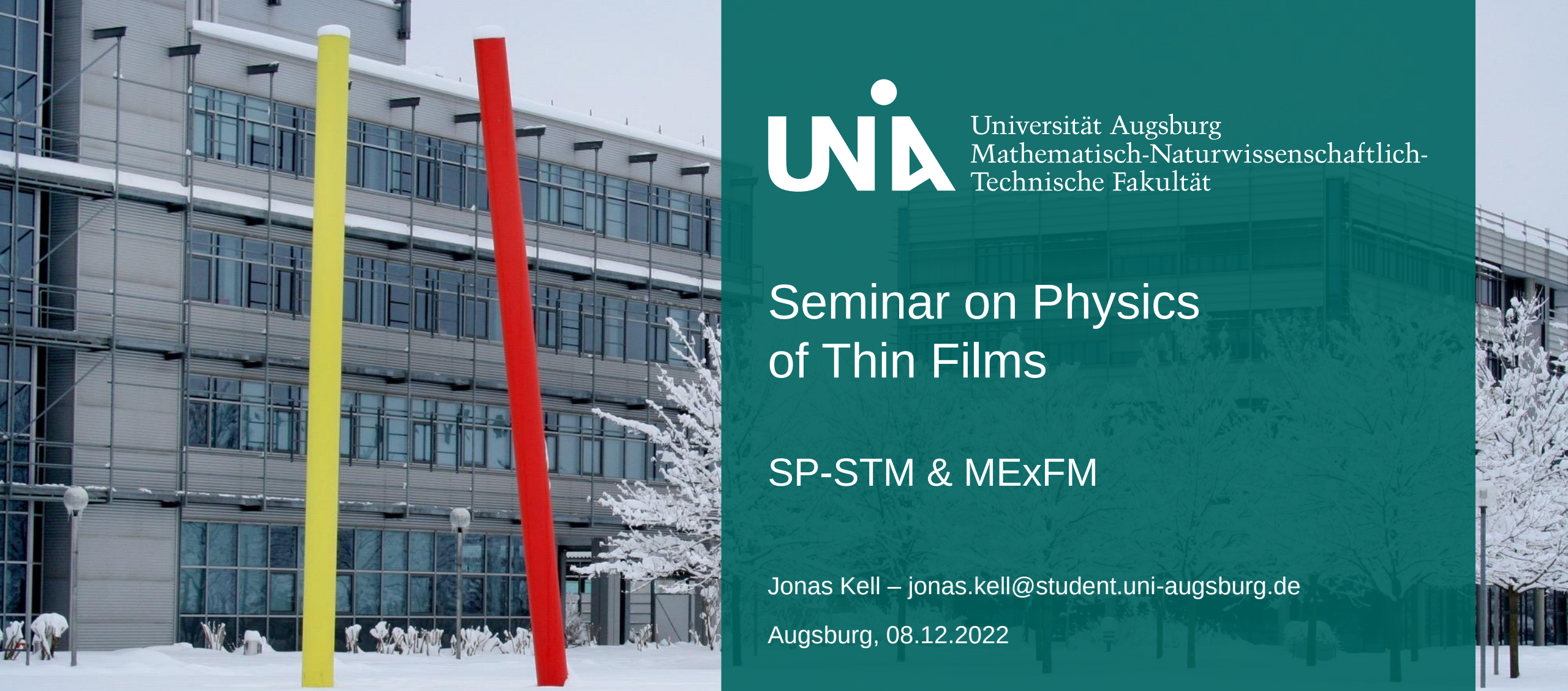


Universität Augsburg
Mathematisch-Naturwissenschaftlich-
Technische Fakultät

Seminar on Physics of Thin Films

SP-STM & MExFM

Jonas Kell – jonas.kell@student.uni-augsburg.de

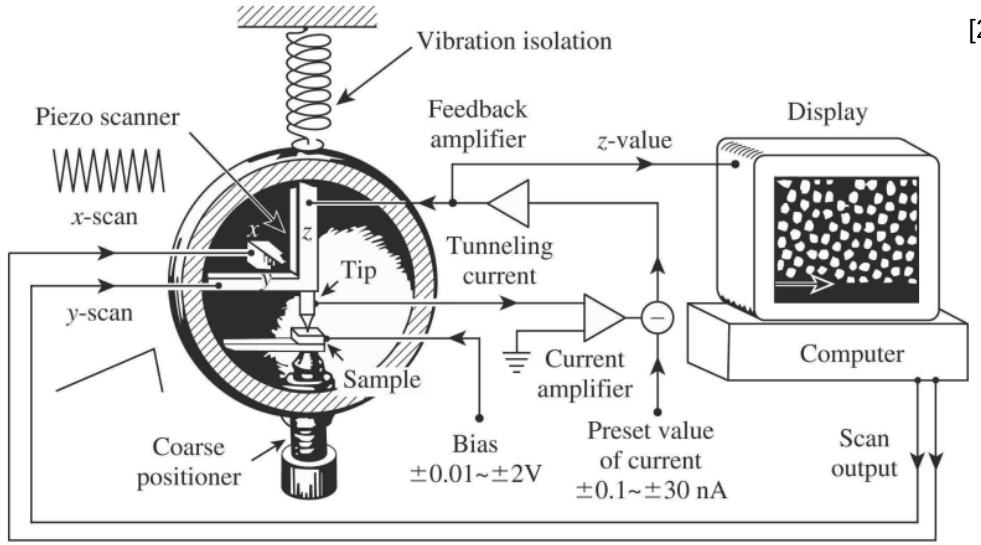
Augsburg, 08.12.2022

Outline: Spin-Polarized-Scanning-Tunneling-Microscope

1. General Functionality & Construction
2. Spin Resolved/Polarized STM (SP-STM)
3. Experiments & Applications
4. Outlook: Magnetic Exchange Force Microscopy (MExFM)
5. Summary and Conclusion

Construction & Current Feedback Mechanism

General Functionality & Construction



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Construction & Current Feedback Mechanism

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- Piezo electric crystals allow for very fine control

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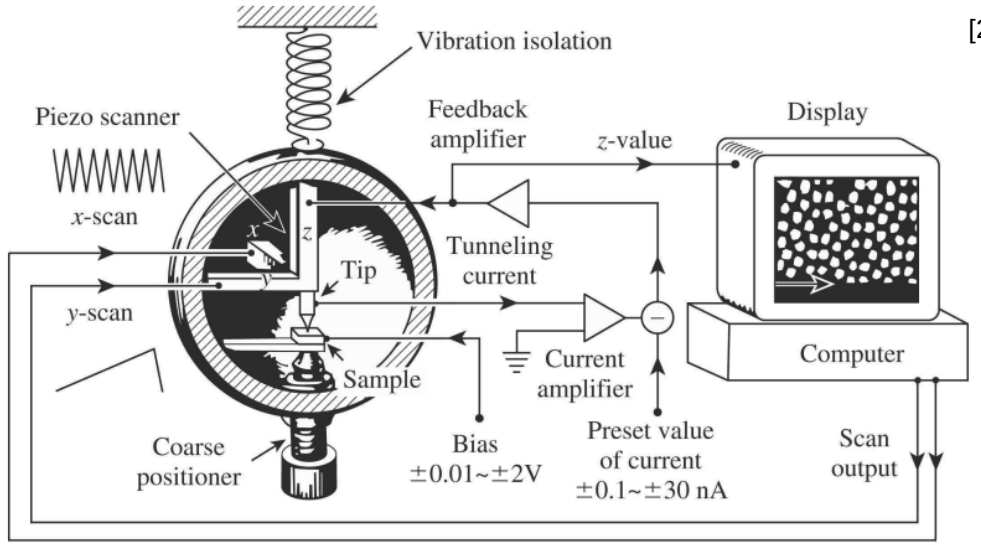

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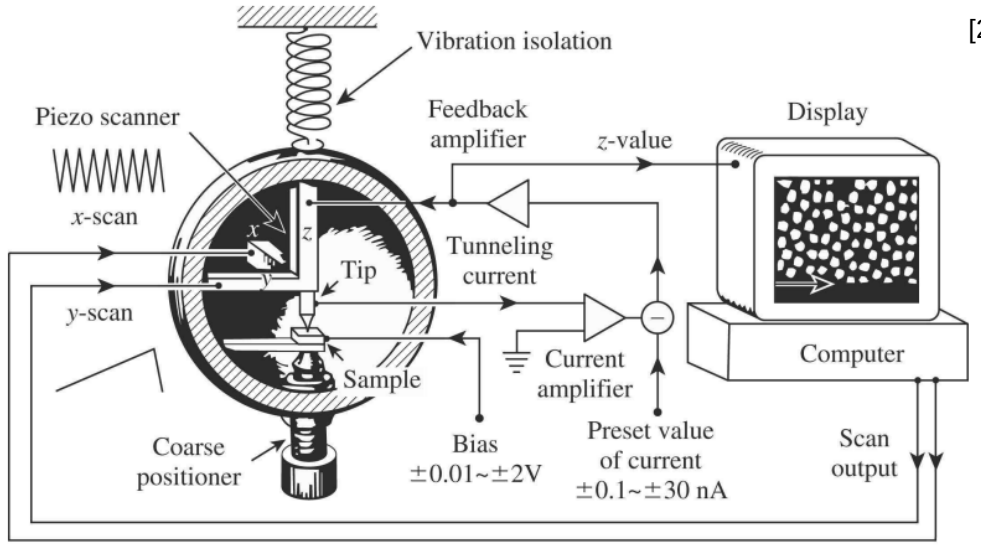

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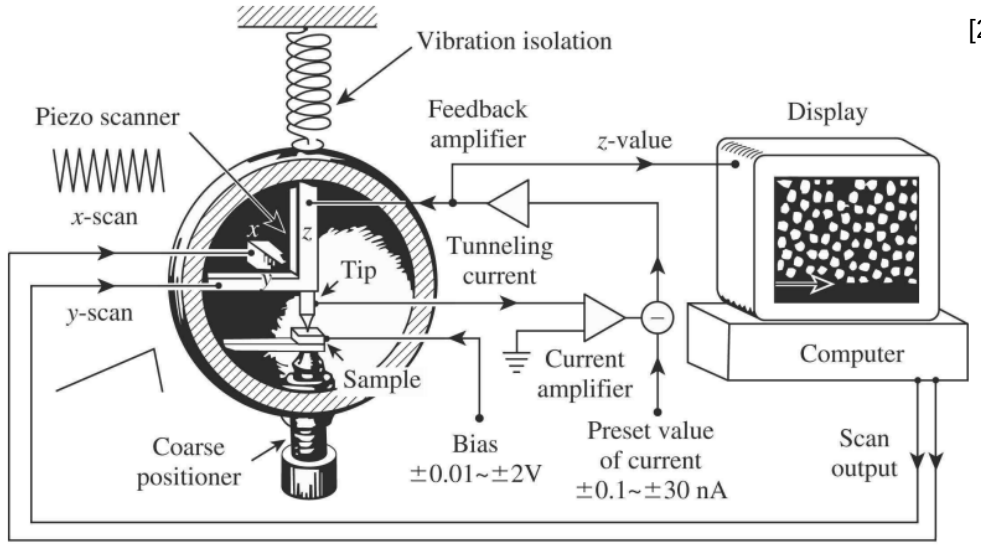

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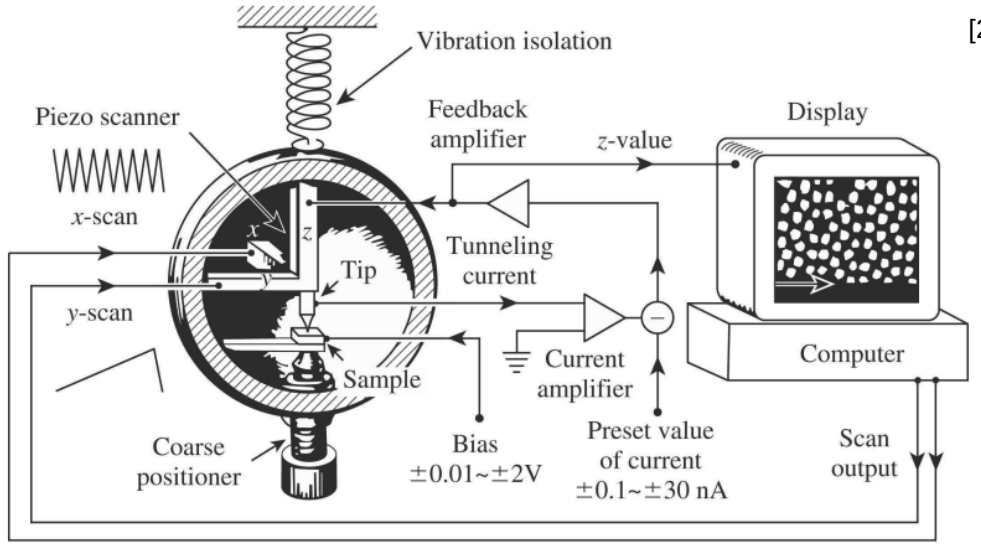
- Combination with different control signals produces different scanning modes
  - A-Scan (dot, often time resolved)
  - B-Scan (line)
  - C-Scan (surface)



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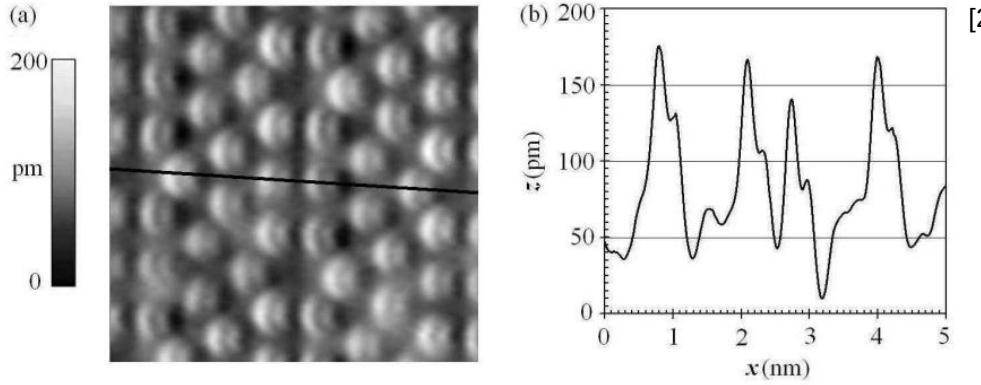
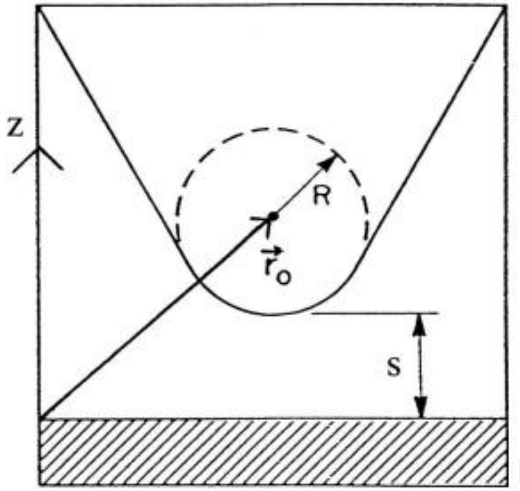


[2]

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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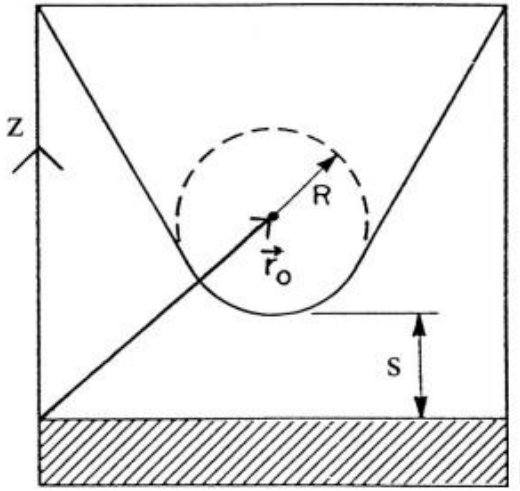

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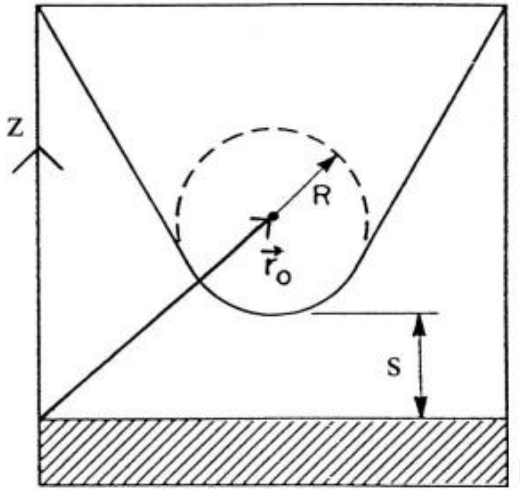

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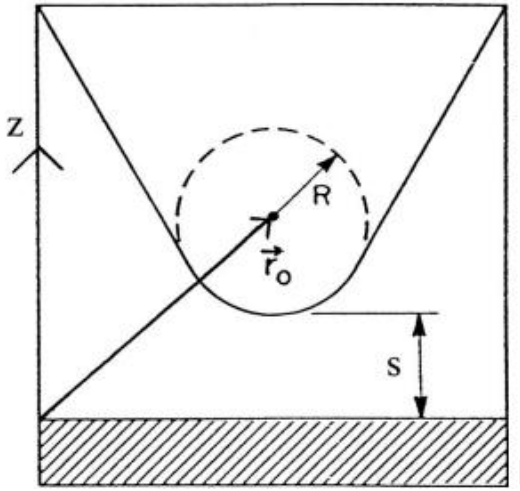

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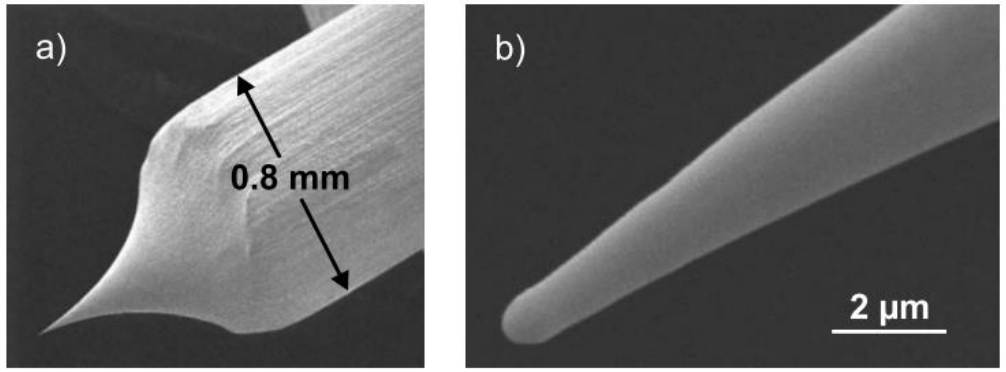
$$\Psi_\mu = \frac{1}{R} e^{-\kappa R} \qquad I \propto \exp(-2\kappa s)$$

Environment & Generating Tips

General Functionality & Construction

- Temperature range generally in the region of mK to some K

- Measuring at atom-scale resolution generally requires ultra-high-vacuum (UHV) setups



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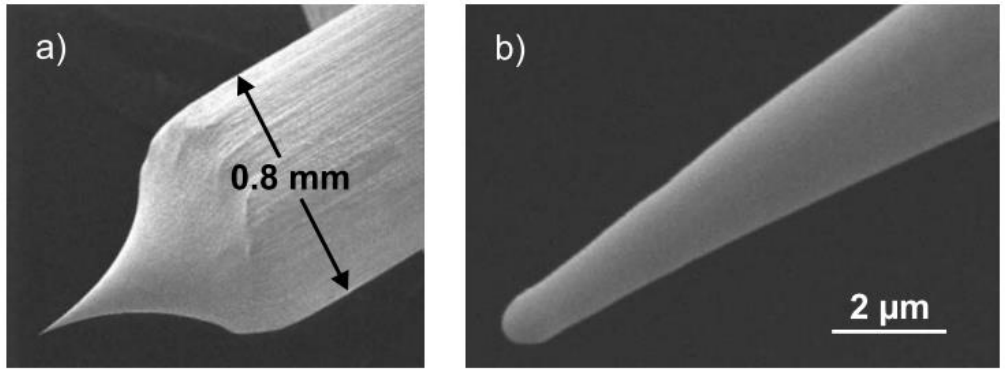

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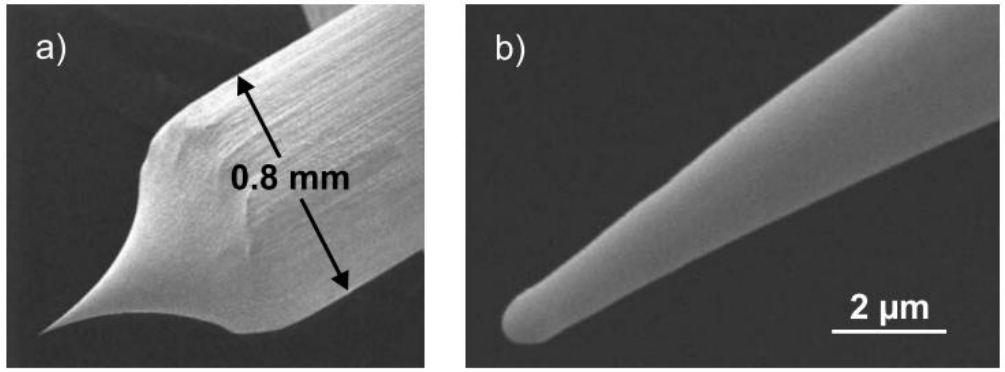

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  - Kinetic energy of gas molecules causes noise through collisions
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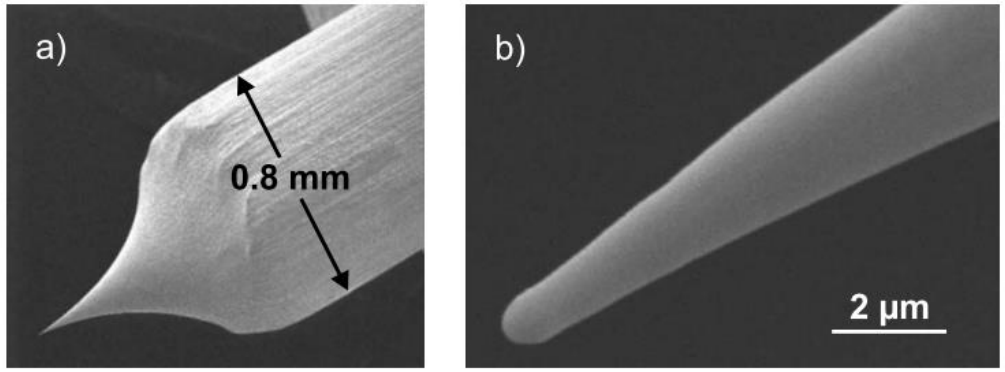
- Tip preparation
  - Generally performed *in situ* to avoid contaminations
  - Pulling procedures
  - Electrochemical etching methods
  - Cleanup through electron/ion bombardment



[1]

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

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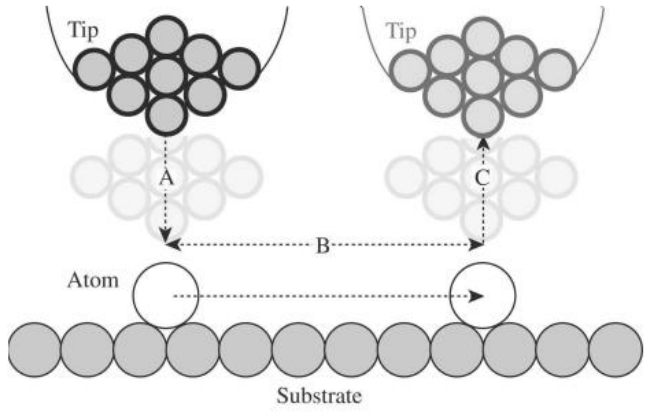

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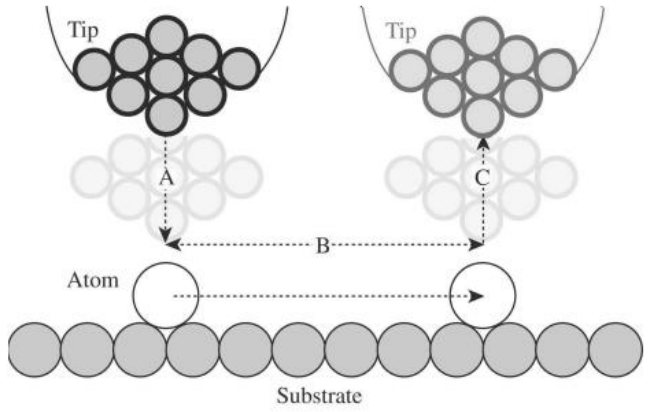

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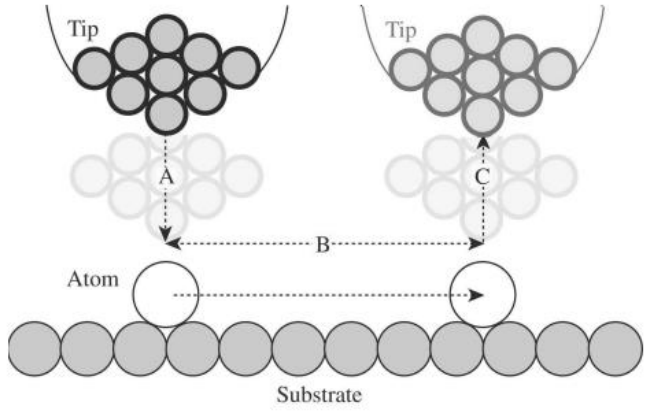
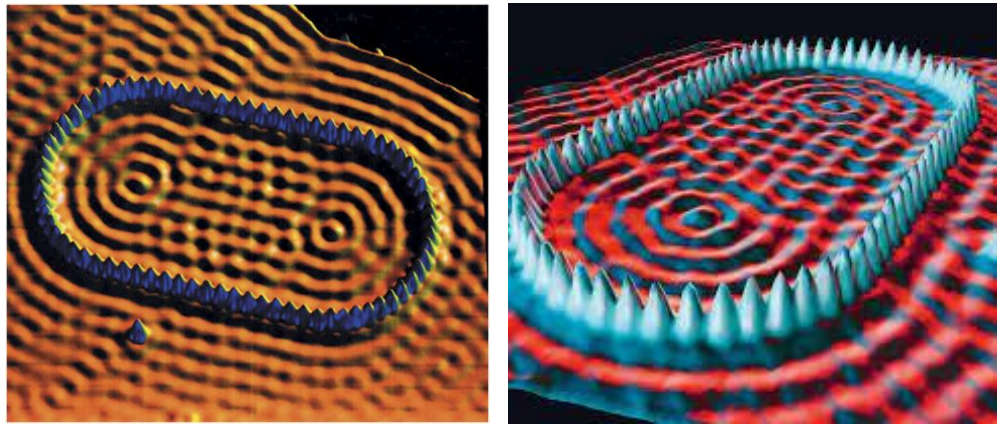


- “Quantum Corrals”



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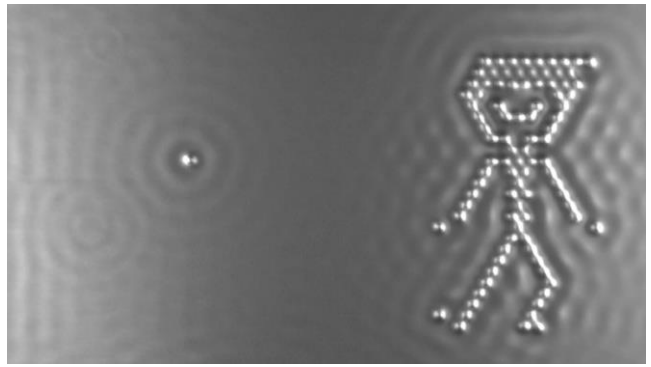
[9]



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
  - $n_t = n_t^{\uparrow} + n_t^{\downarrow}, \quad n_s = n_s^{\uparrow} + n_s^{\downarrow}$
  - $m_t = n_t^{\uparrow} - n_t^{\downarrow}, \quad m_s = n_s^{\uparrow} - n_s^{\downarrow}$
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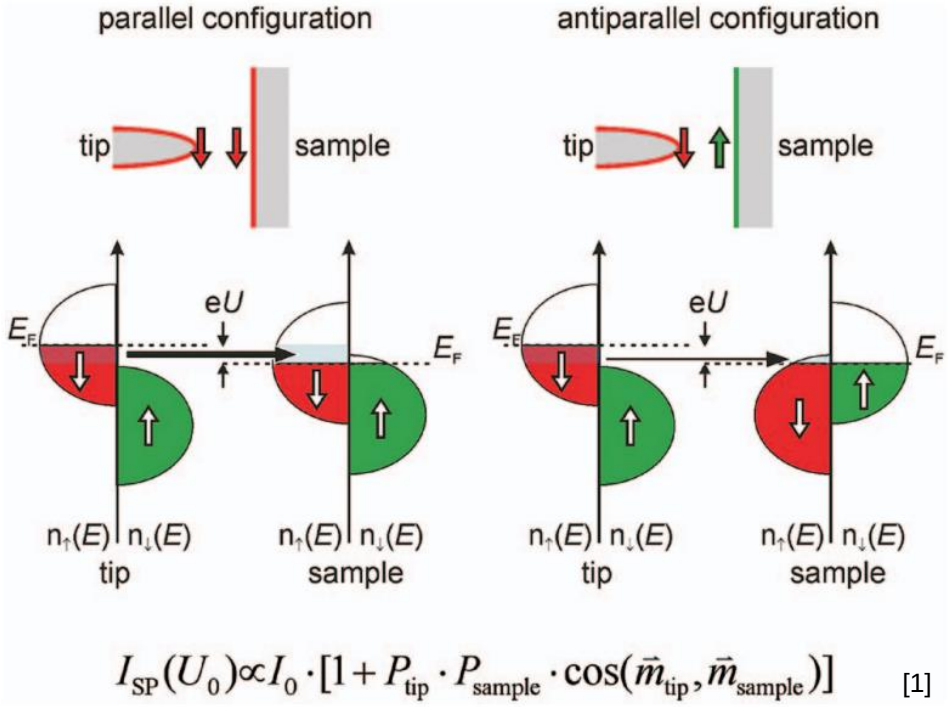

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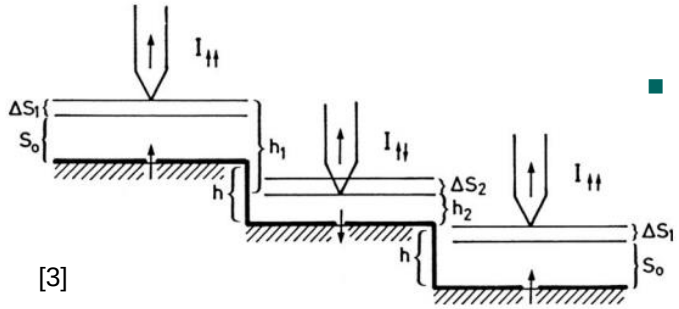
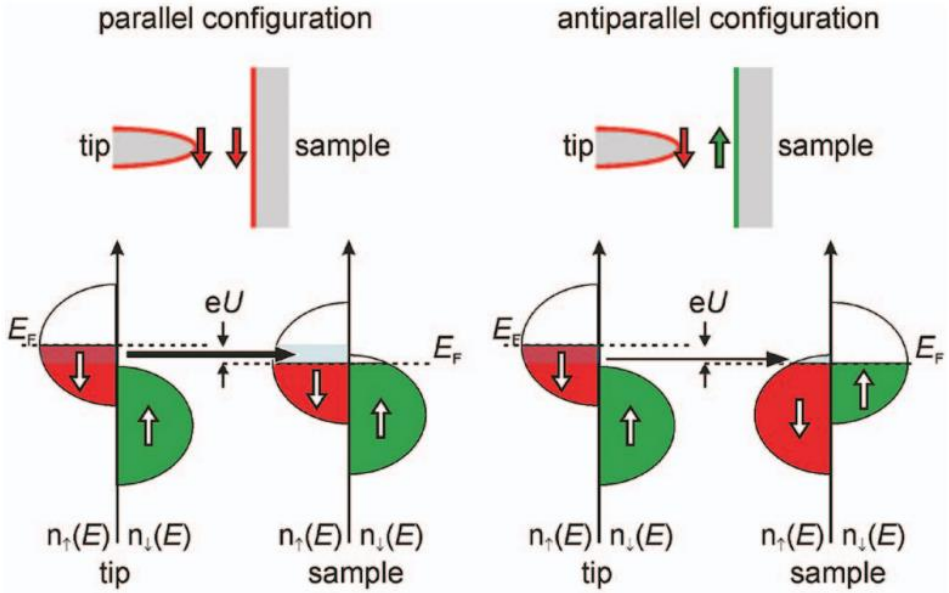
  - $P_t = m_t/n_t, \quad P_s = m_s/n_s$
- First time experimentally confirmed for stepped antiferromagnetic coordinated, stepped chromium surface



[3]

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



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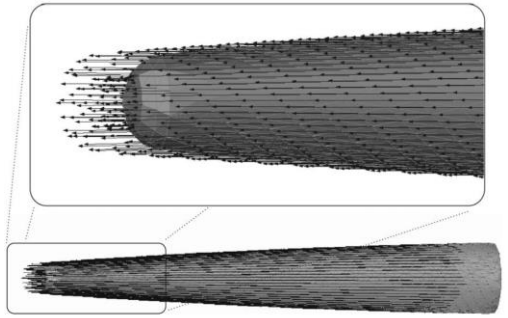

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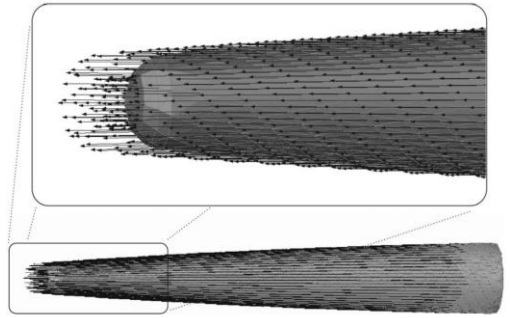
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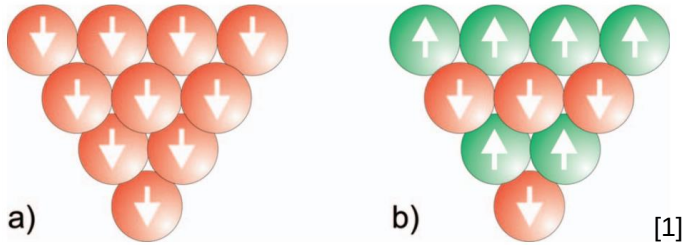

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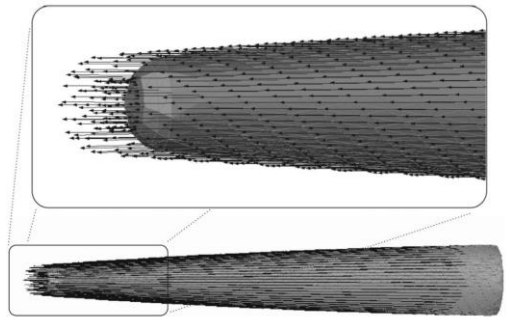
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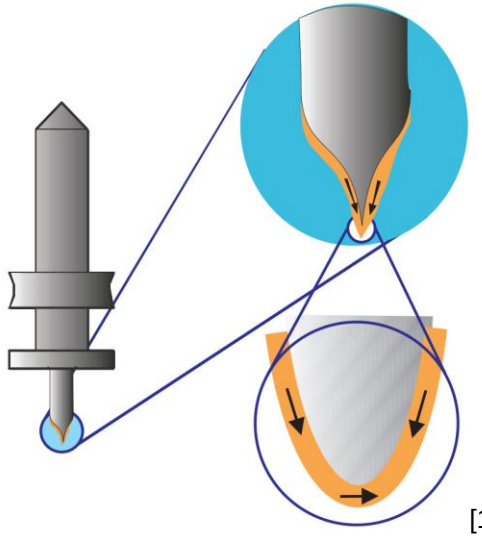
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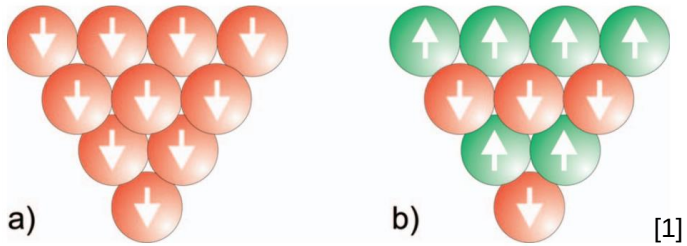

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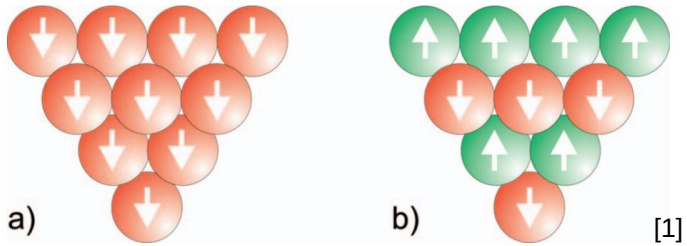
    - Very easy tip generation process



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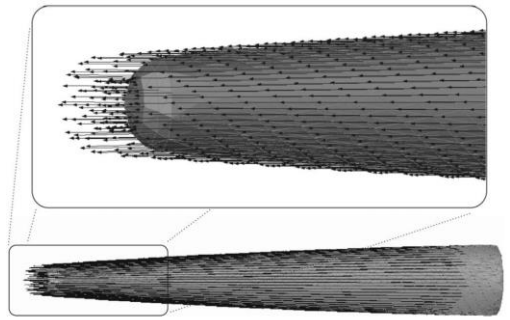
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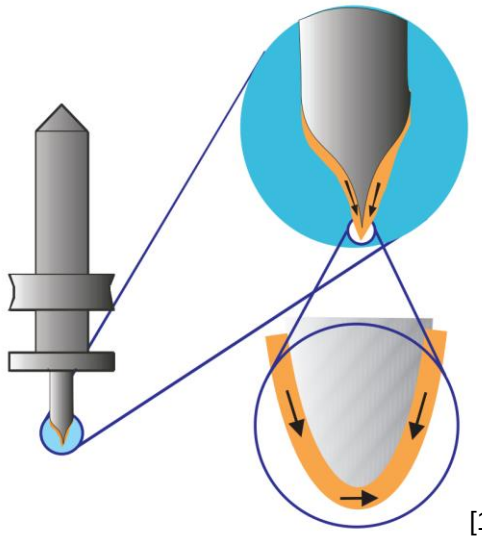
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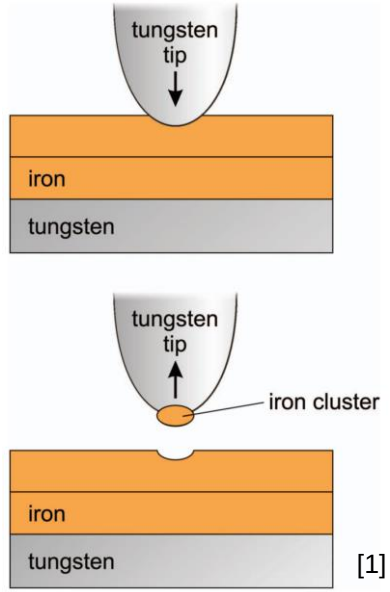

[1]

Modes of Operation

Spin Resolved/Polarized STM (SP-STM)

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- Modulated tip

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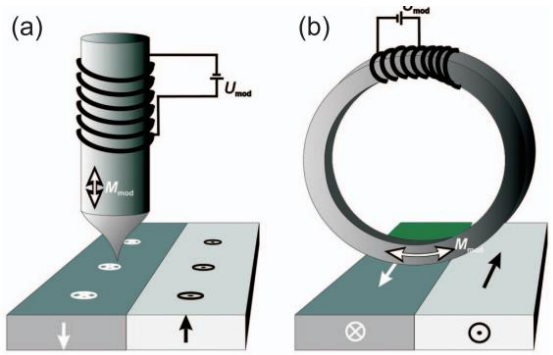
- Modulated tip
  - Aims to provide separation between electronic structure and magnetic structure
  - Magnetization of the tip is modulated periodically
  - Additionally requires bias voltage modulation and tip distance modulation



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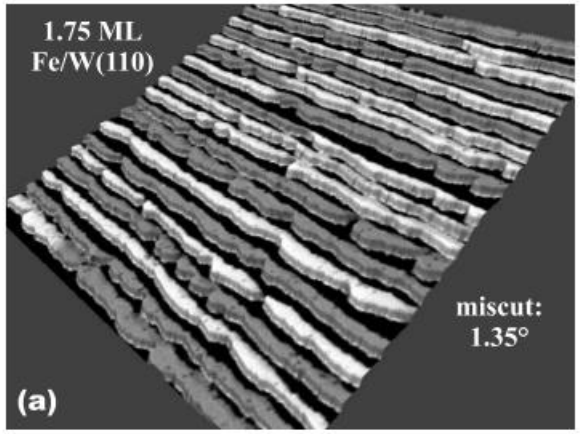
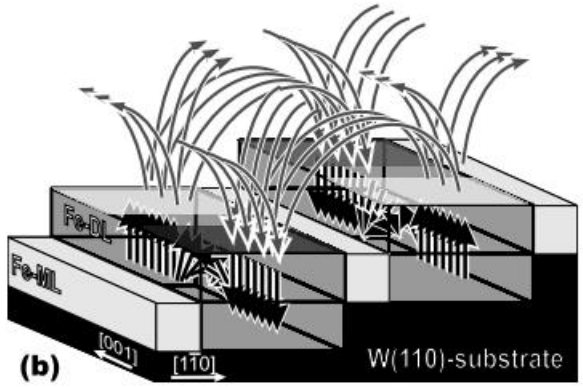
Nanostripes on stepped Surfaces

Experiments & Applications

- Nanostripes get formed when material is deposited on stepped substrate





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Nanostripes on stepped Surfaces

Experiments & Applications

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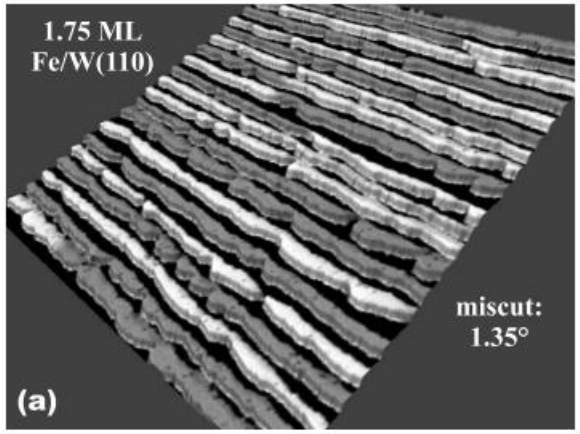
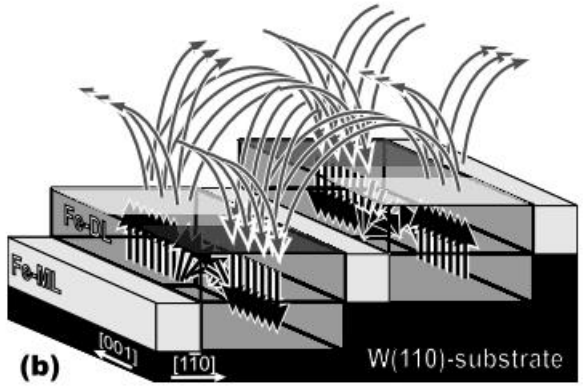
- Magnetic effects may emerge that depend on the topology
  - Influence of the width?
  - Influence of the height?
  - Influence or the distance between stripes?





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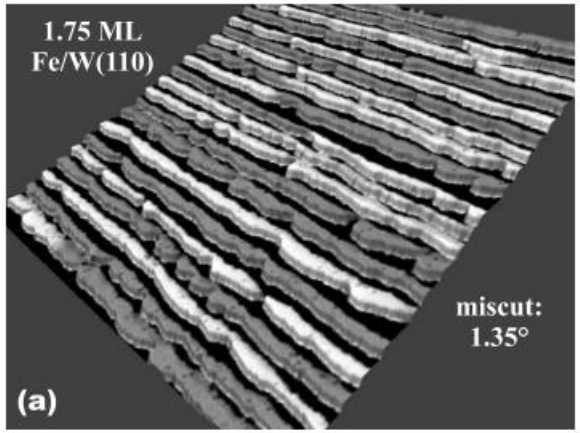

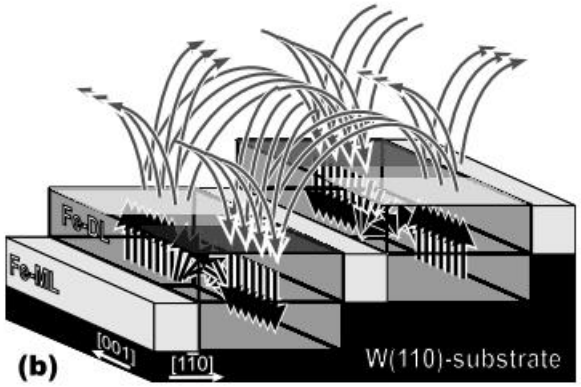

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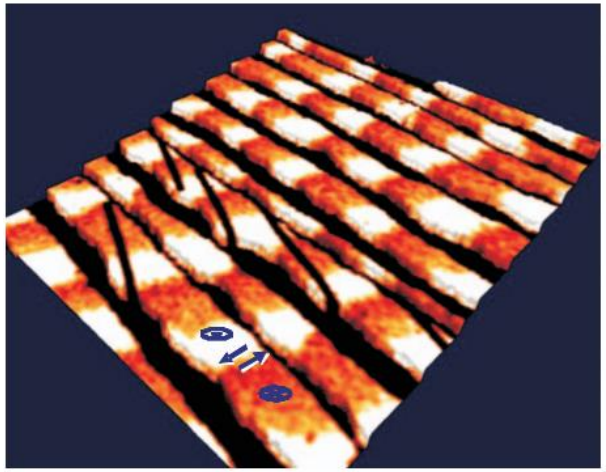

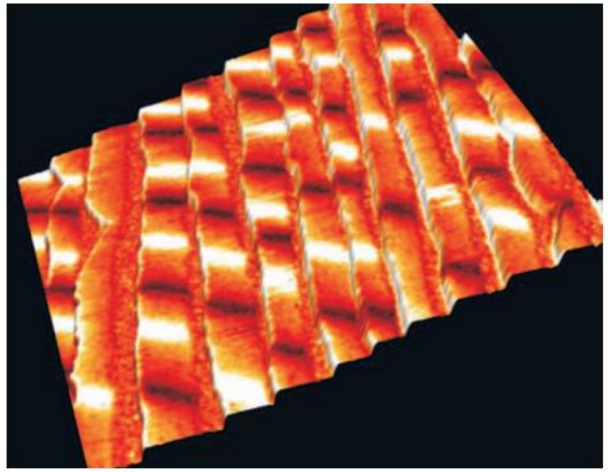

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  - Spin polarization of tip can be determined
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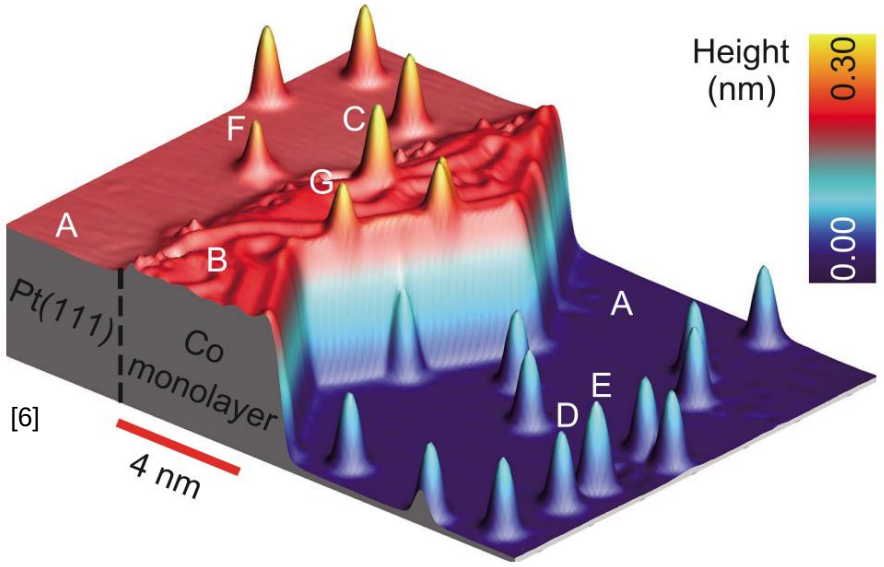

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- Sample composition
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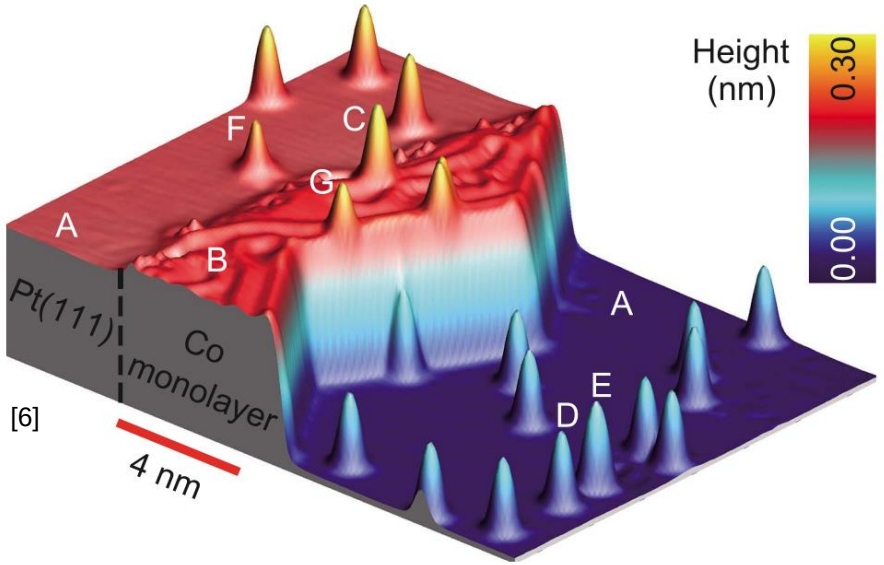
- Spin polarization effect of large magnitude when looking at a Co-dimer



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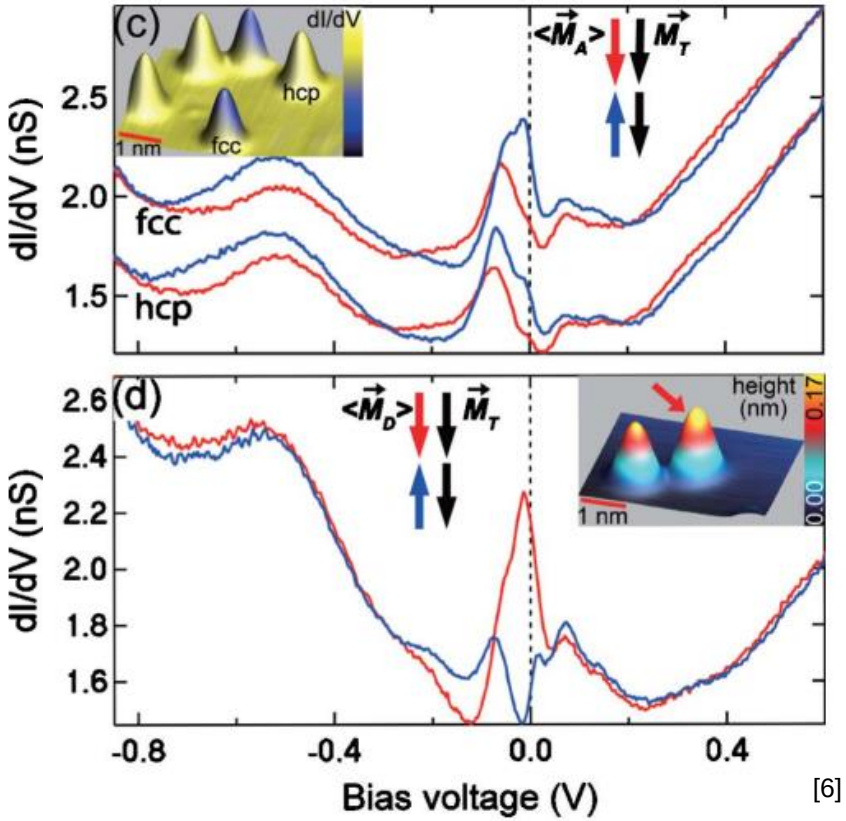

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Antiferromagnetic Arrangements

Experiments & Applications

- Averaging measuring procedures do not allow resolving antiferromagnetic superstructures
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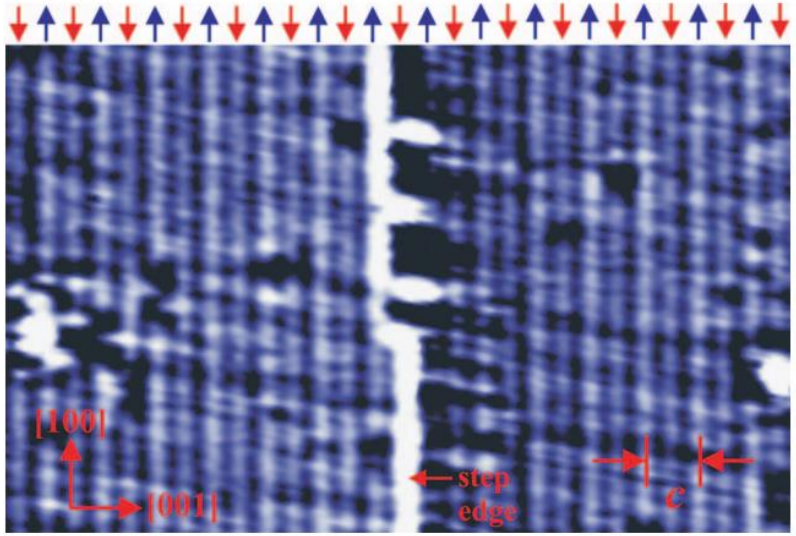

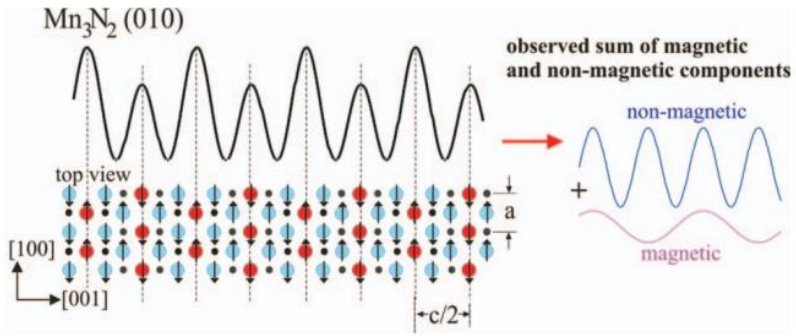

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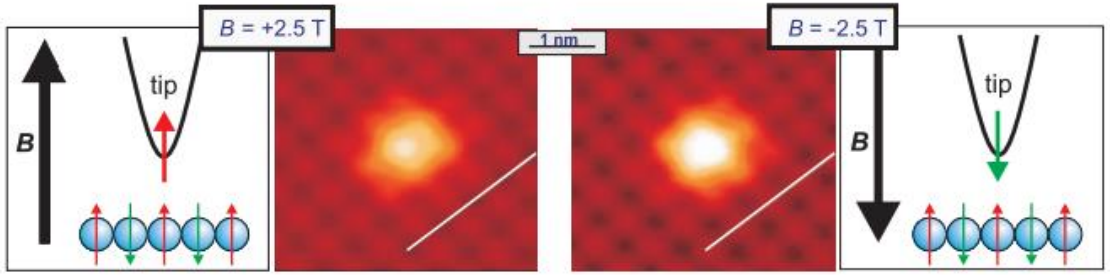
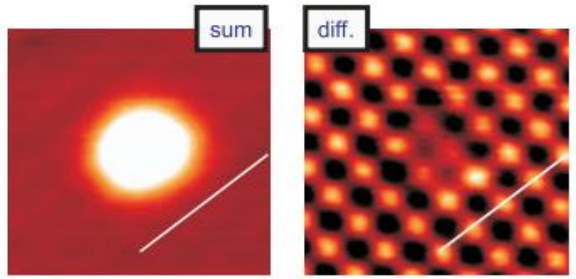


- Sample composition
  - W(001)
  - Fe Monolayer



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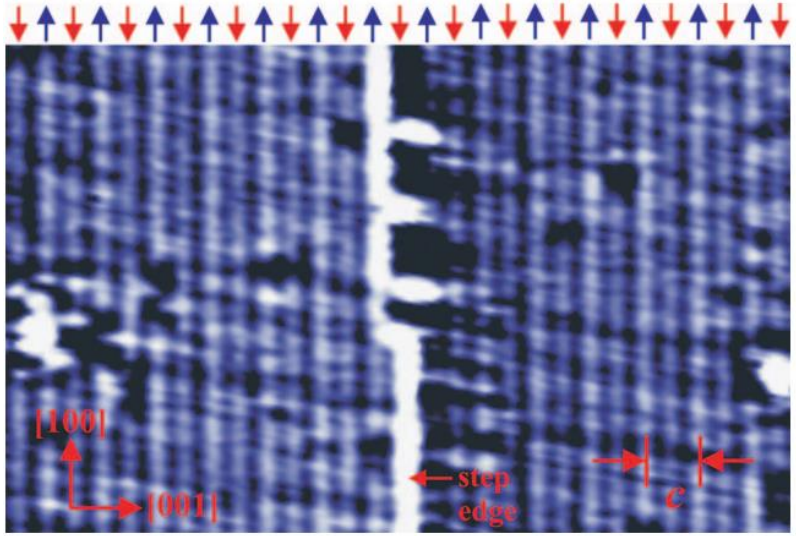

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Experiments & Applications

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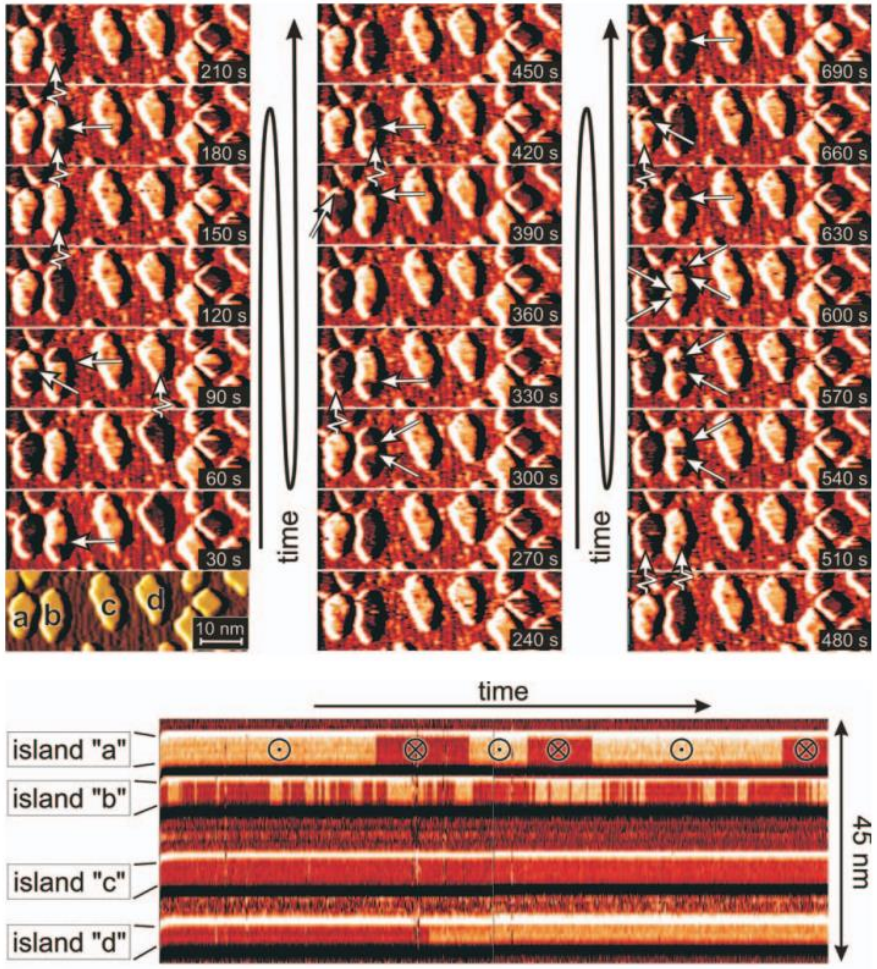

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  - Mo(110)
  - Fe islands (area < 40nm²)
- Antiferromagnetic tip required
  - Magnetic stray field of a ferromagnetic tip would influence switching behavior

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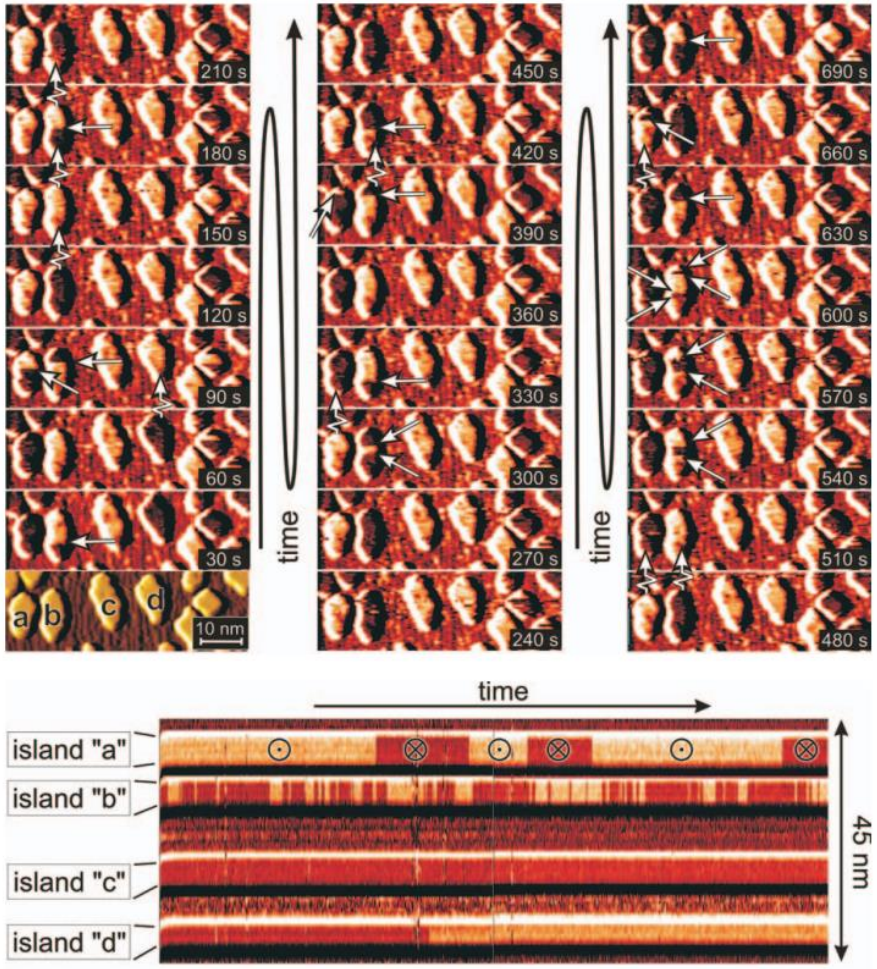
Time Resolved Experiments

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



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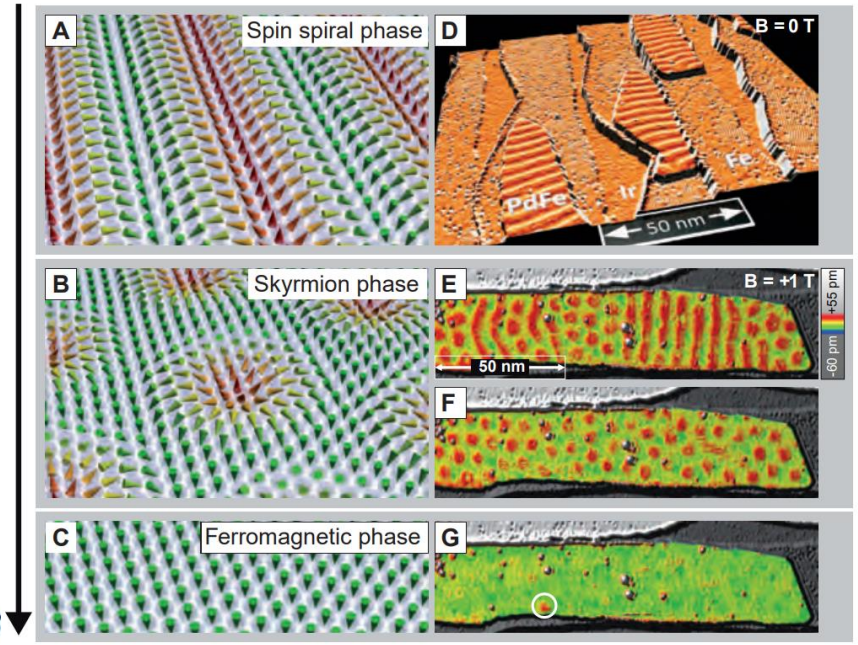
Magnetic RAM through Skyrmion Manipulation

Experiments & Applications



[7]

T~8 K

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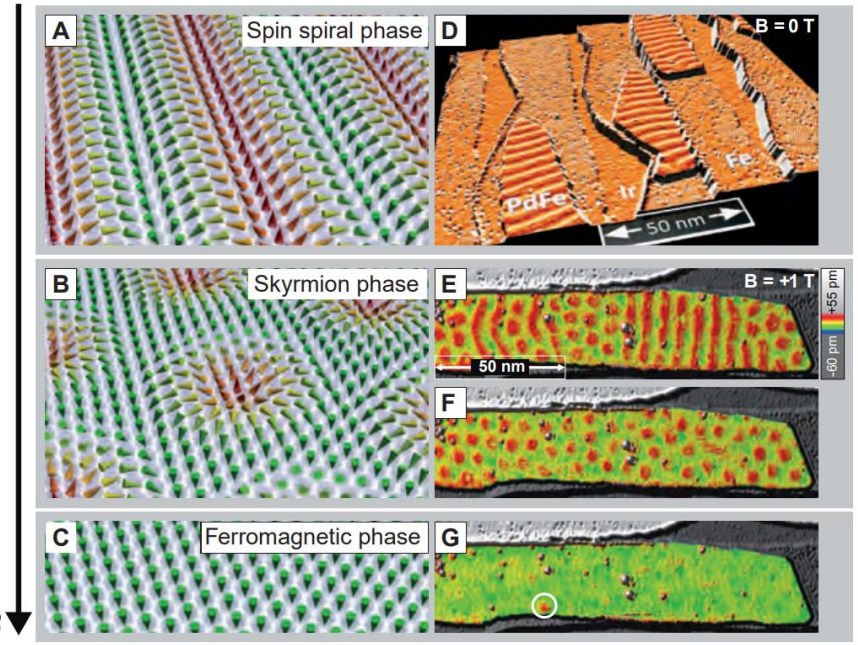
Experiments & Applications



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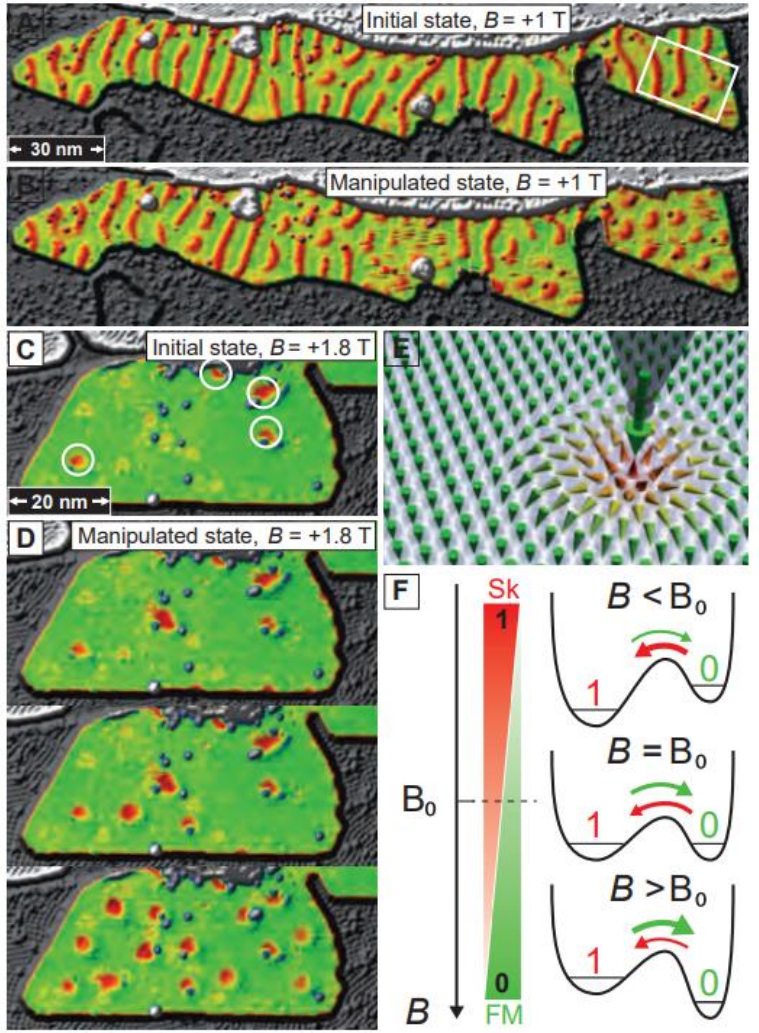

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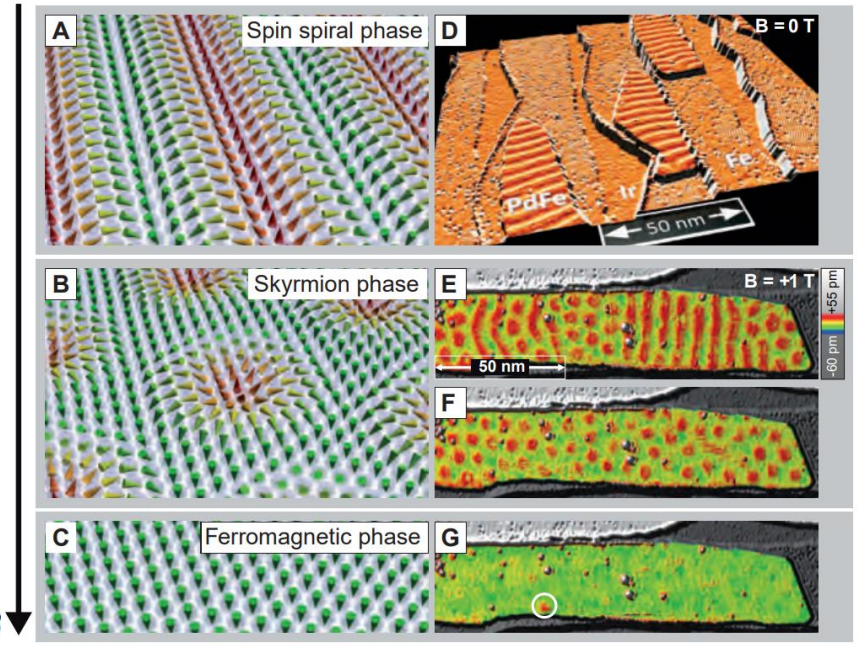

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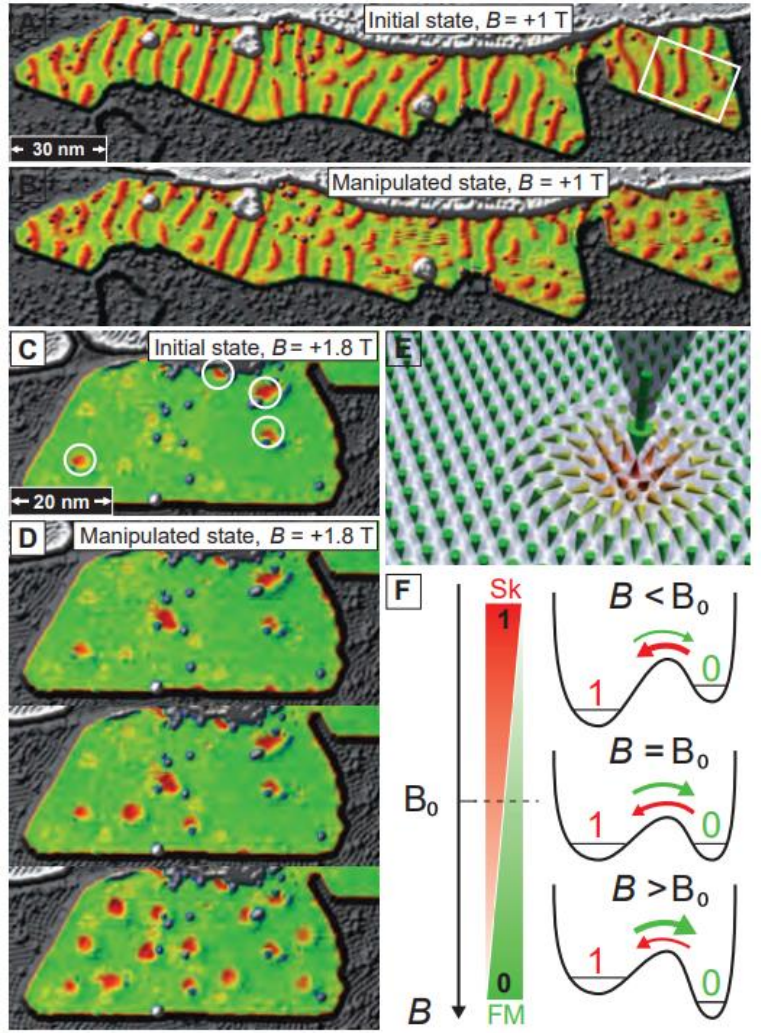

- High temperature (T~8 K)
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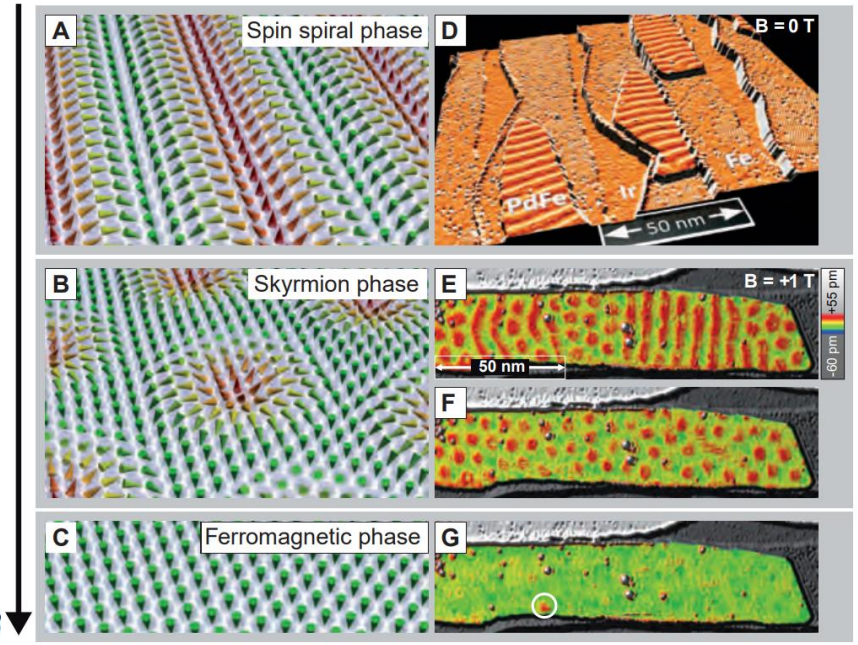
Experiments & Applications



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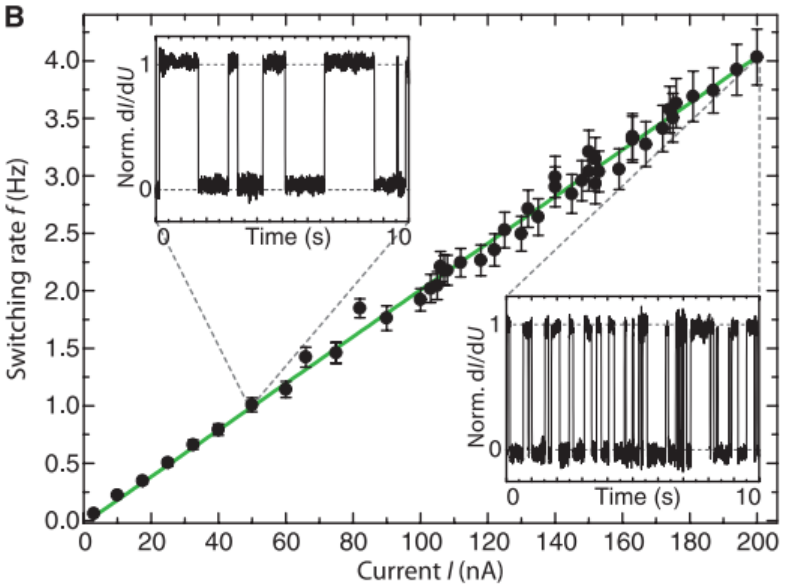

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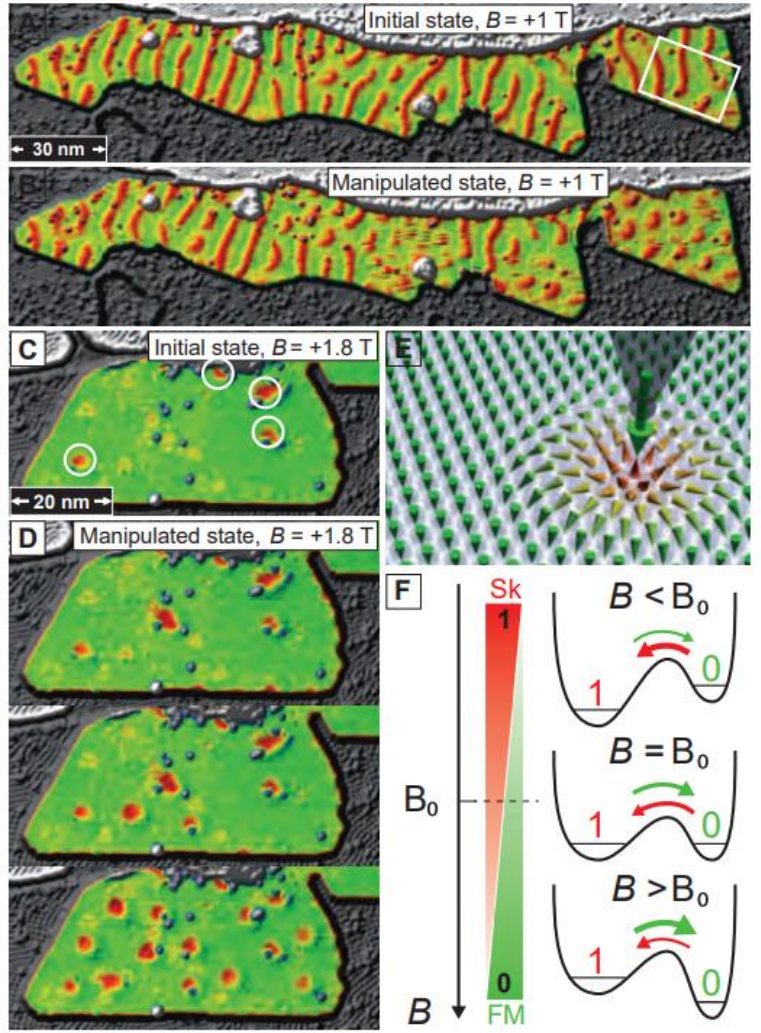


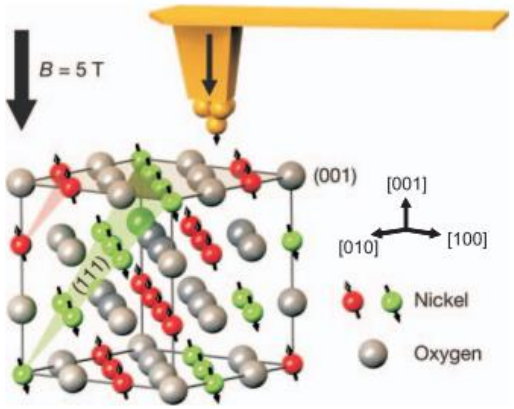
- Switching rate
  - Depends linearly on the tunnel current
  - Also voltage dependent (not shown)

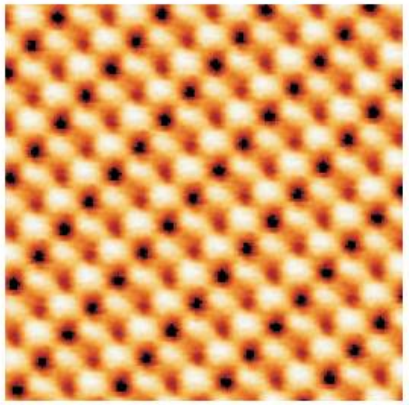
Spin Resolved Microscopy for Insulators?

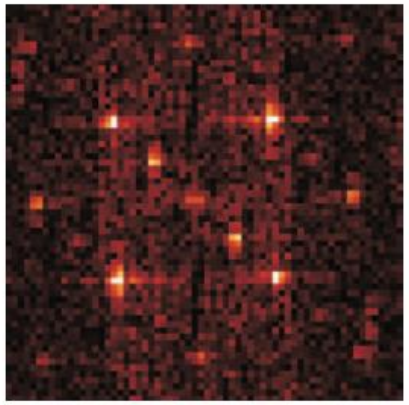
Outlook: Magnetic Exchange Force Microscopy (MExFM)

- No conductive samples needed
  - Electromagnetic exchange forces are used to deflect a cantilever that carries the probe tip
- Modes of operation

- Magnetized tips may be used to resolve spin dependent interaction forces







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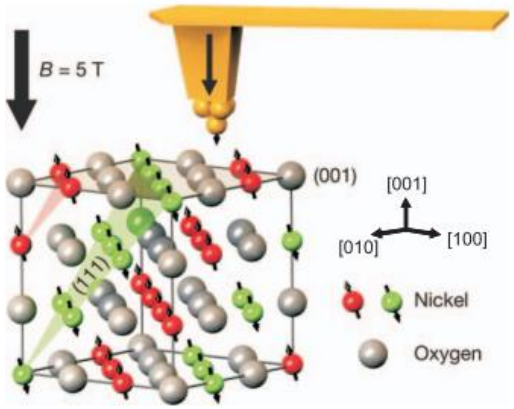

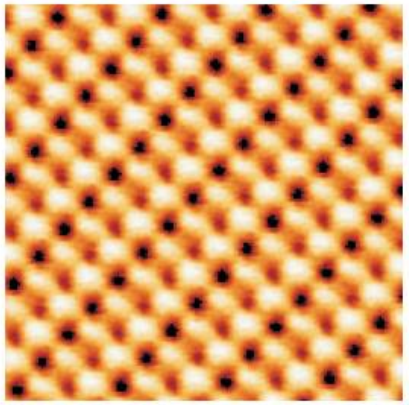

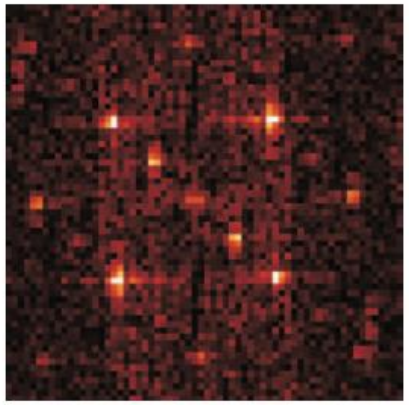

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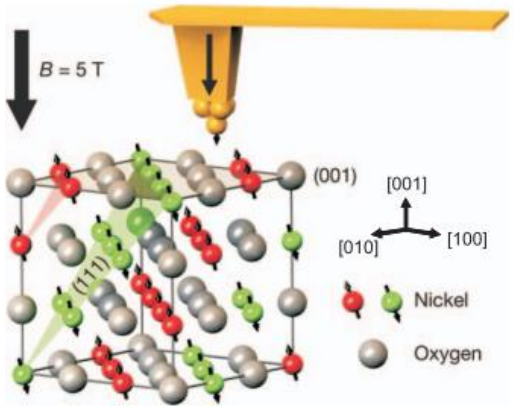

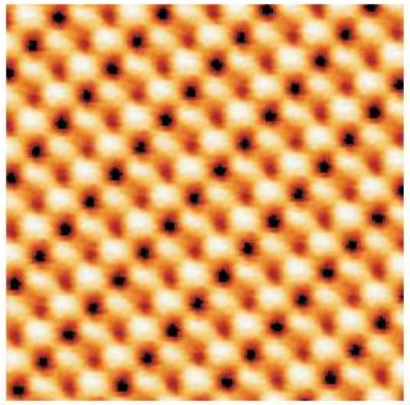

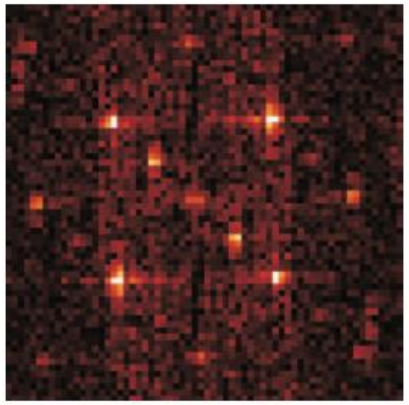

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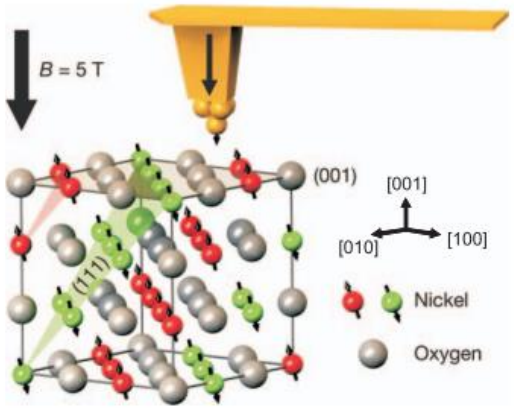

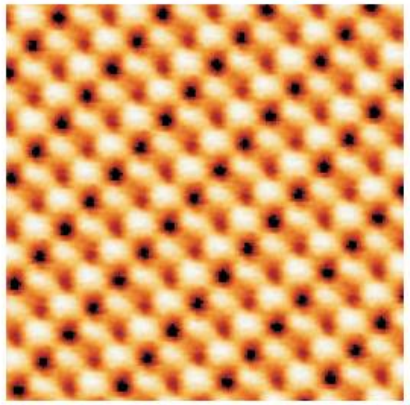

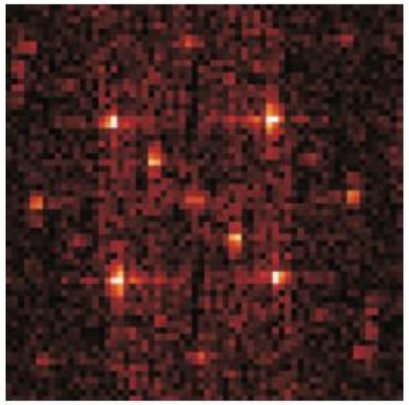

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Head-to-head Comparison: MExFM ↔ SP-STM

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- Temperature range
- UHV environment
- Supports probing with external magnetic fields
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  - 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
- Magnetic moment can be resolved locally
- Possible for metals, as well as insulators
- Comparably high time-resolution
- Active manipulation of sample possible (on measurement-scale)

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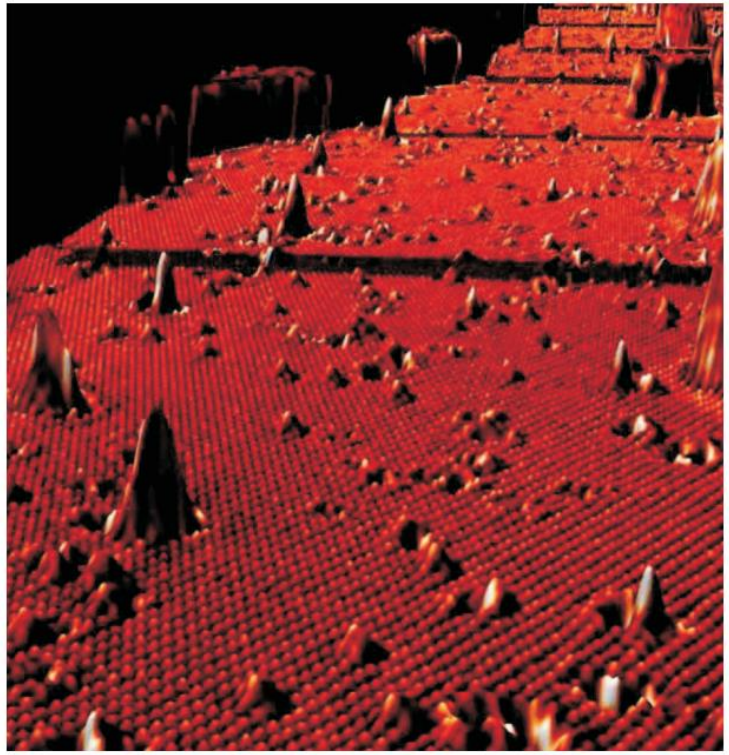
  - Measurements are performed in real-space, contrary to most atom-scale measurement methods
- Magnetic moment can be resolved locally
  - Avoids missing substructures with on average neutral magnetic moments
- Possible for metals, as well as insulators
  - SP-STM for metals
  - MExFM for insulators
- 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]

Universität Augsburg
Mathematisch-Naturwissenschaftlich-Technische Fakultät

Jonas Kell

Augsburg University

jonas.kell@student.uni-augsburg.de

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