Seminár

MAGNETIC FORCE MICROSCOPY

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1 Abstract

Magnetic force microscopy is one of the best methods to observe magnetic structures on nanoscale. It uses atomic force microscope with specially prepared tips. Only recently, however, has atomic resolution been reached by spin-polarized tunneling on a scanning tunneling microscope. This revolutionary new method is now being used to help the development of magnetoelectronic random access memory (MRAM). This is a promising data storage candidate that could in the future replace all existing RAM, ROM and even hard disk technologies.

2 Magnetic force microscopy

Scanning probe microscopes [2], invented in early 1980’s, have revolutionized surface microscopy. They allow us to resolve local structures at an atomic scale on literally every kind of surface. Scanning is possible in a variety of environments from ultra high vacuum to different gas atmospheres at room temperature or at very low temperatures. And because SPM’s cause no damage to the sample imaging of phase transitions or biological phenomena is made possible.

There are many different kinds of SPM’s of which scanning tunneling microscope (STM) and atomic force microscope (AFM) are the most known. Our interest will however be magnetic force microscope (MFM) which can measure local magnetic fields. We will use it to observe magnetic structure of thin film elements that could be in the future used as data storage devices. Spin-polarized STM, another microscope that is used to observe magnetic structures will also be part of the discussion. Its main advantage over MFM is that it has atomic resolution.

Essential elements of MFM (and most other SPM’s or STM’s) are:

- piezoelectric scanner
- tip mounted on a cantilever
- detector
- feedback system
- computer

2.1 Scanner

We know two basic types of piezoelectric scanners: tripod and tube scanner. The latter is most commonly used because of its simplicity. The design of tube scanner
is shown in Fig. 1. A tube made of piezoelectric material is coated with metal. The outside coating is sectioned into four quadrants: +X, +Y, -X, and -Y. The inside is made of only one electrode Z. The bending of the tube in x direction is achieved by applying opposite and equal voltages to X electrodes. Similarly, +Y and -Y electrodes are used for bending in y direction. The third kind of movement is stretching of the tube which is done by applying voltage to the Z electrode.

When scanning, the piezoelectric tube moves in a pattern similar to one used to display image on the TV screen. On each line of the scan the data is read and there is usually a choice between 256 or 512 data points per line. The size of the scan in x and y directions can go from less than 10 nm to more than 100 µm. In the vertical direction piezoelectric scanners can distinguish height variations from the sub-angstrom range to about 10 µm.

![Figure 1: A piezoelectric tube with attached electrodes.](image)

2.2 Cantilever and tip

The probe of MFM consists of a tip mounted on a cantilever. These two parts are the most critical since they define the lateral resolution.

The cantilever is a thin plate approximately 100 – 200 µm long, 10 – 40 µm wide and 0.3 – 2 µm thick and it bends because of different forces between the sample and the tip. By measuring the deflection we can for example get the magnetic scan of the surface. The most important property of the cantilever is its spring constant. It depends on the dimensions of the cantilever and the material it is made of and is typically from $10^{-2}$ to 100 N/m. For contact scanning soft cantilevers that do not damage the surface are used whereas for non-contact mode we need stiffer cantilevers.
There are two kinds of tips: pyramidal and conical. The most important requirement is that they are sharp. Ideally, there would be only one atom at the end of the tip and it would interact with only one atom on the sample. This is not so but to get true images the tip should be sharper than the smallest feature on the sample.

There are many tip manufacturing techniques from chemical etching to photolithography. Chemical etching for example, uses pieces of silicon that are etched from all sides until a sharp tip is created. Tips made this way have tip radii in 10 nm range but this can be further enhanced by growing a thin needle on top of the silicon tip. Lateral resolution of the tip is determined by the interaction area between the tip and the sample, which is only a fraction of the tip radius. The sharpest commercial tips can typically provide lateral resolution of $1 - 2$ nm.

For use in a MFM, tips have to be ferromagnetic so that there is magnetic interaction between the tip and the sample. That is why silicon tips are coated with a suitable magnetic film. This is done by sputtering or evaporation. The preferred coatings are layers of thin film recording materials such as Co/Cr.

![Figure 2: Cantilever with integrated tip.](image)

### 2.3 Detector

Although there are many deflection detectors including STM’s and mechanical resonance detectors, most current MFM’s use optical detectors.

The first type uses optical interferometry, which can measure cantilever deflections in z direction. An optical fiber is brought close to the cantilever. The light emitted from a laser is then reflected from the cantilever and from the end of optical fiber. As the distance between the end of the optical fiber and the cantilever varies, the interference pattern changes and we can calculate cantilever deflection.

The second type of optical detector uses much simpler mechanism. Laser beam is reflected from the cantilever at an angle. When the cantilever bends, the
angle of reflection is changed and this change is detected by position sensitive photo detector. This way we can measure not only z deflection but also torque.

### 2.4 Feedback and computer

The final thing we need in a MFM system is a way of driving the piezo tube and taking in the data. This is done by using computer which also has some more advantages like post processing (slope subtraction, FFT, etc.).

The other part needed is the feedback system which is used in constant force mode to apply a voltage to the Z piezo electrode so that the force on the cantilever is always constant. Other functions of the feedback system are signal amplification, noise reduction, etc.

### 2.5 Principle of operation

To understand how MFM’s work we need to know what forces act on the tip. Since our focus are magnetic materials there are two main forces: magnetic force and inter-atomic force.

A typical curve, showing inter-atomic force, is plotted in Fig. 3. When atoms are separated by large distances there is slight attractive van der Waals force. As the atoms are brought closer together this attractive force vanishes because of a much larger repulsive force that comes from Pauli exclusion principle. In practice this means that the tip and the sample are in contact. This way contact mode topographic images can be made.

To make magnetic images, magnetic force has to be taken into account [3]. When there is ferromagnetic tip and ferromagnetic sample the magnetic force can be written as $\vec{F} = (\hat{\mu} \cdot \nabla)\vec{B}$, where $\hat{\mu}$ is the magnetic dipole moment of the tip and $\vec{B}$ is the stray field of the sample. But because ferromagnetic tips are made by evaporation, these tips have magnetization along their symmetry axis. This means that only z component of tip’s magnetic dipole moment is different from zero and thus the normal force, acting on the tip, is given by

$$F_z = \mu_z \frac{\partial B_z}{\partial z}$$

This also means that only out-of-plane component of the stray field of the sample can be detected by MFM.

There is another, more detailed view of the sample-tip interaction. The interaction force can be estimated by assuming a direct interaction between magnetic moments per unit volume of the tip ($\hat{\mu}_1$) and of the sample ($\hat{\mu}_2$):
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Figure 3: Attractive van der Waals force at large distance (non-contact) and repulsive Pauli force at small distance (contact) contribute to the total inter-atomic force.

\begin{align}
    F(z) &= \int_{\text{tip}} d^3 \vec{r}_1 \int_{\text{sample}} d^3 \vec{r}_2 f_z(\vec{r}_1 - \vec{r}_2) \\
    f_z(\vec{r}) &= \left( \frac{\mu_0}{4\pi} \right) \frac{\partial}{\partial z} \left( \frac{3(\vec{r} \cdot \vec{\mu}_1)(\vec{r} \cdot \vec{\mu}_2)}{r^5} - \frac{(\vec{\mu}_1 \cdot \vec{\mu}_2)}{r^3} \right)
\end{align}

If the sample is paramagnetic or diamagnetic it has no spontaneous magnetization and there is no direct magnetic interaction between the sample and the tip. But because the tip is ferromagnetic its stray field causes the sample to magnetize. As a result of this there is a small magnetic force which is not significant in observations.

There is one problem not discussed before. We would like to separate magnetic forces from inter-atomic forces. The easiest solution is to scan the sample twice, but at different heights. On the first scan we take in the topography. The distance between the tip and the sample is typically $20 - 50$ nm and at this distance inter-atomic forces dominate. Then we take the second scan with the tip raised about $100$ nm above the previously measured topography and thus measure only magnetic forces.
3 Applications of MFM

The first uses of MFM’s included scanning of magnetic tapes and hard disk surfaces. Recently however, magnetic nanostructures are becoming more and more important objects of observation. An interesting and promising example are circular nanostructures that exhibit in-plane magnetic vortex and can be used as basic elements of magneto-electronic random access memory (MRAM).

3.1 Giant magnetoresistance (GMR)

To understand how MRAM works, giant magnetoresistance (GMR) has to be explained. GMR is an effect that appears in magnetic multilayers and is much larger than ordinary, anisotropic magnetoresistance. In multilayers, ferromagnetic materials such as Fe or Co are separated by non-magnetic materials (Cr, Cu, Ag,...). If the thickness of non-magnetic layers is less than spin diffusion length, GMR occurs.

The reason for such huge resistance can be found in different magnetizations of adjacent ferromagnetic layers. Suppose that electrons come from one layer with magnetization \( \vec{m}_1 \). The spin of these electrons will then depend on \( \vec{m}_1 \) and because the non-magnetic layers are thin, electrons will have the same spin when they enter the next ferromagnetic layer with magnetization \( \vec{m}_2 \). Since \( \vec{m}_2 \) is in general different from \( \vec{m}_1 \) there is additional electron scattering that causes additional resistance proportional to \( \vec{m}_1 \cdot \vec{m}_2 \). This can cause up to 100% change in resistivity.

There are two geometries for observing GMR effects. The first discovered was current-in-plane (CIP) GMR where electric current flows in the layer planes. The second, more interesting because of 3–10 times higher resistance, is current perpendicular to plane (CPP) geometry \([5]\). Typical resistance of a sample 1 mm\(^2\) and 1 \( \mu \)m thick is \( 10^{-7} - 10^{-8} \Omega \), which looks very small only because of short and wide geometry that is inevitable in CPP GMR.

3.2 Switching of GMR devices

The basic function of RAM is to switch between two states 0 and 1 and thus store information. In GMR memory elements this is done by switching between low and high resistance \([6]\).

Process flow for fabrication of such element is shown in Fig. 4. Multilayer has to be made of soft and hard magnetic layers. Soft magnetic layers are soft primarily because they are thinner and they change orientation prior to the hard magnetic layers because of reduced pole density. Vertical GMR devices can be made using optical lithography and have diameters in range 0.3 – 0.7 \( \mu \)m. Small size is important since these devices work best in the state without domain walls.
The switching of GMR devices is achieved simply by passing current vertically through the device (Fig. 5). The current causes rotational magnetic field which changes magnetization configuration in multilayer. At low magnetic fields only soft magnetic layers change orientation and the device is in high-resistance state. When the magnetic field gets higher, hard magnetic layers also change orientation and the device returns into low-resistance state. Low field switching of the soft layers occurs at $\sim 4\text{mA}$ and high field switching of the hard layers at $\sim 15\text{mA}$. These current levels are similar to those used in present RAM technology.

This kind of switching has one drawback. The reading of the data is destructive since current has to flow through the device to measure its resistance. This simply means that after every read the data has to be rewritten which needs extra time. In comparison with the popular SDRAM memories, MRAM is a little slower. Typical access time of a MRAM memory is $\sim 50\text{ns}$ while SDRAM can access data in less than 10ns.

### 3.3 Spin-polarized STM (SP-STM)

Basic MRAM elements are in a state without domain walls. Theoretical predictions have been made that this state is a vortex and recently, magnetic vortex cores have been verified by MFM. But there are three major drawbacks in using conventional MFM:
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3.3 Spin-polarized STM (SP-STM)

Figure 5: Resistance of a multilayer device. The measurement was repeated 10 times.

1. lateral resolution (20 – 100 nm) is larger than the vortex core
2. magnetic stray field of the tip interferes with the vortex
3. the sensitivity is restricted to the out-of-plane component of the stray field

This is why an improved variant of MFM was invented that uses ferromagnetic or even antiferromagnetic tip coatings and tunneling current for measuring tip to sample distance. It is called spin-polarized scanning tunneling microscopy (SP-STM) and is capable of resolving magnetic structures down to the atomic scale. Furthermore, it has recently been shown [7] that interference of the tip with the sample can be avoided by using antiferromagnetic tips. And finally, by varying the thickness of the antiferromagnetic layer on the tip it is possible to make tips sensitive to either in-plane or out-of-plane components of the sample’s stray field. The only serious drawback of SP-STM is that sample has to be made of conducting material. Otherwise there is no tunneling current.

SP-STM basic idea is that the tunneling electrons are spin-polarized. Then the tunneling current strongly depends on the sample spin state. Spin-polarized electrons can be produced in tunneling through metal-insulator-metal junctions. In ferromagnetic materials electron energy bands are split into two subbands with different spin polarization. Unequal electron population in these bands causes non-zero magnetization without any external magnetic field. Most simple explanation of the spin-polarized tunneling current is that these two energy bands cause
two separate currents of spin-up and spin-down electrons. Thus spin polarization of the tunneling current can be defined as

\[ P = \frac{n_\uparrow - n_\downarrow}{n_\uparrow + n_\downarrow} \] (4)

where \( n_\uparrow \) and \( n_\downarrow \) are densities of spin-up and spin-down electrons respectively. Some values of spin polarization are shown in Table 1.

<table>
<thead>
<tr>
<th>Ferromagnet</th>
<th>( P )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe</td>
<td>0.40</td>
</tr>
<tr>
<td>Co</td>
<td>0.35</td>
</tr>
<tr>
<td>Ni</td>
<td>0.23</td>
</tr>
<tr>
<td>Gd</td>
<td>0.14</td>
</tr>
</tbody>
</table>

Table 1: Spin polarization of electrons tunneling from ferromagnetic materials.

As the tip moves across the surface the spin state under it changes which leads to different scattering of spin-polarized electrons. There is maximum scattering when spin-polarizations of the electrons and of the sample are antiparallel and minimum scattering when they are parallel. The tunneling current changes accordingly. That is, when the scattering is huge there is small tunneling current. The differential conductance at the location \( \vec{r} \) on the surface for a bias voltage \( U_0 \) can be written as

\[ \frac{dI}{dU}(\vec{r},U_0) = C(1 + P_T P_S \cos \theta) \] (5)

where \( C \) is the spin-averaged differential conductance, \( P_T = P_T(E_F) \) is the spin polarization of the tip at the Fermi energy, \( P_S = P_S(E_F + eU_0) \) is the spin polarization of the sample at energy \( E_F + eU_0 \) and \( \theta \) is the angle between the tip magnetization \( \vec{M}_T \) and the sample magnetization \( \vec{M}_S(\vec{r}) \). This equation is valid also for antiferromagnetic tips if the term \( \vec{M}_T \) is interpreted as the magnetic moment of the atom at the tip apex \( \vec{m}_T \). This atom is responsible for spin polarization of tunneling electrons although the net magnetization of antiferromagnetic tips equals zero.

3.4 Observations

The first SP-STM results were obtained on a Cr (001) surface with atomic steps that have alternating magnetization (Fig. 6). In this experiment, the surface was first imaged using the non-magnetic and then the magnetic tip. On the non-magnetic scan the height of the steps appeared to be the same (0.14 nm), but magnetic scan showed alternation between 0.16 and 0.12 nm. In later experiments however, there was no need to scan the sample twice with different tips.
because topographic and electronic contributions can be successfully separated by spectroscopic techniques [9].

Figure 6: Alternating magnetization gives additional contribution to the tunneling current. Therefore we get larger apparent height $h_1$ when magnetizations of sample and tip are parallel and smaller $h_2$ when magnetizations are antiparallel.

The observations of vortex cores were made on nanoscale Fe islands [8]. The lateral dimensions of such islands are 200 to 500 nm by 150 to 250 nm and the average thickness is 8 to 9 nm. This size is very important because the islands are too large to form a single-domain state but they are also too small to form domain walls. The solution is that magnetic ground state is a vortex which drastically reduces the stray field energy. The magnetization of the vortex continuously curls around its core but in the core it turns into the surface normal as shown in Fig. 7.

Topographic and magnetic measurements (Fig. 8-10) were made with a low-temperature STM at the sample and tip temperature of 14 K. By varying the thickness of antiferromagnetic layer on the tip, in-plane or out-of-plane sensitive tips can be made.
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3.4 Observations

Figure 7: Schematic of a vortex core. In the center the magnetization is perpendicular to the surface.

Figure 8: Topography (A) and magnetic scan (B) of a single Fe island. Arrows indicate orientation of the vortex but because the sign of spin polarization and the magnetization of the tip are unknown, the orientation could also be reversed.
Figure 9: Magnetic maps measured with an in-plane (A) and out-of-plane (B) sensitive tips. In (B) the bright area is the vortex core with magnetization perpendicular to the plane.

Figure 10: Differential conductance signals for in-plane and out-of-plane sensitive tips. The measurement parameters were (C) $I = 0.6 \text{nA}, U_0 = -300 \text{mV}$ and (D) $I = 1.0 \text{nA}, U_0 = -350 \text{mV}$.
4 Conclusion

Magnetic force microscopes are used to observe magnetic structures of a sample. We have learned what basic parts of MFM are and have introduced an improved version of MFM, which is called spin-polarized STM. SP-STM’s advantages are that it has atomic resolution and is sensitive to in-plane and out-of-plane magnetic fields. The recent research area involving SP-STM’s have been thin film giant magnetoresistance devices, that are a promising candidate for nonvolatile data storage devices (MRAM). Theoretical predictions have been made that these devices have a curling magnetic structure (vortex). Using SP-STM, direct observations of spin structure of vortex cores have been made.

References


