Imaging of micro- and nanomagnetic structures

C. König, F. Kiendl, U. Rüdiger, and G. Güntherodt*
II. Physikalisches Institut, Aachen University, Aachen, Germany
**Fachbereich Physik, Konstanz University, Konstanz, Germany*

There is a great interest in understanding the micromagnetic behavior of thin ferromagnetic layers, driven by their technological exploitation in magnetic field sensors and magnetic random access memory devices (MRAM). As a high storage density is a key goal in the design of such memory devices, recent research has been concentrating on the investigation of ferromagnetic elements with submicrometer lateral dimensions. For a magnetic storage cell to define a bit (0 or 1), it must have two stable remanent magnetization states that are uniformly magnetized, i.e. form a single magnetic domain, independent of its magnetic history.

Apart from other powerful magnetic imaging techniques, we focus on two particular techniques to investigate the magnetic domain configurations of micro- and nanomagnetic structures: Magnetic Force Microscopy (MFM) [1,2] and Scanning Near-Field Optical Microscopy (SNOM) [3,4].

MFM

The MFM detects the magnetic stray fields (blue arrows in Figure 1) which are generated at the edges of magnetic elements

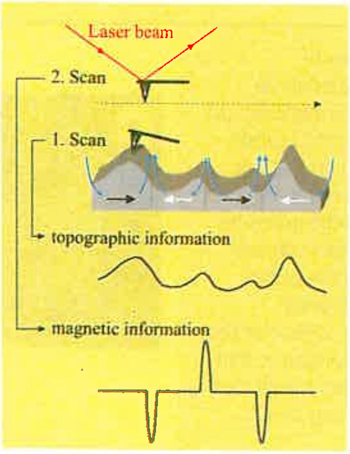


Fig. 1: Imaging mechanism of a Magnetic Force Microscope.

(bits) or in domain walls. For this purpose a small magnetic needle (tip) which is magnetized along the needle axis is attached to the end of a cantilever. This tip is being attracted or repelled by the magnetic stray fields pointing into or out of the surface of the magnetic element (bit), respectively. The deflection of the cantilever resulting from this dipole-dipole-interaction is detected by a laser beam which is reflected at the upper side of the cantilever and hits a four-segment detector. Figure 1 shows schematically how the magnetic information is extracted from this signal. To avoid a cross talk by "atomic force" information the MFM first scans the topography.

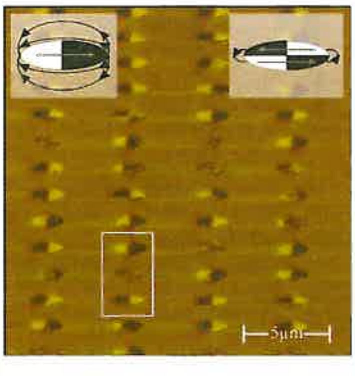
The magnetic information is subsequently recorded by lifting the tip to a height of approximately 90 nm and scanning along the topographic profile obtained in the first scan. This method yields the typical MFM images with "dark and bright contrast" depending on direction and strength of the magnetic stray fields.

Figure 2 shows an MFM image of microstructured Fe(110) ellipsoid-shaped elements with lateral dimensions of 1.5 µm 500 nm. Starting with a 25 nm thick iron film with (110) orientation these elements have been fabricated by using electron beam lithography and argon ion etching [6]. After applying a magnetic field of 1 Tesla perpendicular to the long axis of the elements - i.e. along the magnetic hard axis - the MFM image exhibits three different remanent magnetic states for zero magnetic field (see white frame in Figure 2).

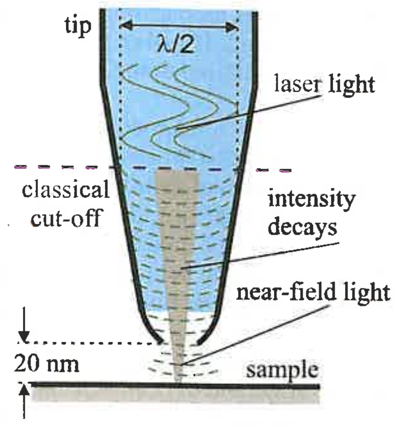
If the bright contrast represents an attractive interaction between the tip and the stray fields the upper element in the white frame shows a single domain state (or dipole state) with the magnetization pointing to the right side as illustrated in the upper left inset in Figure 2. According to this the magnetization of the lower element in the white frame is pointing to the right. The element in the middle shows a less pronounced magnetic contrast. This is an evidence for a multi domain state (or demagnetized state). By forming such a state the stray fields are minimized by closing the magnetic flux within the element (see the upper right inset in Figure 2).

SNOM

When a magnetic sample is illuminated with polarized light, it rotates the polarization of the transmitted (Faraday effect) and reflected (Kerr effect) light by an amount proportional to its magnetization. Therefore, a pattern of differently magnetized domains produces a contrast in a polarization-sensitive magneto-optical (MO) microscope. For this microscopy to work, neither a vacuum nor atomically clean surfaces are required. It can be used in an external magnetic field to probe the dependence of the



◀ **Fig. 2:** MFM image of microstructured ellipsoid-shaped Fe(110) elements [5].

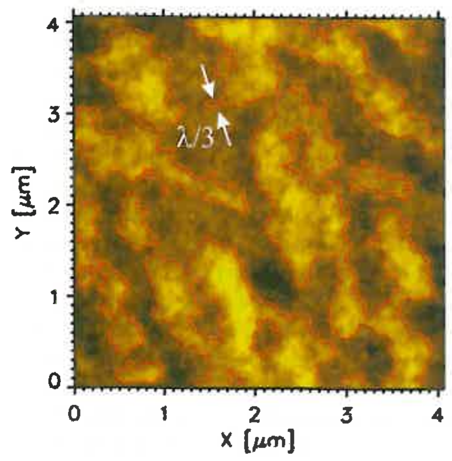


▶ **Fig. 3:** Imaging mechanism of a scanning near-field optical microscope.

domain pattern on the field. Also, unlike in MFM, there is no danger that the domain pattern is altered by the imaging process itself. Any optical microscopy, however, is limited in its resolution by diffraction. Every illuminated spot on the sample produces its own diffraction pattern, which cannot be distinguished from the diffraction pattern of another spot located less than $\lambda/2$ away, where λ is the light's wavelength. Smaller structures therefore cannot be resolved.

Scanning near-field optical microscopy (SNOM) eliminates the need to distinguish diffraction patterns from one another. In the most common "aperture configuration" (Figure 3), a probe with an aperture much smaller than l illuminates only one small spot on the sample at a time. No matter how the light is being diffracted, it is known which spot on the sample it corresponds to. A complete image of the sample is generated by scanning the probe across a grid of spots and assembling the information from all spots by computer.

How is it that light can be emitted from such a small aperture at all? Isn't there a cut-off diameter of $\lambda/2$ below which an aperture is not transparent? That depends on how close to the aperture you look. Light is actually transmitted through the aperture, but it is strongly (exponentially) damped as soon as the tip gets narrower than $\lambda/2$. Its intensity decreases by a factor of $1/e$ every 20 nm. The light is therefore called evanescent or near-field light, and for it to interact with the sample at all, the aperture must be brought to



▲ **Fig. 4:** Magneto-optical SNOM image of a Co/Pt multilayer film.

features

within 20 nm of the sample surface. Part of the light is converted back into normal, propagating light by the sample and can therefore be detected. If polarized light is used (MO-SNOM), differently magnetized domains produce a contrast in the image as usual.

Figure 4 shows a magneto-optical image produced with our magneto-optical SNOM set-up [7,8] on a Co/Pt multilayer film. The magnetization of such a film is stable when it is perpendicular to the film plane, pointing either out of it ("up") or into it ("down"). Before the image was taken, the film was exposed to a high (2 T) magnetic field in the film plane. When the field was switched off, there was nothing to keep the magnetization in this unstable orientation, so it relaxed into a random pattern of domains magnetized either "up" or "down". These domains appear as bright and dark areas in the image; the domain boundaries are marked by red lines. Rotating the detection set-up reversed the image contrast, proving its magneto-optical origin. The smallest domains visible in Figure 4 are about $\lambda/3$ in size, using an aperture of about 100 nm in diameter and laser light with wavelength λ=488 nm.

References

[1] Y. Martin and H. K. Wickramasinghe, Appl. Phys. Lett. **50**, 1455 (1987)

[2] J. J. Sáenz, N. García, P. Grütter, E. Meyer, H. Heinzelmann, R. Wiesendanger, L. Rosenthaler, H. R. Hidber, and H.-J. Güntherodt, J. Appl. Phys. **62**, 4293 (1987)

[3] D. Pohl, European patent application No. 0112401, Dec. 27 (1982); US patent 4,604, Dec. 20 (1983)

[4] A. Lewis, A. Harootunian, M. Isaacson, E. Kratschmer, Biophys. J. **49**, 269 (1983)

[5] C. König, M. Sperlich, R. Heinesch, R. Calarco, J. O. Hauch, U. Rüdiger, S. Kirsch, B. Özyilmaz, A. D. Kent, and G. Güntherodt, Appl. Phys. Lett. **79**, 3648 (2001)

[6] J. Yu, U. Rüdiger, A. D. Kent, L. Thomas, and S. S. P. Parkin, Phys. Rev. B **60**, 7352 (1999)

[7] G. Eggers, A. Rosenberger, N. Held, A. Münnemann, G. Güntherodt, P. Fumagalli, Ultramicroscopy **71**, 249 (1998)

[8] P. Fumagalli, A. Rosenberger, G. Eggers, A. Münnemann, N. Held, G. Güntherodt, Appl. Phys. Lett. **72**, 2803 (1998)