

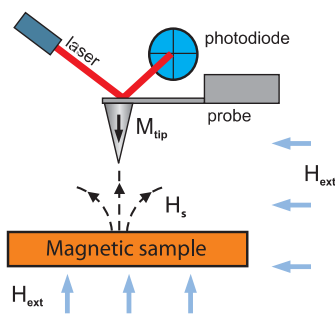
Magnetic Force Microscopy: nanoscale magnetic imaging and lithography

NTEGRA Aura

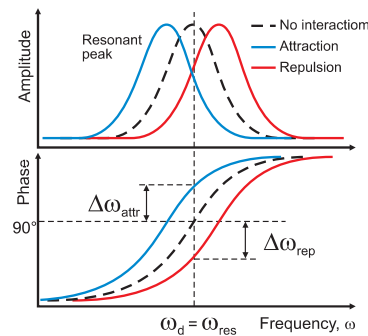


The principle of Magnetic Force Microscopy (MFM) is based on the detection of the interaction between the sample and a nanosized magnetic probe. The standard magnetic probe is an AFM cantilever covered by thin magnetic film. MFM measurements reveal magnetic structure of thin films, bulk samples, nanostructures and nanoparticles with resolution down to nanometer scale. The best resolution is achieved by using special high-aspect ratio tips. There are two main methods of MFM signal detection: measurements of static cantilever deflection and dynamic MFM detecting amplitude, phase and frequency of oscillating cantilever. Standard MFM methods are available with all SPM models produced by NT-MDT.

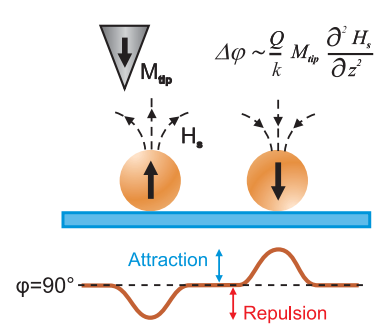
Scheme of MFM measurements



Principle of phase-detecting dynamic MFM



MFM image formation



NT-MDT solution for MFM includes:

- **Static and dynamic MFM, as well as single-pass and two-pass techniques**

Measurements of both cantilever deflection and resonant peak shift. The single-pass technique is used for imaging of magnetically soft materials; the two-pass technique is used for constant tip-sample distance during measurements.

- **Measurements with external magnetic field**

Both vertical (up to 0,8 Tesla (8 000 Gauss) standard, or up to 1 Tesla (10000 Gauss) by request) and horizontal (up to 0.6 Tesla, or 6 000 Gauss) magnetic fields are available.

- **MFM in vacuum**

Measurements in vacuum significantly improve sensitivity of MFM because of increased cantilever quality factor.

- **Temperature range from 50 K up to 593 K**

Wide range of temperatures allows for investigation of different phenomena such as magnetic phase transitions.

- **Available for measurements with Phase-Locked Loop (PLL)**

PLL is a useful tool for fast scanning in vacuum and measurements of magnetic dissipation

- **Highly accurate closed-loop scanner**

For high-resolution magnetic lithography and non-distorted MFM images.

- **Use of scripting language for AFM control**

Scanning algorithm and external magnet performance can be controlled and modified by the user utilizing the available scripting.

Magnetic Force Microscopy

MFM imaging of the magnetic structures in films, nanoparticles and nanostructures

MFM is widely used for imaging of domain structures of different magnetic materials. Resolution better than 50 nm is routinely observed by MFM with standard, commercially available, thin-film magnetic probes. The use of specially designed advanced probes improves resolution.

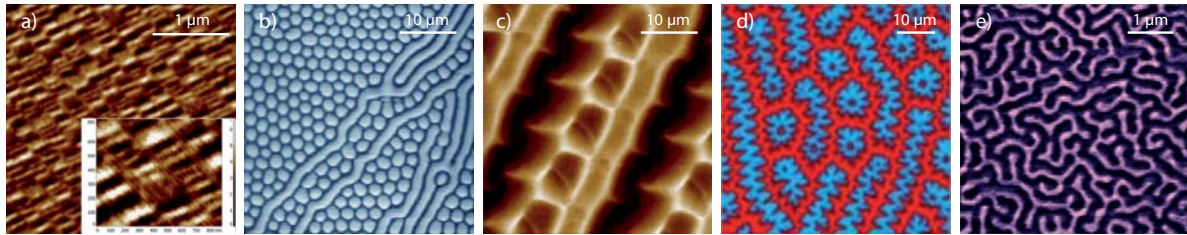


Figure 1. (a) a magnetic structure of a hard disk drive with bit size down to 30–40 nm, which was obtained by cobalt alloy coated probe in ambient conditions; (b–d) domain structures of different magnetically soft garnet films. One-pass method of imaging and thin magnetic coatings on the tip were utilized in order to reduce disturbance of the sample structure by the tip during measurements; (e) the domains in Co/Au multilayered structure obtained by two-pass method and tip with low magnetic moment.

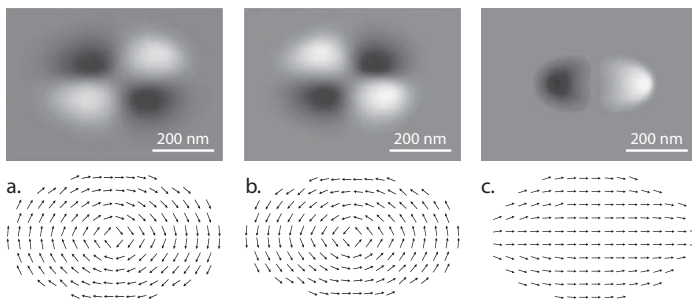


Figure 2. MFM images (top row) and simulated magnetization distribution (bottom row) in elliptical FeCr particles. Vortices with different chiralities (a–b) and a state with uniform magnetization (c) are shown.

J. Chang et al. *J. Appl. Phys.* 100, 104304, 2006.

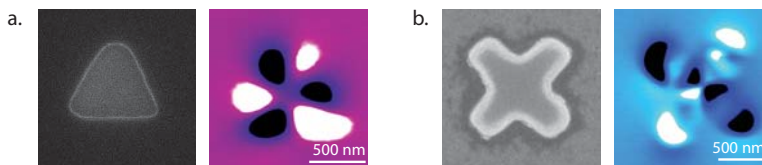


Figure 4. Electron microscopy images (left) and MFM images (right) of triangular and cross-like ferromagnetic structures. Magnetic states correspond to vortex (a) and antivortex (b) in triangle and cross-like structure, correspondingly. V.L. Mironov et al. *Phys. Rev. B.* 81, 094436, 2010. Image courtesy: B. Gribkov, V. Mironov (IPM RAS, Russia)

MFM imaging with external magnetic field

The use of an in-situ magnetic field during MFM measurements allows the investigation of magnetization reversal processes. Some examples of the external field application are listed below.

Horizontal external magnetic field

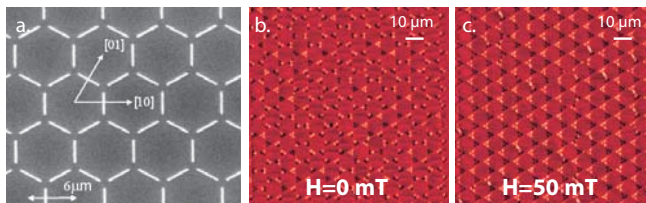


Figure 5. MFM images of artificial spin ice (honeycomb magnetic structure shown in image (a)): (b) demagnetized state, (c) the same place with highly ordered structure in horizontal magnetic field of 50 mT applied in the [11] direction.

A. Schumann, et al. *Appl. Phys. Lett.* 97, 022509, 2010.

Magnetic Force Microscopy

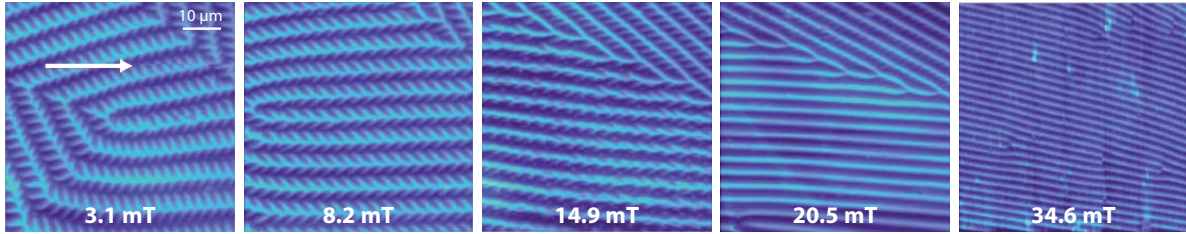


Figure 6. Reorganization of the garnet film domain structure in external horizontal magnetic field. Direction of field is indicated by arrow.

Vertical external magnetic field

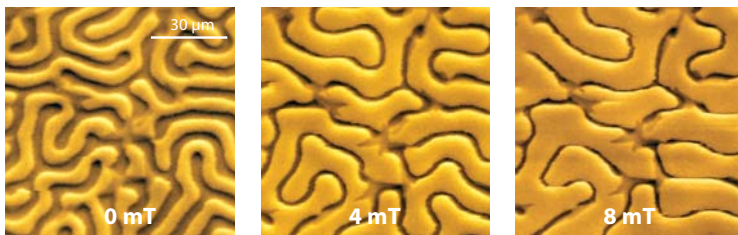


Figure 7. MFM images of garnet film in vertical magnetic field. Extension of domains with magnetization direction coinciding with direction of the external field is clearly seen.

Sample courtesy: Prof. F.V. Lisovsky (IRE RAS, Russia).

Study of magnetic phase transitions

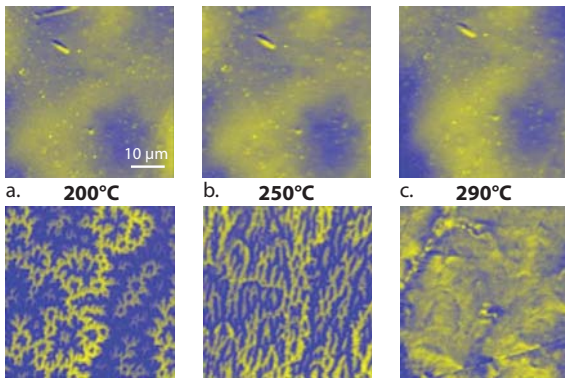


Figure 8. Magnetic phase transition in bulk cobalt single crystal with uniaxial anisotropy studied by in-situ sample heating. Topography (top) and corresponding MFM images (bottom) obtained at: (a) 200°C, (b) 250°C, (c) 290°C. The MFM contrast changes are caused by following changes of magnetocrystalline anisotropy under heating: uniaxial anisotropy – easy cone – easy plane.

Sample courtesy: Prof. Yu. G. Pastushenkov (Tver State University, Russia).

MFM in vacuum and low-temperature measurements

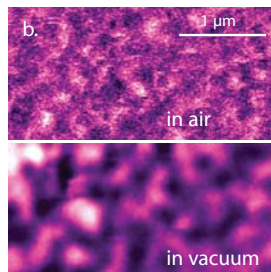
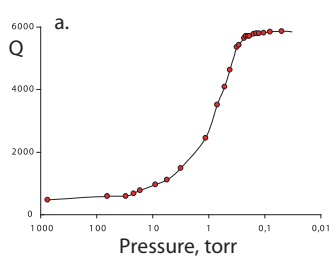


Figure 9. MFM measurements in vacuum significantly improve signal-to-noise ratio due to rise of the cantilever quality factor Q (a). Saturation of cantilever quality factor value is already achieved in low vacuum. (b) Shows influence of vacuum conditions on measured MFM contrast.

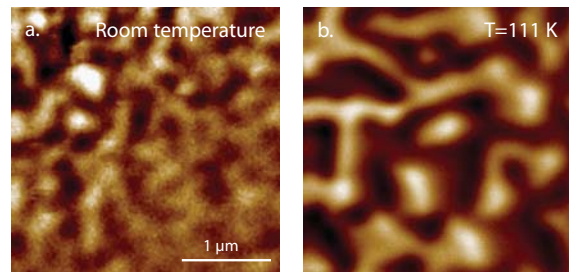


Figure 10. Measurements at low temperatures require high-vacuum conditions. Different domain structures in Mo/Au/Co 1.5 nm/Au film were measured at vacuum level $5 \cdot 10^{-8}$ torr: (a) MFM image at room temperature, (b) MFM image at 111 K.

Magnetic Force Microscopy

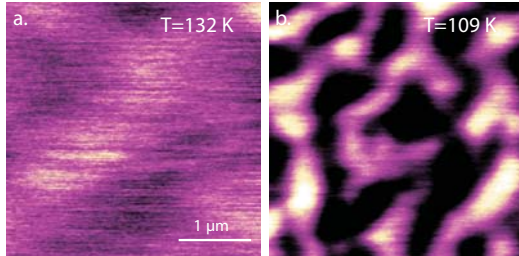


Figure 11. Another example of magnetic phase transition at low temperatures. The appearance of a domain structure in magnetic semiconductor after cooling down below Curie temperature:

(a) $T=132$ K, (b) $T=109$ K.

The results at low temperatures were obtained by the group of Prof. A. Maziewski (Bialystok University, Poland).

Magnetic Nanolithography

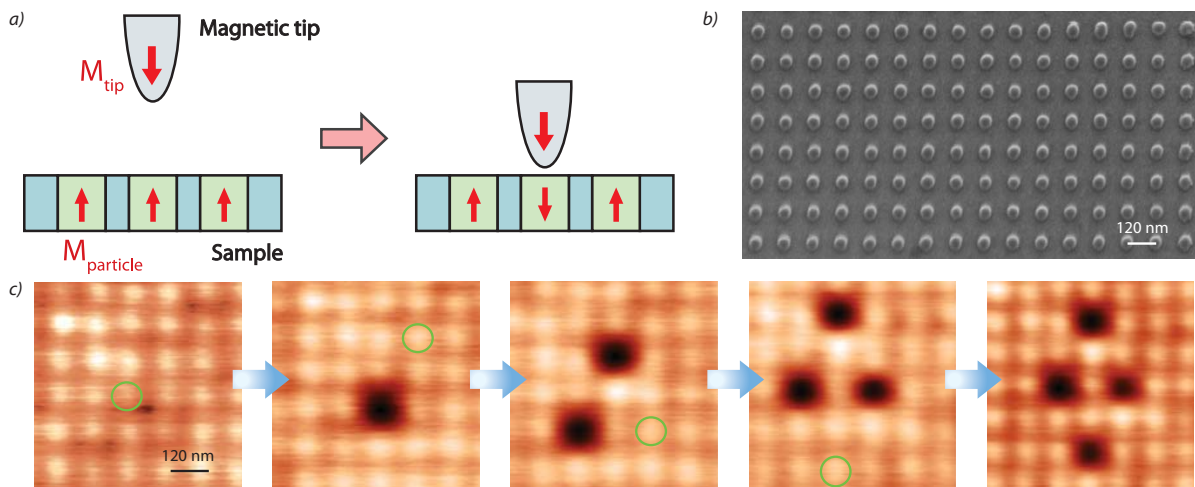


Figure 12. (a) Scheme of controllable magnetization reversal in selected magnetic nanoparticle: tip changes magnetization direction of the particle by approaching the sample surface; (b) The array of CoPt discs with perpendicular magnetic anisotropy is shown in electron microscopy image. Disc diameter is 35 nm, the thickness is 10 nm and the period of structure is 120 nm; (c) MFM images obtained on the same area in low vacuum conditions. Each image is obtained after magnetic reversal in one disc following scheme (a), and, finally, desired distribution of magnetic moments is achieved.



Figure 13. Magnetic lithography. Letter "P" is written by magnetic tip in continuous CoPt film with perpendicular anisotropy by similar way as shown in Figure 12.

V.L. Mironov et al. *J. Appl. Phys.* 106, 053911, 2009.
Images courtesy: B. Gribkov, V. Mironov, (IPM RAS, Russia),
A. Alekseev (NT-MDT).

Specification of the NT-MDT MFM

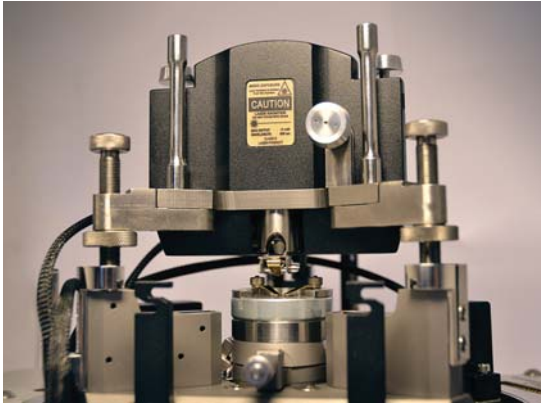
NTEGRA Aura

- Both scanning by tip and by sample configurations are available
- External magnetic field: horizontal up to 0.6 Tesla (6 000 Gauss) and vertical up to 0,8 Tesla (8 000 Gauss) standard, or up to 1 Tesla (10000 Gauss) by request
- Vacuum down to 10^{-2} torr
- Controllable atmosphere
- Temperature range: from room temperature up to 573 K
- Scanning range up to $200 \times 200 \times 20$ μm (DualScan™ mode)

Additional features: possibility of dissipation measurements, use of different cantilever modes and harmonics, magnetic measurements with surface potential compensation etc.

NT-MDT's New Developments

Up to 1 Tesla vertical magnetic field for AFM



Presently, the vertical magnet is one of the most demanded options for AFM researchers who need to apply high magnetic fields to their samples to stabilize orientation of the magnetic materials. Conventional electric magnets cannot routinely provide high enough fields. NT-MDT has developed a novel magnetic field module* integrated into the NTEGRA SPM platform. In combination with a special scanning head it allows AFM and MFM imaging with a vertical field up to 0,8 Tesla (8 000 Gauss) standard, or up to 1 Tesla (10000 Gauss) by request. The AFM probe shift while changing the magnetic field is very small due to the special AFM head design.

* Patent number: PCT/RU2012/000039

Key features of the new magnetic field module

- Up to 0,8 Tesla (8 000 Gauss) standard, or up to 1 Tesla (10000 Gauss) by request vertical and up to 0.6 Tesla (6 000 Gauss) horizontal magnetic field with the same module
- No external cooling of the magnet required (e.g. no extra vibrations)
- No sample heating occurs
- The module is fully compatible with the existing NT-MDT NTEGRA AFM systems

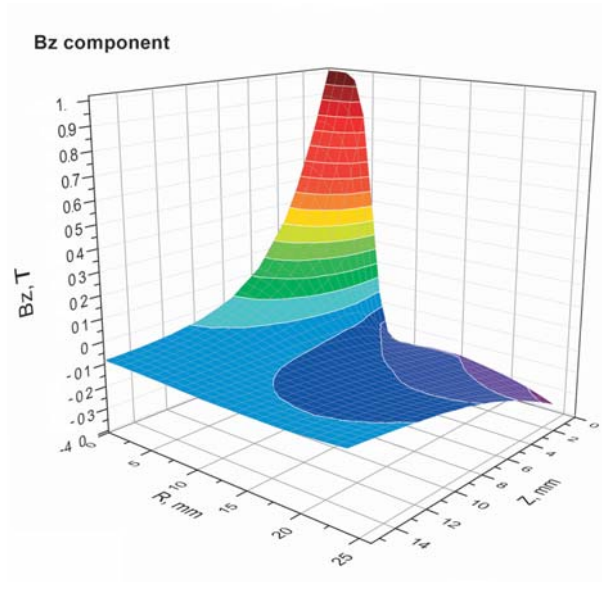


Figure 15. Measured vertical magnetic field component versus vertical distance (Z) from the surface and radial distance (R) from the central axis

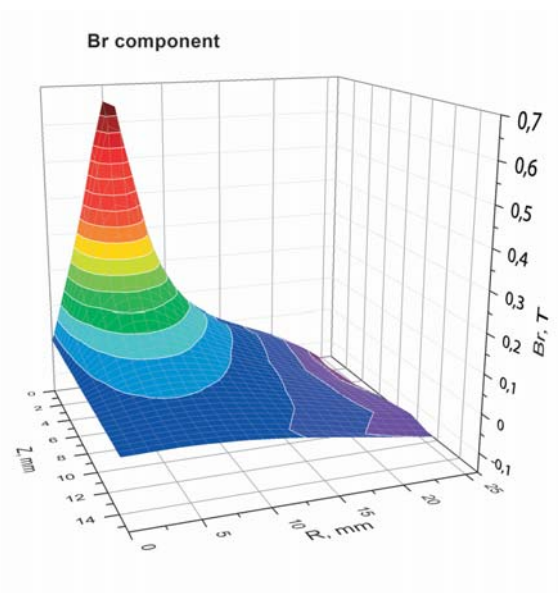
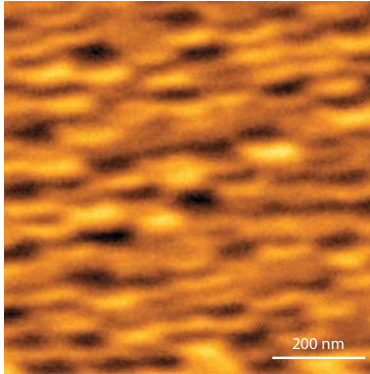


Figure 16. Measured horizontal magnetic field component versus vertical distance (Z) from the surface and radial distance (R) from the central axis

Magnetic Force Microscopy

High resolution long lifetime magnetic probes MFM01 and MFM10



The choice of the proper probe is very important for magnetic measurements. The magnetic probe should provide high resolution images. In addition, it should “survive” under high-humidity conditions.

NT-MDT offers new development - high resolution long lifetime magnetic probes MFM01 and MFM10. Special protective layers help to avoid oxidation and increase the cantilever lifetime substantially. Sharp silicon tip with coating less than 40 nm allows obtaining magnetic resolution down to 20–30 nm!

Magnetic structure of a hard disk drive (500 GByte) with bit size down to 20–30 nm, which was obtained by MFM01 probe in ambient conditions

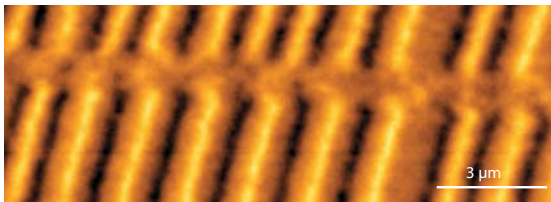
Probe Specification:

- Standard chip size: 1.6x3.4x0.3 mm compatible with most of commercial AFM devices.
- The base silicon is highly doped to avoid electrostatic charges.
- High reflective Al back side coating.
- Tip side is coated with CoCr magnetic coating with additional layers protecting from oxidation.
- Total coating thickness 30–40 nm*.
- Typical curvature radius of the tip is about 40 nm.
- Guaranteed cantilever lifetime is 1 year if it’s stored at normal conditions (humidity 30–40%).

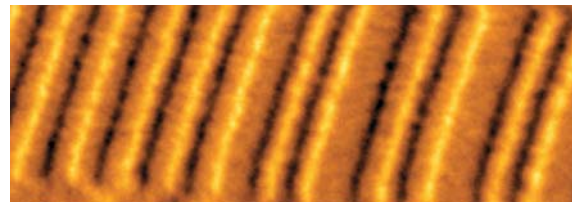
Cantilever series	Cantilever length, L±5 µm	Cantilever width, W±3 µm	Cantilever thickness, T±0.5 µm	Resonant frequency, kHz			Force constant, N/m		
				min	typical	max	min	typical	max
MFM01	225	32	2.5	47	70	90	1	3	5
MFM10	125	30	2.0	87	150	230	1.45	5.1	15.1

* At customer request we can make probes with different coating thickness to achieve different magnetic moments, which will be the best for measuring of your samples.

Survival test — 30 days in high humidity conditions! (close to 100% without water condensation)



Magnetic structure of a hard disk drive, which was obtained by MFM01 probe in ambient conditions



Magnetic structure of a hard disk drive obtained by MFM01 probe which was kept in the high humidity conditions for 30 days