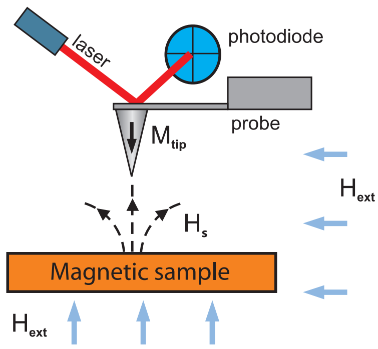
Magnetic Force Microscopy

Magnetic Force Microscopy: nanoscale magnetic imaging and lithography

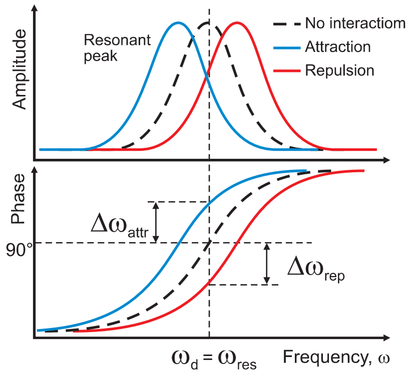
NTEGRA Aura

The principle of Magnetic Force Microscopy 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.

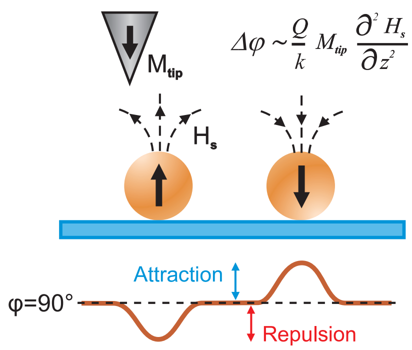
Scheme of MFM measurements



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 1 T) and horizontal (up to 0.6 T) magnetic fields are available.
- **MFM in vacuum**
  Measurements in vacuum significantly improve sensitivity of MFM because of increased cantilever quality factor.
- **Temperature range: from room temperature up to 300 C**
  Wide range of temperatures allows for investigation of different phenomena such as magnetic phase transitions.
- **Near field optical head for high resolution magneto-optical imaging**
  Near field polarization microscopy with aperture cantilevers allows obtain high resolution optical image of domain structure
- **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.

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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.

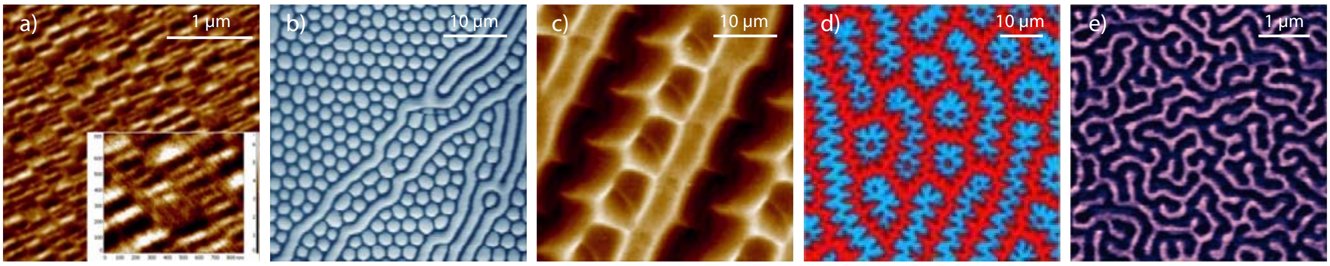

Figure 1. (a) a magnetic structure of a hard disk drive with bit size down to 30–40 nm, which was obtained by cobalt alloy coated probe in ambient conditions; (b–d) domain structures of different magnetically soft garnet films. One-pass method of imaging and thin magnetic coatings on the tip were utilized 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.

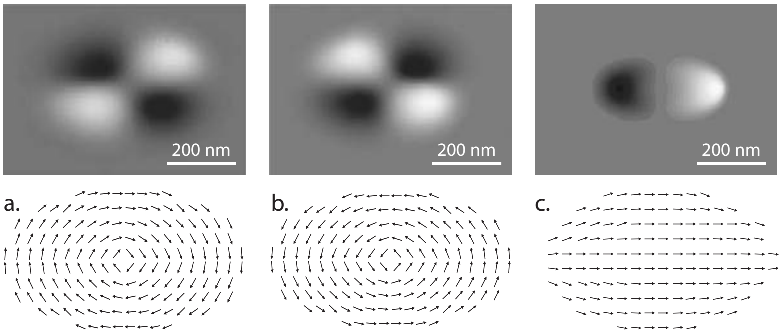

Figure 2. MFM images (top row) and simulated magnetization distribution (bottom row) in elliptical FeCr particles. Vortexes with different chiralities (a–b) and a state with uniform magnetization (c) are shown.

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

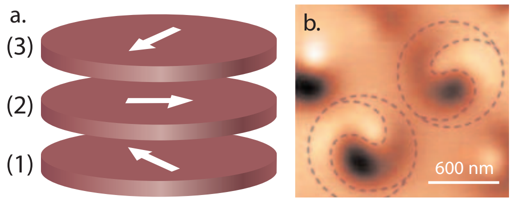

Figure 3. Array of stacks with three Co discs separated by Si layers. (a) scheme of single stack structure; (b) MFM image of two stacks with helical structure with different chirality.

A. A. Fraerman, et al. J. Appl. Phys. 103, 073916, 2008.

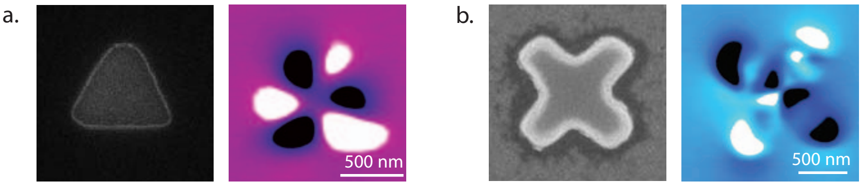

Figure 4. Electron microscopy images (left) and MFM images (right) of triangular and cross-like ferromagnetic structures. Magnetic states correspond to vortex (a) and antivortex (b) in triangle and cross-like structure, correspondingly.

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

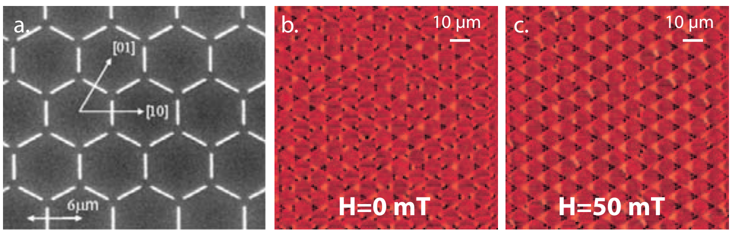

Figure 5. MFM images of artificial spin ice (honeycomb magnetic structure shown in image (a)): (b) demagnetized state, (c) the same place with highly ordered structure in horizontal magnetic field of 50 mT applied in the [11] direction.

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

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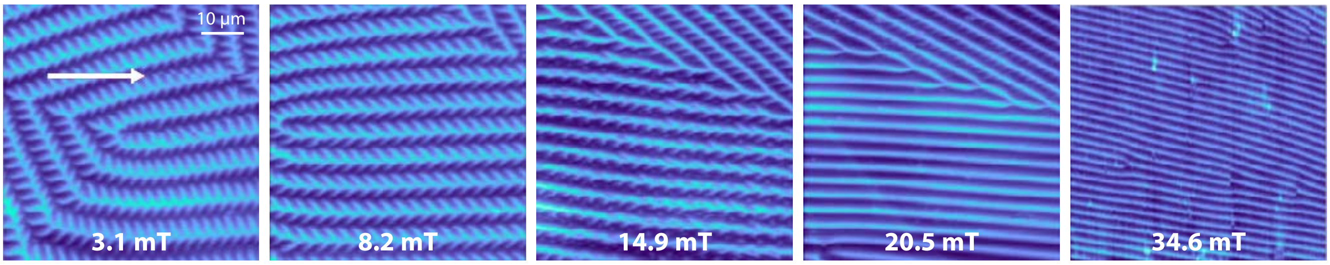

Figure 6. Reorganization of the garnet film domain structure in external horizontal magnetic field. Direction of field is indicated by arrow.

Vertical external magnetic field

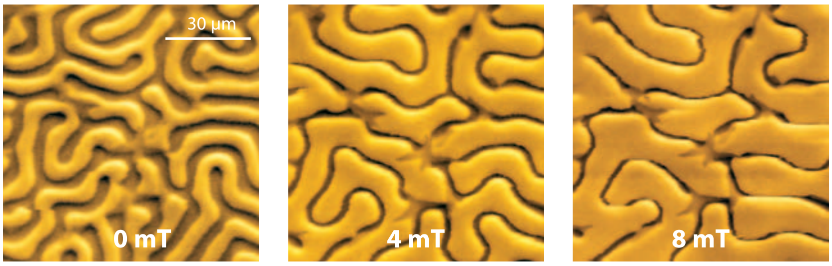

Figure 7. MFM images of garnet film in vertical magnetic field. Extension of domains with magnetization direction coinciding with direction of the external field is clearly seen.

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

Study of magnetic phase transitions

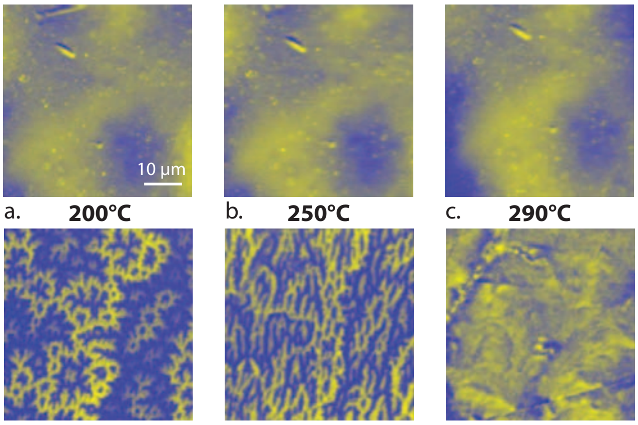

Figure 8. Magnetic phase transition in bulk cobalt single crystal with uniaxial anisotropy studied by in-situ sample heating. Topography (top) and corresponding MFM images (bottom) obtained at: (a) 200°C, (b) 250°C, (c) 290°C. The MFM contrast changes are caused by following changes of magnetocrytalline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

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

Magneto optical polarization near field microscopy

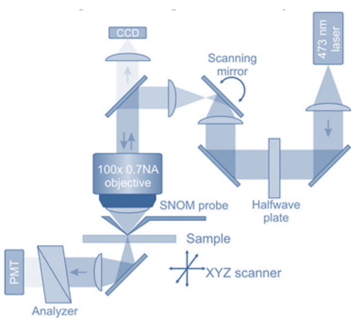

Figure 9. The scheme of the High Resolution Magneto-optical system

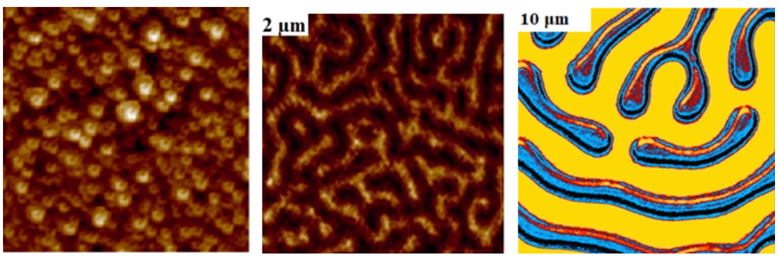

*Figure 10. Topography and magneto optical near field imaging of magnetic domain structure. (*Samples were provided by V.I. Vernadsky Crimean Federal University, T.V. Mikhailova and A.N. Shaposhnikov*

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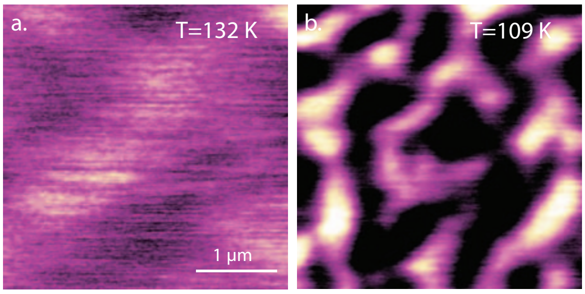

Figure 11. Another example of magnetic phase transition at low temperatures. The appearance of a domain structure in magnetic semiconductor after cooling down below Curie temperature:
(a) T=132 K, (b) T=109 K.
The results at low temperatures were obtained by the group of Prof. A. Maziewski (Bialystok University, Poland).

Magnetic Nanolithography

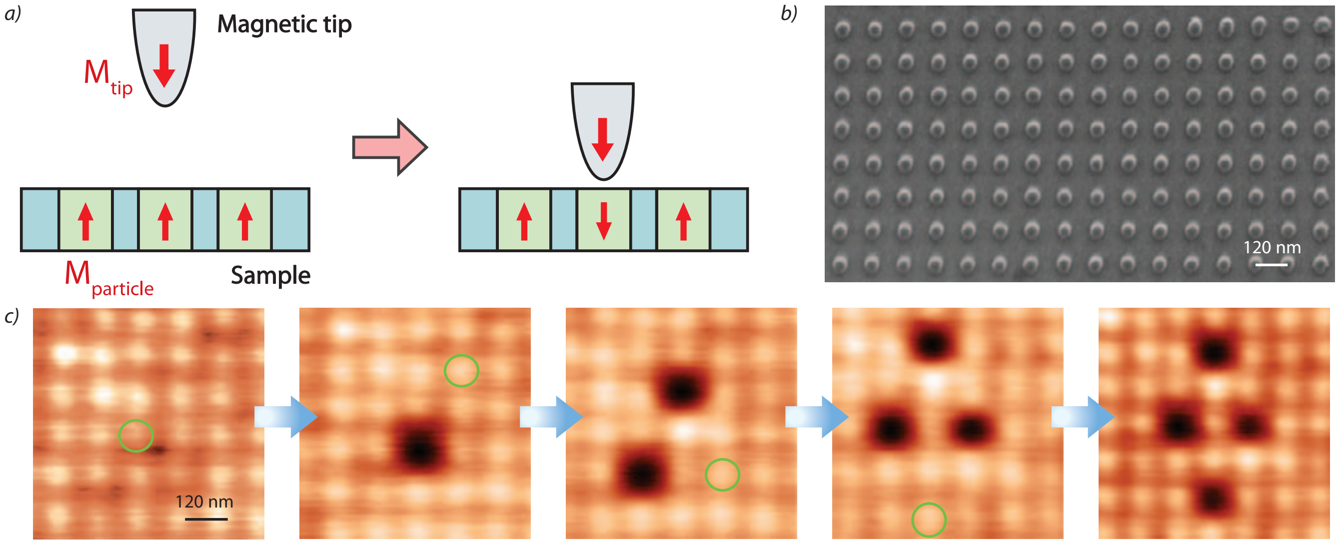

Figure 12. (a) Scheme of controllable magnetization reversal in selected magnetic nanoparticle: tip changes magnetization direction of the particle by approaching the sample surface; (b) The array of CoPt discs with perpendicular magnetic anisotropy is shown in electron microscopy image. Disc diameter 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

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- Both scanning by tip and by sample configurations are available
- External magnetic field: horizontal up to 0.6 T and vertical up to 1 T
- Vacuum down to 10^{-2} torr
- Controllable atmosphere
- Temperature range: from room temperature up to 300 C
- Scanning range up to 200×200×20 µm (DualScan mode)

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