European School on Magnetism 2015
From basic magnetic concepts to spin currents

Magnetic Force Microscopy practical

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Survival kit of MFM theory

The dynamics of an AFM cantilever is modeled by a mechanical oscillator:

$$m\frac{\mathrm{d}^2 z}{\mathrm{d}t^2} + \Gamma\frac{\mathrm{d}z}{\mathrm{d}t} + k(z - z_0) = F(z,t) \tag{1}$$

$F(z,t)$ is a force arising from either the operator or from the tip-sample interaction, and z_0 is the equilibrium position without applied force. m, Γ and k are the oscillator mass, damping and stiffness, respectively. We use the notation $\omega_0 = \sqrt{k/m}$ and $Q = \sqrt{km}/\Gamma$, the latter being called the quality factor. Discuss qualitatively the amplitude and phase of the free oscillation (no right member to this equation).

The cantilever is excited by the operator with $F(t) = F_{\mathrm{exc}}e^{j\omega t}$. Perform a first-order expansion of this force around the equilibrium point, and discuss the change in the response for low force, in terms of amplitude and phase versus excitation frequency. In the scheme of many AFM, especially in air (but not all), the cantilever is excited close to its resonance angular frequency ω_0. The phase then undergoes a shift proportional to the vertical gradient of the (vertical) force $\partial F/\partial z$ felt by the tip: $\Delta\varphi = -(Q/k)\partial F/\partial z$. In practice magnetic images are gathered using a so-called two-pass technique: each line of a scan is first conducted in the tapping mode with strong hard-sphere repulsive forces probing mostly topography (so-called first pass), then a second pass is conducted flying at constant height (called the lift height) above the sample based on the information gathered during the first pass. Forces such as Van der Waals are assumed to be constant during the second pass, and the forces measured are then ascribed to long-range forces such as magnetic.

The difficult point with MFM is the interpretation of the images, and the possible mutual interaction between tip and sample. Crude however effective models consist in modeling the MFM tip with a magnetic monopole or a magnetic dipole. Discuss which physical situation these two models intend to cover. Is can be shown easily that the expected signal of static deflection and phase response in ac-mode are as shown in Table 1. This, in the as mode, MFM is sensitive to a vertical derivative of the sample stray field projected along the direction of magnetization of the tip. In practice, MFM images are interpreted assuming that the phase contrast reflects qualitatively the stray field itself.

Table 1: Expected MFM signal with respect to the vertical component $H_{\mathrm{d},z}$ of the stray field in static (cantilever deflection) and dynamic (frequency shift during the second pass) modes versus the model for the MFM tip.

Tip model	Static response	Dynamic response
Monopole	$H_{\mathrm{d},z}$	$\partial H_{\mathrm{d},z}/\partial z$
Dipole	$\partial H_{\mathrm{d},z}/\partial z$	$\partial^2 H_{\mathrm{d},z}/\partial z^2$

Sample and assignment

The sample features patterned soft magnetic film - permalloy[1] on a Si substrate. Various structures - shapes are present as depicted in Fig. 1. The sample was fabricated by Yann Perrin (NanoFab@Institut

[1] Permalloy-$Ni_{80}Fe_{20}$, slightly different composition is mentioned as well from time to time.

Néel, France) using Electron beam lithography. The thickness of the permalloy magnetic layer is 30 nm, total thickness around 40 nm: 5 nm Ti/30 nm NiFe/3 nm Al (Ti serves as seed layer, Al as capping protective layer).

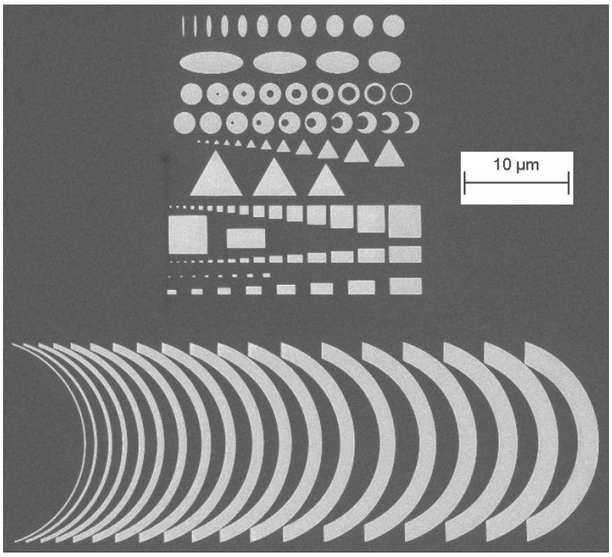


Figure 1: Scanning electron microscopy image of the sample used in MFM practicals.

Due to the limited amount of time devoted to the MFM practical, only one type of sample may be imaged:

1. **Various magnetic configurations** in array of different shapes (ellipses, rectangles, ...)
2. **Domain walls** in bent strips (wires with rectangular cross-section)

Your task is to determine (guess) possible magnetic configuration in these permalloy elements, best prior to the MFM measurement. You can also try to sketch these together with possible contrast in magnetic force microscopy (displays magnetic charges). Depending on the sample, it may or may not have been exposed to an external magnetic field prior to imaging..

Hints and possible solutions will be listed below. Sometimes multiple solutions are possible - states with similar or even the same energy - therefore your chance to determine the correct structure is higher. If you get stuck or simply do not know, do not panic. After all, this is just a practical.

It is possible that in MFM measurement some configurations will be distorted or altered as the structures might be influenced by the magnetic tip used for the imaging.

Hints, possible solution

General hints

Given that our magnetic material possesses negligible magnetocrystalline anisotropy, we can consider that the magnetic state is determined by the competition between exchange a demagnetization energy. Considering the material and the thickness, the magnetization lies preferentially in-plane, except some smaller regions like vortex cores with out-of-plane magnetization as will be mentioned below.

All small elements (exchange dominates) tend to be (near) single domain, large elements multi-domain.

In our analysis we can use to some extent the Van den Berg geometrical construction. This approach is described in [1, 2]. The main idea is to obtain a configuration with lowest possible dipolar (demagnetizing) energy, in other words reduce *magnetic charges*, which are defined as follows:

- volume charges: $\rho_\mathrm{m} = \mu_0 \vec{\nabla} \cdot \vec{M} = -\mu_0 \vec{\nabla} \cdot \vec{H}$
- surface charges: $\sigma_\mathrm{m} = \mu_0 \vec{n} \cdot \vec{M}$, $\vec{n}$ is the outward normal to the local surface

To reduce surface charges magnetization tends to be parallel to the edges of the structure. Further, flux-closure patterns avoid volume charges.

On the next pages typical micromagnetic configurations are featured together with some experimental MFM images obtained from the above-mentioned sample.

1. Various magnetic configurations

Examples of some basic configurations in permalloy elements of different shapes is given in Fig. 3.

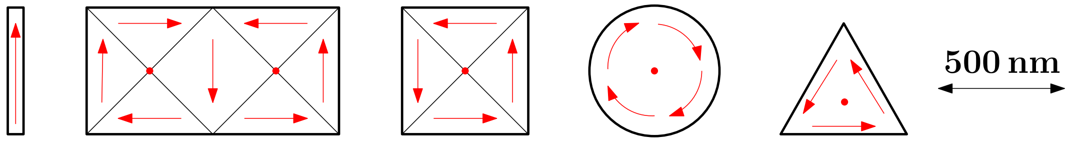


Figure 2: Various magnetic configurations in soft magnetic patterned permalloy film with schematic magnetization depicted in red arrows. Dots mean that magnetization lies out-of-plane. From the left: uniform magnetization, diamond state (compare with MFM contrast in Fig. 3) and magnetic vortex in a (die)square, disk and triangle (triangular prism). In all depicted structures, magnetization tends to be parallel to the structure edges and except for small high aspect ratio rectangle (single domain-uniform magnetization), magnetization forms flux-closure pattern, thus minimizing both surface (parallel to the edges) and volume (flux-closure) magnetic charges. Many other configurations are possible: e.g. flux-closure with opposite sense - both clockwise and counter-clockwise has the same energy. If there is vortex core with out-of-plane magnetization we have again two possibilities with the same energy . . .

Large variety of micromagnetic states is demonstrated on rectangular elements in Fig. 3.

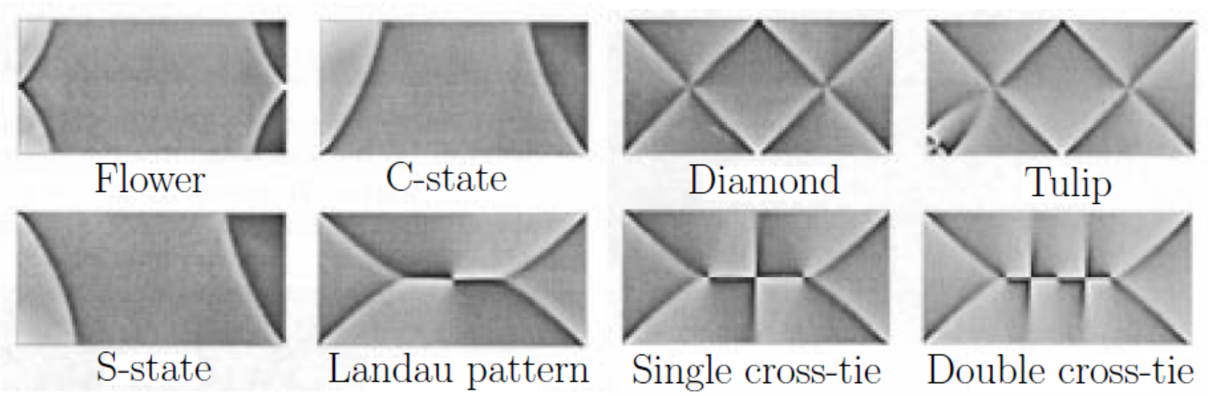


Figure 3: Various magnetic configurations in soft magnetic rectangular thin film element. These are results of simulations highlighting magnetic charges - thus these images are close to experimental MFM images. Similar magnetic configurations can be found for similar aspect ratios. Here, element with dimensions 2 μm×1 μm×20 nm favours diamond state. But other states such as Landau pattern and cross-tie have only slightly higher energy. Taken from [3].

Experimental AFM and MFM images are captured in Fig. 4.

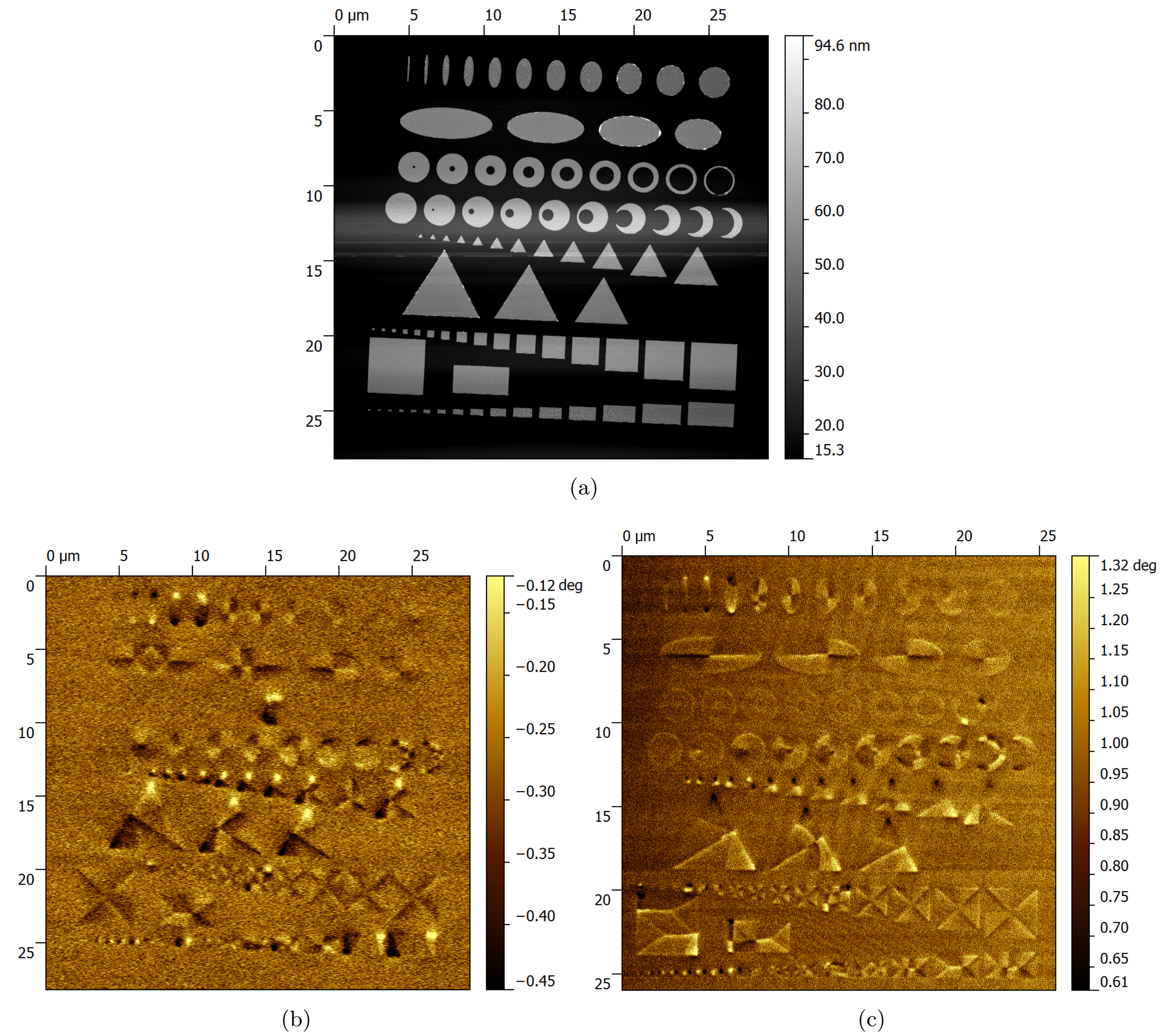
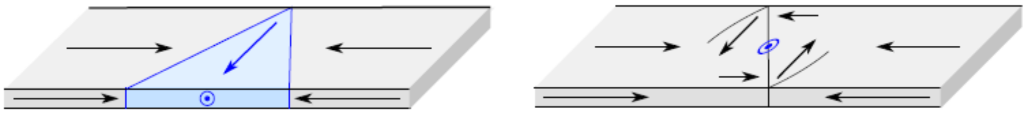


Figure 4: (a) topography and (b), (c) MFM image of the array of permalloy microstuctures. The height of the structures is 40 nm (30 nm magnetic layer), but there are some impurities on top of the strips. Both MFM images were acquired with the same tip and similar conditions. You can spot several differences, these changes of configurations may be caused by the magnetic tip itself, as the energy difference between some states is really low. AFM tip with 20 nm CoCr magnetic layer.

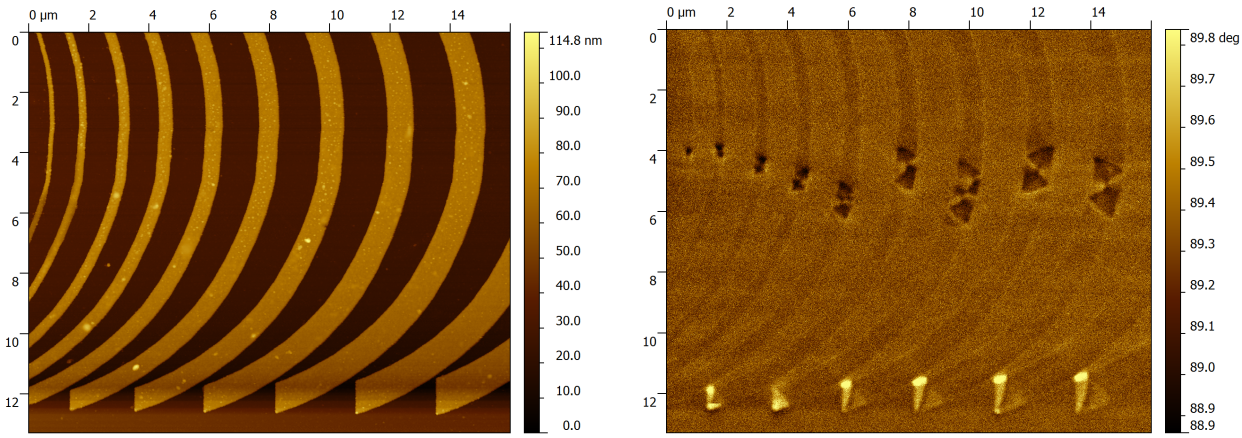
2. Domain walls

Bent rectangular wires are used for trapping a domain wall in the bent part after application (and removal) of magnetic field in transverse direction (with respect to wire axis).



(a) (b)

Figure 5: Domain walls in soft magnetic nanostrips with in-plane magnetization. (a) transverse domain wall and (b) vortex wall.



(a) (b)

Figure 6: (a) topography and (b) MFM image of bent rectangular wires (strips) with magnetic domain walls in the bent part. The height of the structures is 40 nm (30 nm magnetic layer), but there are some impurities on top of the strips. In (b) All domain walls except for the the first from the left are vortex DWs, although some of them slightly distorted - e.g. third from the right, in part due to the curvature of the strips. First two vortices on the right have opposite chiralities. The first DW from the left might be transverse DW, but imaging at higher resolution might be needed to prove this claim. AFM tip with 20 nm CoCr magnetic layer.

References

[1] H.A.M. Van den Berg. A micromagnetic approach to the constitutive equation of soft-ferromagnetic media. Journal of Magnetism and Magnetic Materials, 44(1):207–215, 1984.

[2] H.A.M. Van den Berg. Self-consistent domain theory in soft-ferromagnetic media. ii. basic domain structures in thin-film objects. Journal of Applied Physics, 60(3):1104–1113, 1986.

[3] W. Rave and A. Hubert. Magnetic ground state of a thin-film element. IEEE Transactions on Magnetics, 36(6):3886–3899, Nov 2000.