Magnetic Force Microscopy

Magnetic Force Microscopy (MFM) is based on the principles of Atomic Force Microscopy (AFM). In both cases, the behavior of a cantilever in the proximity of a sample is monitored, where the defining feature of MFM is that the observed response is caused by magnetic interaction. The cantilever tip consists of a non-magnetic core covered by a magnetic coating. This device is employed to sense the magnetic stray fields close to the surfaces of magnetic materials. Depending on the magnitude of the response, the cantilever may be operated in a *static* or a *dynamic* mode.

In case of sufficiently large deflections, the static (or DC) mode of observation may be preferred. This technique involves laser beam reflection from the cantilever tip in order to determine the amount and the direction of deflection, i.e. the magnitude and the sign of $\Delta z = F_z/k$ where z denotes the coordinate perpendicular to the surface of the sample, and F_z the corresponding magnetic force felt by the tip.

In the dynamic mode, an external oscillating force is applied on the device, inducing vibrations of the cantilever close to its resonance frequency. The oscillations of the tip are traced by the deflection sensor of the microscope. In the presence of magnetic interactions, the natural resonance frequency ω_0 will be shifted due to a change of the natural force constant, k_0, according to

$$k = k_0 - \frac{\partial F_z}{\partial z}, \tag{1}$$

such that the change of the cantilever eigenfrequency yields the derivative of the magnetic force perpendicular to the sample surface. This change can be found from the shift of maximal amplitude of the forced cantilever oscillation.

If the stray field is described by an external magnetic field $H_s(\mathbf{x})$ its interaction with is the tip magnetization, $M_{tip}(\mathbf{x})$ gives rise to a magnetic potential energy, namely

$$E_{mag} = \mu_0 \int \mathbf{M}_{tip} \cdot \mathbf{H}_s dV_{tip}. \tag{2}$$

From this expression, the magnetic force is readily found from

$$\mathbf{F} = -\boldsymbol{\nabla} E_{mag} = \mu_0 \int \boldsymbol{\nabla}(\mathbf{M}_{tip} \cdot \mathbf{H}_s) dV_{tip}, \tag{3}$$

If the stray field derives entirely from a distribution of magnetizations within the sample, $\mathbf{M}_s(\mathbf{x})$ ($\mathbf{j}_s = \mathbf{0}$, the field $\mathbf{H}_s$ may be obtained from the magnetostatic potential Φ_s:

$$\mathbf{H}_s(\mathbf{x}) = -\nabla \Phi_s(\mathbf{x}). \tag{4}$$

The magnetostatic potential is found from

$$\Phi_s(\mathbf{x}) = \frac{1}{4\pi} \int d^2 \mathbf{s} \frac{\mathbf{M}_s(\mathbf{s})}{|\mathbf{x} - \mathbf{s}|} - \int d^3 \mathbf{x}' \frac{\nabla \cdot \mathbf{M}_s(\mathbf{x}')}{|\mathbf{x} - \mathbf{x}'|} \tag{5}$$

Inserting this formula into Eq.[3] leads to a relation between the experimentally accessible force and the magnetic structure of the sample, as represented by the quantity $\mathbf{M}_s$ in formula [5].

The MFM technique dates back to 1987 [1] and thus the early days of AFM experimentation. It has since been used to study a wide variety of magnetic systems, including thin films, nanoparticles (as highlighted in Chapter 12 of the main text), recording media, and much more. The popularity of the method may be ascribed to several obvious advantages, among them its relative insensitivity to environmental conditions. MFM equipment does not require low temperature or vacuum for proper operation. In general, no special treatment of the sample surface is needed, since detected quantity, the magnetic stray field due to sample magnetism, is weakly dependent on non-magnetic contamination of the surface. Further, the analyzed material does not have to electrically conductive. The spatial resolution of the method tends is in the order of 20 nm.

While these features are commendable, some caveats apply as well. In particular, it is hard to extract quantitatively accurate knowledge from MFM data. This is mostly related to the dependence of the results on the tip magnetization (see Eq. [2]) which is usually is incompletely known. Also, the recorded quantity, the magnetic stray field, provides only indirect access to the sources of this field. Only the comparison between measurements and predictions resting on computational models can ultimately reveal the magnetic structure of the investigated material. Lastly, MFM measurement involves interaction between the magnetizations $\mathbf{M}_s$ and $\mathbf{M}_s$, and care must be taken to prevent the magnetic sensor from affecting the magnetism to be probed. In spite of these concerns, MFM spectroscopy has yielded a large body of information, both qualitative and quantitative, on the magnetic texture of a wide range of materials.

Bibliography

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