The magnetic force microscopy and its capability for nano-magnetic studies - The short compendium

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Almost two decades have passed since the first experimental invention of the scanning probe microscopy principle (SPM). In the course of time the initial idea of probe-based microscopy has developed to many related specific techniques like scanning tunneling microscopy (STM), atomic force microscopy (AFM), magnetic force microscopy (MFM) etc. that merely approved their uniqueness in achieving a submicron resolution. The magnetic force microscopy represents one of the most elegant methods to study surface magnetic properties with high resolution and easily prepared specimen. In the present compendium we briefly discuss the principal ideas connected to the history, structure, operational schemes as well as some recent MFM studies performed in the field of nano-magnetic imaging and bioapplications emanated from the use of magnetic force microscopy.

Keywords Scanning probe microscopy; Magnetic force microscopy;

1. Short historical summary over the MFM

Scanning probe microscopy (SPM) represents a set of experimental methods developed to study surface properties with the submicron resolution as well as obtaining 3D specimen images and their parameters with respect to the spatial coordinates. Surface investigations based on tunneling into vacuum or through a potential barrier are well–proven [1]. After the very first successful tunneling experiment with an externally and reproducibly adjustable vacuum gap invented by Binnig, Rohrer et al. in 1981 [2], the robust development connected to SPM techniques has been noted. In 1982 the scanning tunneling microscope (STM) was presented for the first time [3]. The principle of STM is based on the electron tunneling between the metal tip and the conductive specimen separated by insulating layer (vacuum, gas) section–potential barrier. The tunneling current is responsible for the STM image. It depends on the distance between the tip apex and the sample surface. According to the authors, the crucial aim of the work on the STM was to reveal electrical properties of insulating materials tenuous enough to allow electron tunneling and to be able to image the local conductivity. As a consequence of above mentioned invention, Binnig and Rohrer incepted the Nobel Prize (1986) (see also [4, 5]).

In 1986 Binnig, Quate and Gerber [6] proposed a new application called atomic force microscopy (AFM) to measure forces as small as 10^{-18} N (commonly used of order of 10^{-12} N). The experimental setup consists of the cantilever with attached diamond stylus profilometer embedded between AFM sample surface and STM tip (Au). STM is used to sense the motion of cantilever in order to measure its deflection. This method is able to measure conductors as well as insulators on an atomic scale.

One year later Martin and Wickramasinghe [7] described a new method for mapping the magnetic field distributions on a microscopic scale. This method uses the magnetic forces (or the force gradient) acting between the magnetized sample surface and the magnetized tip latterly entitled as magnetic force microscopy (MFM). 25 μm diameter iron wire was used for cantilever as well as for the tip. The tip's shape was created by tapering the wire down to a 2 μm diameter and electroetched 0.1 nm diameter tip at its end. 40 μm from the end is the wire bowed down such that the axis of the tip is aligned perpendicular to the cantilever. Two modes of operations were performed. As for the first mode (dynamic regime), the magnetized tip is keeping constant height over the specimen, whilst the magnetic field is dynamically

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modulated at specific frequency. Because of the modulated magnetic field the cantilever feels acting long–ranged forces and vibrates with the same above mentioned frequency. The vibrations are detected by optical interferometer (sensitive He–Ne laser heterodyne probe). The second mode (static regime) is based on the modulation of the tip magnetization by pulsing the alternating current and for detecting the deflection of the cantilever at the pulsing frequency is the dynamic regime used as well. The maximum spatial resolution reached to that day was 100 nm.

Another very similar MFM–based set-up was presented by Saenz et al. [8] in 1987. They tried to measure magnetic interactions with previously introduced AFM (see e.g. [9, 10]). As a ferromagnetic sample has been chosen the Ni foil. The ferromagnetic tip was placed on the electrochemically rolled and etched Ni cantilever. They studied forces arising from the tip–sample interaction and their relation to the magnetic topography, which depends on the magnetic behaviour caused by different spin configurations in the specimen. The achieved resolution was also of the order of 100 nm.

2. Magnetic force microscopy principle

The basic MFM principle comes from the AFM technique. Briefly speaking the MFM is AFM with the springy cantilever equipped with sharp magnetic probe on its end. Coming from the fact, that the long-ranged magnetic forces originate because of the magnetized tip-sample interaction, optimal measure organization is performed in terms of the non-contact regime.

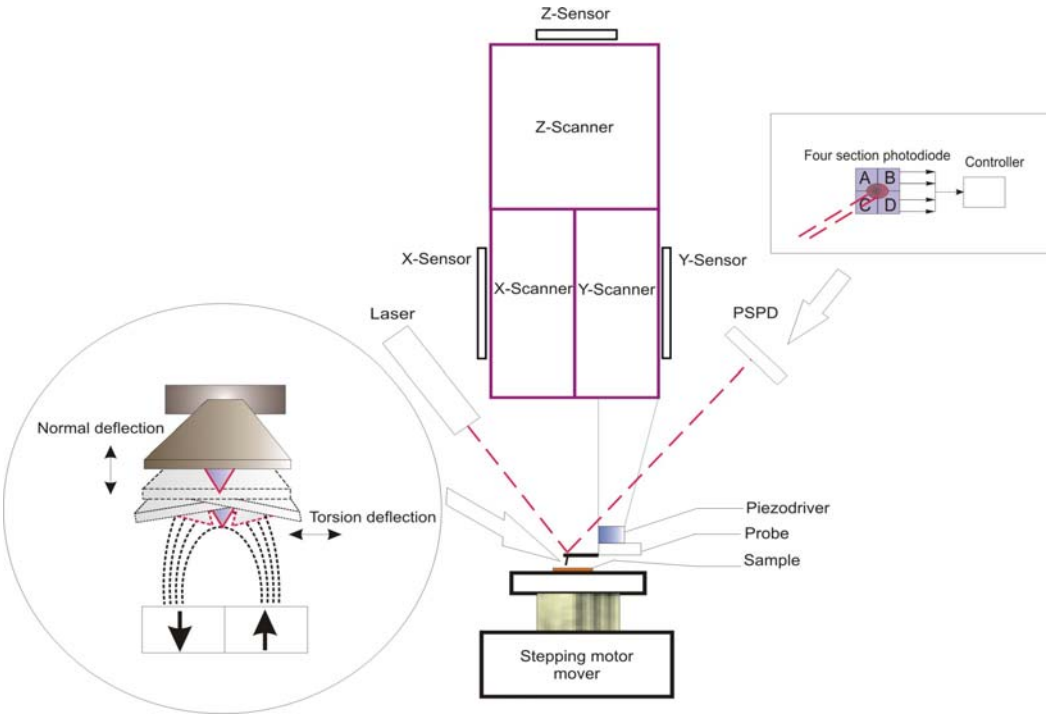


Fig. 1 MFM block controller scheme. The laser beam is focused on the flexible cantilever. While the cantilever feels any stray field changes, the angle of the deflected light changes as well. Reflected light is registered by sensitive detector (four section photodiode PSPD) and transformed to the electric signal (organization known as the optical lever set-up).

As soon as the magnetic probe is brought equally close to the sample surface, generally between units to a hundred nanometers, there occur inconsiderable changes of the cantilever stage caused by mutual

magnetic tip-sample interactions (see circle depiction in Fig. 1.) which can be optically detected. Above mentioned changes form 2D magnetic image due to the probe is scanned across the sample surface or vice versa.

3. MFM operational modes

The MFM gets benefit from two basic detection principles, every for specific type of the magnetic interaction – static (DC) mode and dynamic (AC) mode.

3.1 Static (DC) mode

In this regime cantilever carries over the magnetic force incidence as a product of the tip-sample interaction, where the rising displacement Δz of the cantilever is measured (spring constant is denoted here as k) and thus in the area of elastic deformation obeys Hooke's law

$$\boldsymbol{F} = -k\,\Delta z\,. \tag{1}$$

3.2 Dynamic (AC) mode

This regime keeps up the cantilever at, or very close, to its resonance frequency. It is possible to construe the cantilever as a harmonic oscillator with the resonant frequency f

$$f = \frac{1}{2\pi}\sqrt{\frac{k_{\mathrm{ef}}}{m}}\,. \tag{2}$$

Here m and k_{ef} represent the effective mass and the effective spring constant for a whole system (tip + cantilever). Consequently the effective spring constant k_{ef} falls into two components:

$$k_{\mathrm{ef}} = k - \frac{\partial F}{\partial z}\,, \tag{3}$$

where k represents the cantilever spring constant and the derivative of the force $\partial F/\partial z$ (force gradient) with respect to tip-sample distance can be treated as an interaction spring constant, which is stationary only during one oscillation period. While the probe is approaching the sample surface, the derivative varies due to the mean tip-sample distance.

Let us see how the force gradient changes the resonant frequency after the substitution of equation (3) into (2), namely

$$f = f_0\sqrt{1 - \frac{\partial F/\partial z}{k}}\,, \tag{4}$$

where f_0 is the free resonance frequency of the cantilever with respect to the condition of no tip-sample interaction.

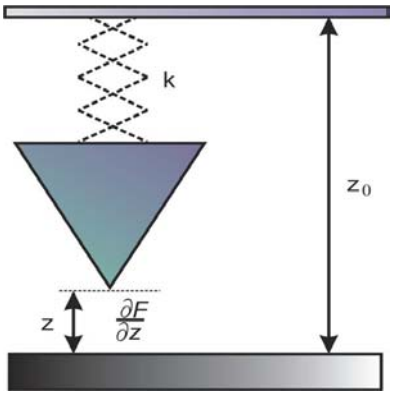
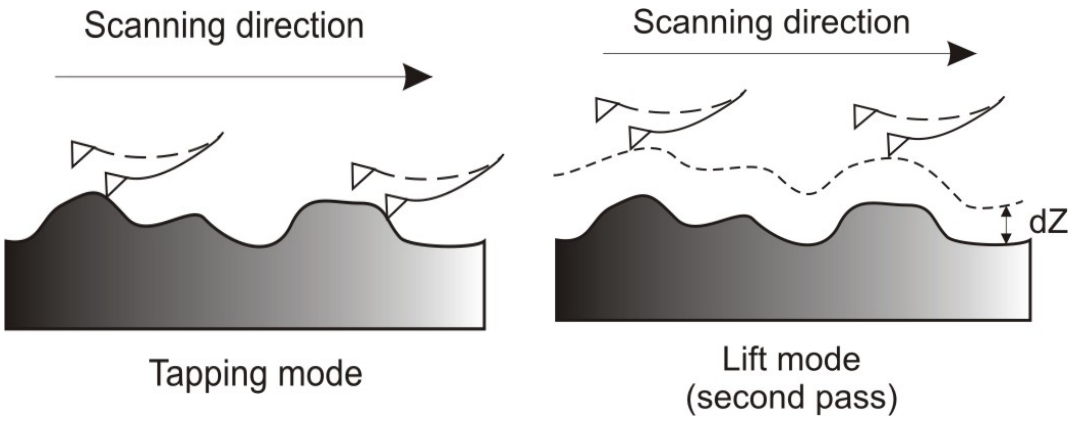


Fig. 2 Modeled tip-sample interaction, where k denotes cantilever constant and the force derivative $\partial F / \partial z$ is schematically depicted here as an additive force interaction constant.

There are two ways to deal with resonance frequency measurement. **The amplitude detection** is based on the cantilever oscillated at given frequency (its value is greater then free resonant frequency), that means the changes in resonant frequency cause deflections of the cantilever. **The frequency detection** can be realized as follows: the cantilever is vibrated accurately at its resonant frequency f where the amplitude is controlled by the feedback loop. Resulting detection is assured by FM demodulator.

With respect to the fact that MFM can be operated in constant frequency shift mode, two-pass (tapping-lift) mode or constant height mode, the crucial issue is to minimize surface topography features on the image of the magnetic forces distribution. To solve this problem, the major part of the MFM measurements are performed in terms of two-pass mode.



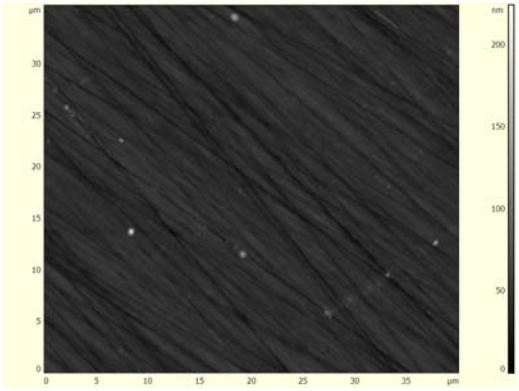


Fig. 3 First pass: surface topography imaging - semi-contact or tapping mode (magnetic recording medium).

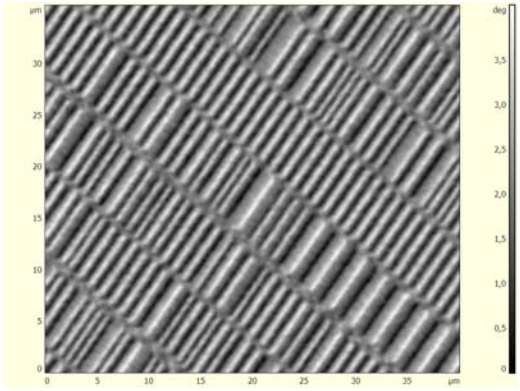


Fig. 4 Second pass: lift scan follows the topography to obtain magnetic contrast image (magnetic recording medium).

In this mode, the first pass is determined by semi-contact (tapping) mode of operation, where the surface topography is obtained while the cantilever follows the scan line direction (Fig. 3). After the first scan, the cantilever is lifted above the surface at required height *dZ* and follows exactly the same topographic contour. Because of the height *dZ*, the cantilever is only affected by long-ranged forces.

4. Magnetic interaction

As we have mentioned above, MFM displays magnetic force (or gradient) fluctuations of the magnetic samples. The distance between the magnetic probe and the sample surface plays important role if the tip is brought to the region of short-ranged forces, the resulting image would be a topographic relic mainly because of there is none or minimum magnetic interaction. The topographic image dominates over the magnetic contrast, roughly speaking the non-contact AFM analogy. The forces acting between the tip and the sample are not of magnetic nature. Its origin involves many others, such as electrostatic or van der Waals interactions, capillary or quantum mechanical forces. However, the magnetic force as a long-ranged force takes effect only in the case of the appropriate tip-sample distance, where the resulting image would be the magnetic field depiction (magnetic contrast).

Let us assume a magnetized element exposed to the magnetic stray field of the sample, where the magnetic potential energy E is given as follows:

$$E = -\mu_0 \int_{\mathrm{V}} \boldsymbol{M}_{\mathrm{t}} . \boldsymbol{H}_{\mathrm{s}} \, dV_{\mathrm{t}} . \tag{5}$$

MFM detects magnetic force or magnetic force gradient conveying the magnetic interactions between the tip and the sample. The magnetic force acting on the tip can be expressed as

$$\boldsymbol{F} = -\nabla E = \mu_0 \int_{\mathrm{V}} \nabla\left(\boldsymbol{M}_{\mathrm{t}} . \boldsymbol{H}_{\mathrm{s}}\right) dV_{\mathrm{t}} , \tag{6}$$

where the integration has to be done over the tip volume, $\boldsymbol{M}_{\mathrm{t}}$ is the tip magnetization and $\boldsymbol{H}_{\mathrm{s}}$ is the sample stray field.

Recently there was a growing interest connected to the quantitative calculations of alternating magnetic field contrast mechanism depending on the tip shape [11, 12], magnetic tip-sample interaction [13]. Within the scope of simplification many models and approximation are rising. Let us mention, e. g., the dipole approximation [14] or theoretically calculated tip templates [15]. There is also progress in the field of computer analysis created even for individual ferromagnetic nanoparticles [16].

5. MFM applications

Let us briefly summarize the most noted applications successfully performed by magnetic force microscopy. First of all, one should mention the magnetic recording studies [17], superconduction phenomena [18] as well as the solid state physics research in general [19]. Additional use is linked to the fields of chemical and nano-biological disciplines. However, phenomenal interest is focused in magnetic nanoparticles studies.

New Fe_3B nanowires analysis were made [20] to verify their utility as feasible magnetic composites, MFM tips or magnetic recording matrices. Unique properties suggest that Fe_3B nanowires are promising one-domain ferromagnetic nanostructures (Fig. 5.)

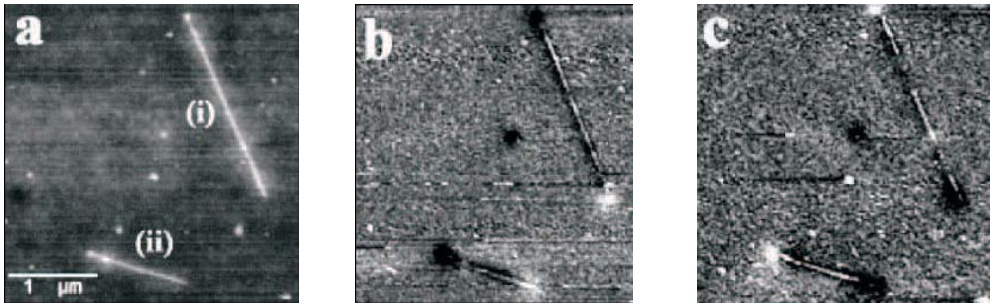


Fig. 5 Fe_3B nanowire image obtained by AFM (a) and the same image obtained by MFM (b). The last image was performed by MFM after the reversion of tip magnetization. The change of magnetization is depicted by alternating bright and dark nanowire ends (reprinted from ref. [20]).

Studies of magnetotaktic bacterium [21] seem to be another very promising application. In cells of magnetotaktic bacterium mineralize magnetic nanoparticles – magnetosomes - one-domain magnetite, Fe_3O_4 or Fe_3S_4 particles covered by lipid-protein membrane. Linear chains of magnetosomes are oriented along the axis of cell symmetry and form permanent magnetic dipole.

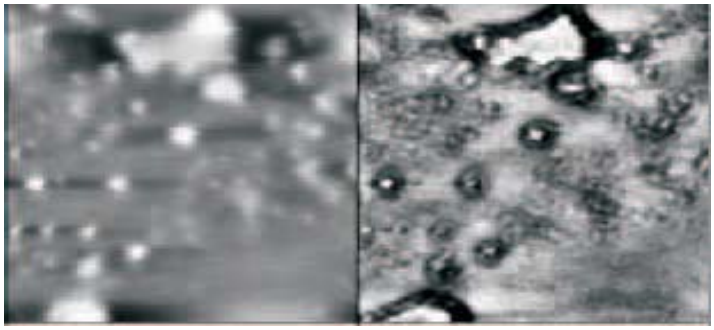


Fig. 6 AFM (left) and MFM (right) images of magnetosomes (reprinted from ref. [21]).

Another opportunity for the magnetic nanoparticles is to characterize them as effective and sensitive detection system for many biological elements e.g. streptavidin. Combination of MFM imaging technique and suitable magnetic markers create promising perspective for bio-detection [22].
Magnetic force microscopy has been also involved in nanomagnetic studies to clarify the dependence of magnetic properties on structural features (see Figs. 7 and 8).

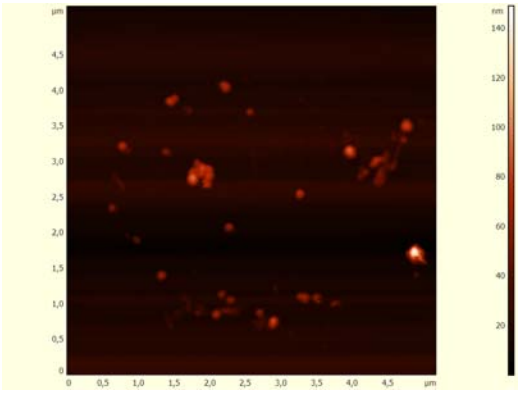


Fig. 7 AFM semi-contact mode regime (mixture of maghemite-hematite nanoparticles - topography image).

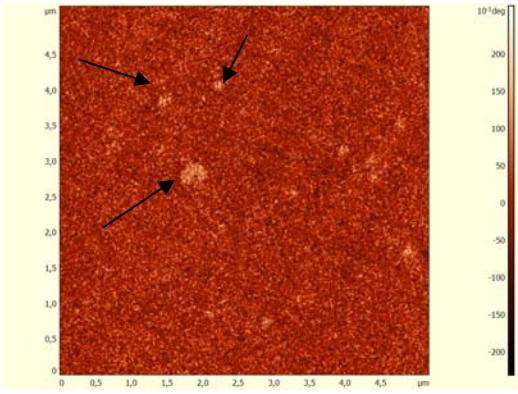


Fig. 8 MFM second pass regime (mixture of maghemite-hematite nanoparticles – phase image).

6. Conclusion

Over the last two decades the magnetic force microscopy has evolved from a purely scientific tool to widely used micromagnetic imaging technique. Without time-consuming preparations this self-adaptable technique leads to comprehensive image displaying of various magnetic sample.

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References

[1] I. Giaever, Phys. Rev. Lett., **5**, 147 (1960).
[2] G. Binnig, H. Rohrer, Ch. Gerber, E. Weibel, Appl. Phys. Lett., **40**, 178 (1982).
[3] G. Binnig, H. Rohrer, Ch. Gerber, E. Weibel, Phys. Rev. Lett., **49**, 57 (1982).
[4] G. Binnig, H. Rohrer, Rev. Mod. Phys., **59**, 615 (1987).
[5] G. Binnig, H. Rohrer, Rev. Mod. Phys., **71**, S324 (1999).
[6] G. Binnig, C. F. Quate, Ch. Gerber, Phys. Rev. Lett., **56**, 930 (1986).
[7] Y. Martin, H. K. Wickramasinghe, Appl. Phys. Lett., **50**, 1455 (1987).
[8] J. J. Sáenz, N. García, P. Grütter, E. Meyer, H. Heinzelmann, R. Wiesendanger, L. Rosenthaler, H. R. Hidber, H. J. Güntherodt, J. Vac. Sci. Technol. A., **62**, 4293 (1987).
[9] H. Heinzelmann, E. Meyer, P. Grütter, H. R. Hidber, L. Rosenthaler, H. J. Güntherodt, J. Vac. Sci. Technol. A., **6**, 275 (1988).
[10] P. Grütter, E. Meyer, H. Heinzelmann, L. Rosenthaler, H. R. Hidber, H. J. Güntherodt, J. Vac. Sci. Technol. A., **6**, 279 (1988).
[11] A. Wadas, J. Hug., J. Appl. Phys., **72**, 203, 1992.
[12] A. Wadas, P. Grütter, Phys. Rev. B., **39**, 12013, 1989.
[13] P. Bryant, S. Schultz, D. R. Fredkin, J. Appl. Phys., **69**, 5877, 1991.
[14] U. Hartmann, Phys. Lett. A., **137**, 475, 1989.
[15] S. L. Tomlinson, A. N. Farley, J. Appl. Phys., **81**, 5029, 1997.
[16] D. V. Ovchinnikov, A. A. Bukharev, AIP Conference Proceedings, **696**, 634, 2003.
[17] Rugar D. et al., J. Appl. Phys, **68**, 1169-1183, 1990.
[18] Coffey M. W. et al., Int. J. Eng. Science., **36**, 1493-1509, 1998.
[19] Folks L. et al., J. Magn. Magn. Matter., **190**, 28-41, 1998.
[20] Li Y. et al., Chem. Matter., **18**, 2552-2557, 2006.
[21] Proksch R. B. et al., Appl. Phys. Lett., **66**, 2582-2584, 1995.
[22] Amemiya Y. et al., J. Biotechnology., **120**, 308-314, 2005.