STM and spectroscopy of nanosized ferromagnetic structures

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Ferromagnetic nanostructures

• $L_{\text{sample}} \approx L_{\text{exch}} \approx L_{\text{domain wall}}$

⇒ monodomaine (Stoner-Wohlfarth switching ?)

Bonet, PRB 69, 024401 (2004)

• Temperature could overcome anisotropy $kT \approx KV$

⇒ superparamagnetism

Bean, JAP 30, 1205 (1959)

• Atoms with low coordination

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


• Quantum effects (discrete states, collective tunneling)

Bernand-Mantel, APL 89, 062502 (2006)
Wernsdorfer, PRL 79, 4014 (1997)
Probing nanomagnetism

Imaging

<table>
<thead>
<tr>
<th>Method</th>
<th>Sensitive to</th>
<th>Typical resolution</th>
<th>Specificity</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOKE</td>
<td>M</td>
<td>500nm</td>
<td>Easy to use and cheap Argyle, JAP 87, 6487 (2000)</td>
</tr>
<tr>
<td>XMCD-PEEM</td>
<td>M</td>
<td>&lt;10nm</td>
<td>Element specific, dynamic, synchrotron Vogel, PRB 72, 220402 (2005)</td>
</tr>
<tr>
<td>Lorentz</td>
<td>∇B</td>
<td>&lt;10nm</td>
<td>Average over sample, no field Chapman, JMMM 200, 729 (1999)</td>
</tr>
<tr>
<td>MFM</td>
<td>∇B</td>
<td>50nm</td>
<td>Insulator OK, not quantitative Folks, APL 76, 909 (2000)</td>
</tr>
<tr>
<td>SP-STM</td>
<td>TMR</td>
<td>&lt;1nm</td>
<td>No insulator, smooth surface, topography and spectro</td>
</tr>
</tbody>
</table>

Magnetometry

- SQUID, MOKE: thin films: OK

  nanoparticles : average over an assembly of identical objects Rohart, PRB 73, 165412 (2006)

- µ-SQUID: 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

Topography image a constant current
Scanning tunneling microscopy

Topography image a constant current

\[ I_{\text{tunnel}} \propto e^{-d\sqrt{\phi - eV}} \]
Scanning tunneling microscopy

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

Topography image a constant current
Scanning tunneling microscopy

- Ultra high vacuum: $10^{-11}$ mbar
- Low temperature: $T = 4$ K
- High magnetic field: $B = 8$ T

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

Surface science, electronic properties and nanomagnetism
Growth of nanostructures studied by STM

**Nanodots**
Co/Au(788)
Repain, EPL 58, 730 (2002)

- Temperature growth \(\Rightarrow\)
  - Diffusion coefficient + trap energy
- Periodical array of similar dots \(\Rightarrow\)
  - 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)

- Chains width of 1, 2 or 3 atoms
- Ferromagnetic behavior with very high magnetic moment
- Reduce dimensionality \(\Rightarrow\)
  - strong magnetic anisotropy
Scanning tunneling spectroscopy

\[ I(\mathbf{r})_{\text{tunnel}} \propto \int_{0}^{eV} \text{LDOS}(\mathbf{r}, E) \, d\varepsilon \]

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

\[ \frac{dI}{dV}(\mathbf{r}, E) \propto \text{LDOS}(\mathbf{r}, E) \]

LDOS map → Electronic structures

Point spectroscopy → LDOS at a nanoscale

\[ \int \rho_{\text{tunnel}}(\mathbf{r}, E) \, d\mathbf{r} = \int \rho_{\text{bulk}}(E) \, dE, \]

where \( \rho_{\text{tunnel}}(\mathbf{r}, E) \) is the density of electronic states available for tunneling.
Principle of Spin-Polarized STM

Magnetic tunnel junction with vacuum


Principle of Spin-Polarized STM

Magnetic tunnel junction with vacuum

Principle of Spin-Polarized STM

Magnetic tunnel junction with vacuum

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 nanostructures

Vortex in Fe island on W(110),

Magnetic surface reconstruction

1ML of Mn on Fe(001)
Gao, PRL 98, 107203 (2007)

In-plane Cr tip
Out-of-plane Cr tip

Single magnetic atoms

Atoms on Co islands
Co island on Cu(111)

Co deposition at 300K on Cu(111)

⇒ Step edge decoration

⇒ Triangular Co islands

50 x 50 nm², -0.36 V, 1 nA

2 monolayer high island

Linescan
Spectroscopy on a single island

Point spectroscopy on the island

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 superparamagnetism and multi-domain island

Switching field

\[ \frac{2K}{M_s} \]

Superpara  Monodomaine  Multidomaine ∼1/V

Volume

Atom number

Switching field (T)

Switching field (T)

\[ \frac{2K}{M_s} \]

Atom number

2430 atoms
4210 atoms
4820 atoms

\[ \frac{dI}{dV} \text{ (arb. units)} \]

Field (T)

0 1 2 3 4

0 1 2 3 4 5 6 7
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
Size dependence of the island switching field

![Graph showing the size dependence of the island switching field.](image)

Legend:
- Red dots: 2430 atoms
- Blue squares: 4210 atoms
- Green triangles: 4820 atoms

Graph on the left:
- x-axis: Field (T)
- y-axis: $\frac{dI}{dU}$ (arb. units)

Graph on the right:
- y-axis: Switching field (T)
- x-axis: Atom number
Observation of Magnetic Hysteresis at the Nanometer Scale by Spin-polarized Scanning Tunneling Spectroscopy


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.
Introduction: context of SP-STM

Surface Science
Scanning tunneling microscope

- Atomic resolution Cu(111), 2x2nm
- Co nanostructure on Cu(111) 50x50nm

Spintronic
Tunnel Magnetoresistance

- Co/Al₂O₃/NiFe tunnel junction

Spin-polarized STM
Principe of TMR

Jullière model:
- Spin is conserved during tunneling
- Conductance $\propto$ DOS of electrodes
  \[ G^P \propto N_1^\uparrow \cdot N_2^\uparrow + N_1^\downarrow \cdot N_2^\downarrow \]
  \[ G^{AP} \propto N_1^\uparrow \cdot N_2^\downarrow + N_1^\downarrow \cdot N_2^\uparrow \]

Open questions:
- TMR sign, depend only of $P_1P_2$ ?
- Interface electrode/barrier ?
- Voltage dependence ?
- Influence of the DOS ?

\[ TMR \equiv \frac{G^P - G^{AP}}{G^P + G^{AP}} = P_1P_2 \]

\[ G = G_0 (1 + P_1P_2 \cos(\vec{M}_1, \vec{M}_2)) \]

Tunnel Magnetoresistance (TMR)

Trilayer: ferro/insulator/ferro

TEM view of a magnetic tunnel junction grown by sputtering

Contacts made by lithography

Top electrode NiFe
Barrier Al$_2$O$_3$
Down electrode Co

Transport

Antiparallel
Parallel

Application: MRAM

Magnetic contrast
External field out of plane

Sample

« Parallel »

« Antiparallel »

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 understood from the LDOS dependence
TMR voltage dependence

- Higher current for $\uparrow \downarrow$ than for $\uparrow \uparrow$: TMR negative for all energy
- Shape can be understand from the LDOS dependence

Stroscio et al. PRL 75, 2960 (1995)