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Differential Magnetic Force Microscope Imaging

YING WANG,[1] ZUOBIN WANG,[1,2] JINYUN LIU, AND LIWEI HOU[1]

[1]Changchun University of Science and Technology, CNM & JR3CN, Changchun, China
[2]University of Bedfordshire, JR3CN & IRAC, Luton, United Kingdom

Summary: This paper presents a method for differential magnetic force microscope imaging based on a two-pass scanning procedure to extract differential magnetic forces and eliminate or significantly reduce background forces with reversed tip magnetization. In the work, the difference of two scanned images with reversed tip magnetization was used to express the local magnetic forces. The magnetic sample was first scanned with a low lift distance between the MFM tip and the sample surface, and the magnetization direction of the probe was then changed after the first scan to perform the second scan. The differential magnetic force image was obtained through the subtraction of the two images from the two scans. The theoretical and experimental results have shown that the proposed method for differential magnetic force microscope imaging is able to reduce the effect of background or environment interference forces, and offers an improved image contrast and signal to noise ratio (SNR). SCANNING 37:112–115, 2015. © 2015 Wiley Periodicals, Inc.

Key words: magnetic force microscope (MFM), reversed tip magnetization, differential MFM imaging

The magnetic force microscope (MFM) is becoming a powerful tool today for the reconstruction of magnetic structures and sample surfaces by detecting the magnetic interactions between the tip and the sample with nano resolution. (Imamura and Kaneko, 2011; Wakaya *et al*., 2011) An MFM uses a sharp magnetized tip, which is a common AFM probe with a magnetic coating, to detect the magnetic interactions with the sample. It usually adopts the lift-mode for magnetic domain imaging by performing two measurements on the sample surface. The sample surface profile is achieved using the tapping mode in the first scan, and then the tip is lifted to a certain distance for the second scan to obtain the magnetic force image. The changes of the oscillating tip in its phase or frequency are used to represent the magnetic interactions between the sample and the tip. The factors affecting the quality of magnetic force images include the tip radius and the tip-sample distance which is usually tens of nanometres to separate the magnetic forces from non-magnetic forces. (Choi *et al*., 2010) With the development of nano magnetic materials, devices and systems, such as magnetic nanoparticles, magnetic random access memories and perpendicular recording media, the demand for measurement systems is highly increased. (Guarisco and Nguy, 2003; Geerpuram *et al*., 2004 Wei *et al*., 2011).

For the improvement of MFM imaging quality, the methods including the use of specially fabricated MFM tips and the adoption of advanced scanning strategies have been developed. Huang et al. (2007) and Koblischka et al. (2003) used focused ion beam (FIB) to fabricate high-aspect-ratio tips. Kirtley et al. (2007) developed carbon nanotube tips to improve the MFM spatial resolution. Koblischka et al. (2004) and Memmert et al. (2000) used the electron-beam deposition (EBD) technique to modify the MFM tips for decreasing the perturbative effect on the soft magnetic structures and obtained the highest spatial resolution. The spatial resolution of magnetic force images could be improved through setting different lift distances, setpoints and scanning speeds. However, such efforts are limited by the background or environment interference forces which unavoidably contribute to the magnetic force images and have significant effects on the imaging quality.

In this work, a method for differential magnetic force microscope imaging is presented to obtain differential

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*Address for reprints: Zuobin Wang, Changchun University of Science and Technology, CNM & JR3CN, Changchun, China, 130022.
E-mail: wangz@cust.edu.cn

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magnetic force images with an improved contrast and SNR. The method was based on a two-pass scanning procedure, and the magnetic sample was first scanned with a low lift distance between the MFM tip and the sample surface, and the magnetization direction of the probe was then changed after the first scan to perform the second scan. The differential magnetic force image was obtained through the subtraction of the two images from the two scans. The magnetic forces were separated from other background forces, and the quality of magnetic images was improved. The method is described in detail in the following sections.

The MFM mainly detects the magnetic interactions between the tip and the sample in the z direction for the magnetic force imaging of the sample surface. Since a force gradient exists between the probe and the sample, a probe phase shift will be introduced. The phase shift can be calculated as (Passeri *et al.*, 2014)

$$\phi \cong \frac{Q}{k}\frac{\partial F_Z}{\partial Z} \tag{1}$$

where F_Z is the component of the force vector in the z direction, k is the cantilever spring constant, and Q is the quality factor of the probe. The distribution of the magnetic forces on the sample surface can be obtained through recording down the phase shift of every scanning point when the probe scans along with the sample surface.

In the scanning process, the background forces (such as the van der Waals force, the electrostatic force, and the force set during the AC tuning of cantilever) and the noise can introduce variations to the magnetic force images. Let φ_1 be the phase shift from the first scan and φ_2 be the phase shift from the second scan. The phase shifts can be expressed as

$$\phi_1 = \phi_0 + \phi_{B_1} + \phi_{N_1} \tag{2}$$

$$\phi_2 = -\phi_0 + \phi_{B_2} + \phi_{N_2} \tag{3}$$

where ϕ_0 is the phase shift introduced by the magnetic forces, ϕ_{B1} is the phase shift introduced by the background forces in the first scan, ϕ_{B2} is the phase shift introduced by the background forces in the second scan, ϕ_{N1} is the noise distribution in the first scan, and ϕ_{N2} is the noise distribution in the second scan.

The phase shift difference between the two scans can be calculated by

$$\begin{aligned}\Delta\phi &= \phi_1 - \phi_2 \\ &= 2\phi_0 + \phi_{B_1} - \phi_{B_2} + \phi_{N_1} - \phi_{N_2}\end{aligned} \tag{4}$$

When $\varphi_{B1} = \varphi_{B2}$, Equation (4) can be simplified as

$$\Delta\phi = 2\phi_0 + \phi_{N_1} - \phi_{N_2} \tag{5}$$

Providing that ϕ_{N_1} and ϕ_{N_2} are zero mean Gaussian noise distributions and they are uncorrelated, $E(\phi_{N_1}) = E(\phi_{N_2}) = 0$, $E(\phi_{N_1}^2) = E(\phi_{N_2}^2) = \sigma_N^2$, and $E(\phi_{N_1} \cdot \phi_{N_2}) = 0$.

Thus, the expectation of the noise term is

$$E(\phi_{N_1} - \phi_{N_2})^2 = 2\sigma_N^2 \tag{6}$$

It can be seen from Equations (5) and (6) that the differential magnetic force signal amplitude is doubled and the background forces are eliminated so that the SNR and the image contrast are significantly improved by differential magnetic force microscope imaging.

Figure 1 shows the principle of differential magnetic force microscope imaging with the reversed tip magnetization. When the probe is magnetized upward, the phase shifts caused by the magnetic forces and background forces between the tip and the sample surface are shown in Figure 1. When the probe magnetization direction is downward as shown in Figure 1B, the magnetic interactions between the tip and the sample are reversed and the background forces remain unchanged. Figure 1C shows the differential magnetic force signal obtained through the subtraction of the two signals in Figure 1A and B, and its amplitude is doubled compared with those in Figure 1A and B. Thus, there is a clear contrast enhancement in the differential magnetic image, as the background forces have been removed and the output signal amplitude is increased. The differential magnetic force image can be analyzed similarly to the magnetic force images with the reduced or removed background forces.

In the experiment, the CSPM5500 scanning probe microscope from Being Nano-Instruments and the standard magnetic probes (BudgetSensors Multi75M-G) with the typical spring constant 3 N/m, resonant frequency 75 kHz, curvature radius 60 nm and taper angle 25° were used. The two-pass scanning procedure was performed with the separation distance of 10 nm. The probe magnetization direction was transformed by the external magnetic field that did not influence the local magnetization of the sample. It is crucial that the two successive images are in the exact same area of the sample. To achieve this, larger images were used to obtain the result by matching the image patches in the selected area (Wang*et al.*, 2013).

Figure 2 shows the topographic images and magnetic force images of a cycloidal shape magnetic structure with a diameter of 2 microns, made by electron beam lithography (EBL) on a silicon wafer substrate with the nickel film thickness of 100 nm. Figure 2A and B are the topographic images corresponding to the magnetic

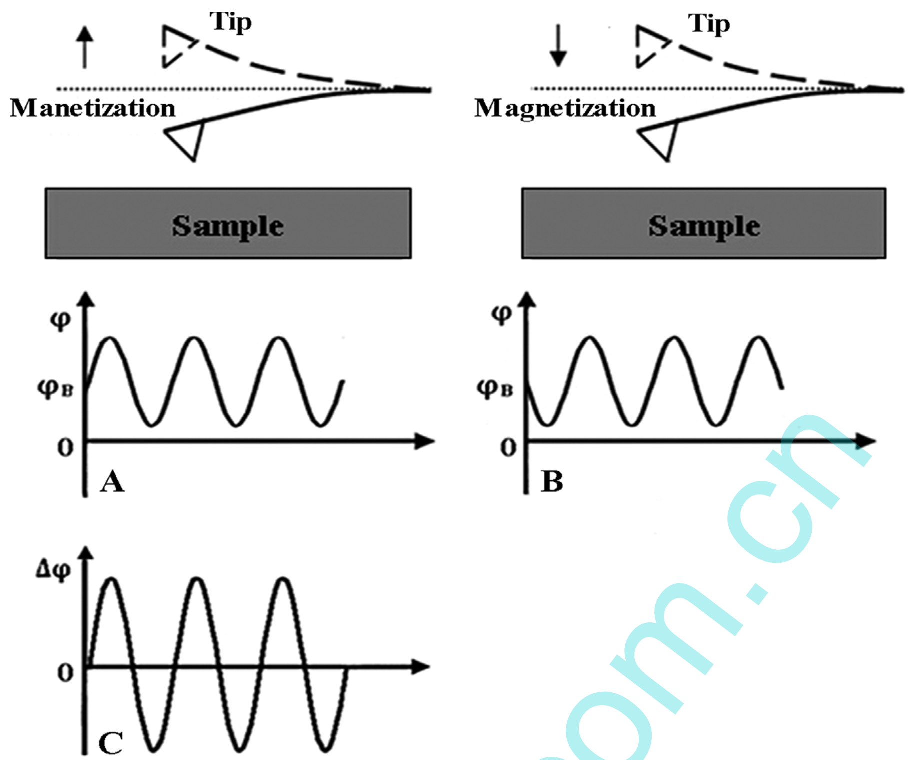

Fig 1. Principle of differential magnetic force microscope imaging. (A) MFM probe magnetized upward. (B) MFM probe magnetized downward. (C) Differential magnetic force signal.

images in Figure 2C and D obtained with the reversed tip magnetization. Figure 2E is the differential magnetic force image. Three selected cross-sectional curves from Figure 2C–E are shown in Figure 3. In the experiment, there were two separate magnetic images captured and the differential magnetic image was then obtained by analyzing the similarity of the images from the two scans, and the Matlab software was used to process the images. Two standard magnets were used to magnetize the tip outside the microscope, and the tip magnetization

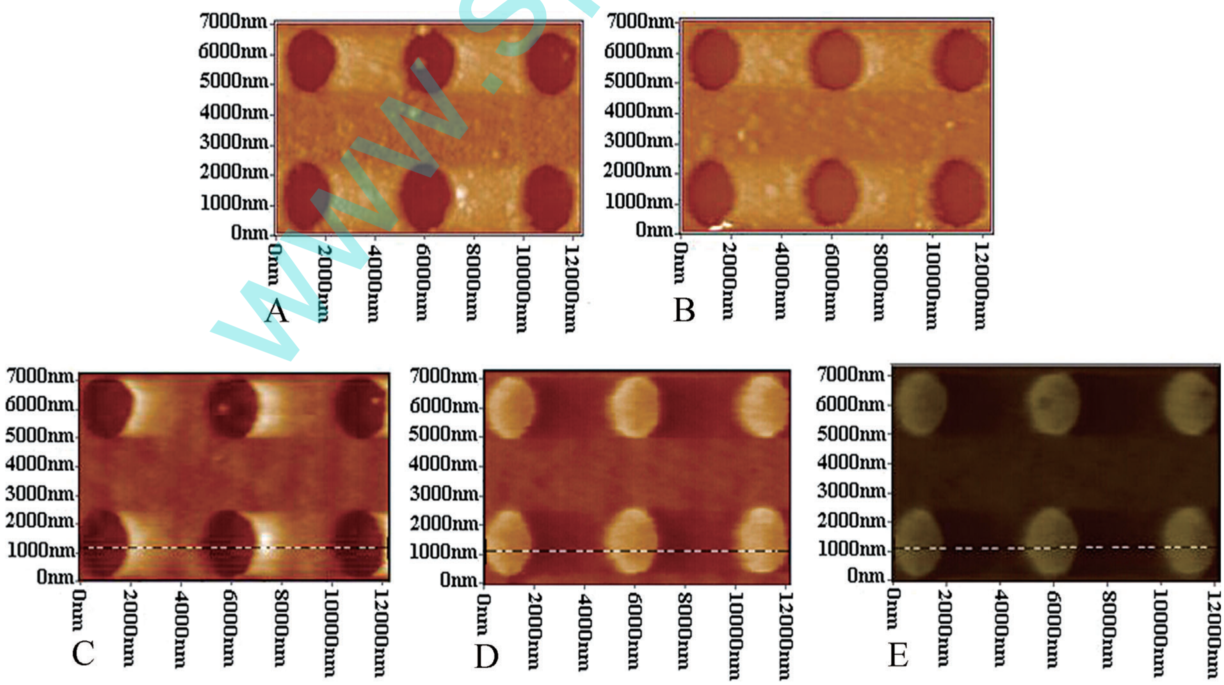

Fig 2. Topographic and magnetic images of the cycloidal magnetic structures made by EBL. (A) and (B) are the topographic images corresponding to the magnetic force images (C) and (D) with reversed tip magnetization; (E) is the differential magnetic force image.

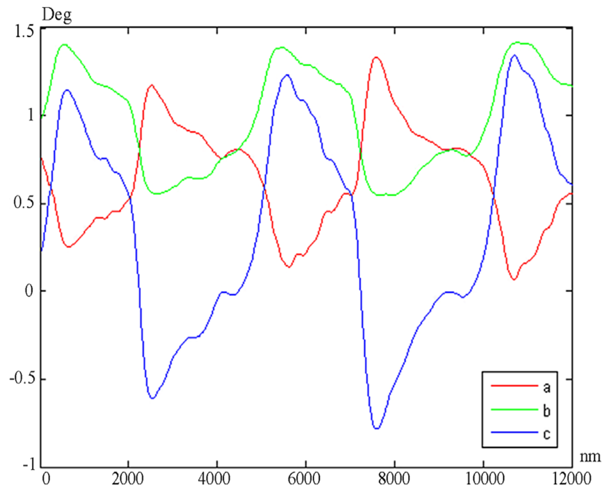

Fig 3. Cross-sectional curves a, b and c from Figures 2C, 2D and 2E.

direction was changed by reversing the magnets after the first scan.

In Figure 3, the curves a and b are two mirror symmetric distributions due to the change of the magnetization direction of the tip leading to the phase inversion of the output signal, and the curve c is the difference of the curves a and b. It can be seen that the differential magnetic force signal amplitude is the sum of those from the curves a and b, and the background forces are significantly reduced. The average contrast values of Figure 2C–E are 0.69, 0.51 and 0.86, respectively. The contrast values in the experiment are estimated by

$$Contrast = \frac{\overline{Max} - \overline{Min}}{\overline{Max} + \overline{Min}} \tag{7}$$

where $\overline{Max}$ is the average of ten maximum amplitude values, and $\overline{Min}$ is the average of ten minimum amplitude values in the images.

It can be seen that the SNR and the image contrast are significantly improved by differential magnetic force microscope imaging. This method is useful for the improvement of the magnetic force image contrast and SNR, and for the acquisition of high quality of magnetic force images.

In this work, the method for differential magnetic force microscope imaging has been investigated based on a two-pass scanning procedure to extract differential magnetic forces and eliminate or significantly reduce background forces with the reversed tip magnetization. The magnetic sample was scanned twice with the change of the probe magnetization direction. The differential magnetic force image was obtained through the subtraction of the two images from the two scans. The difference of the two scanned images was used to express the local magnetic forces. The theoretical and experimental results have shown that the method is useful for the acquisition of high quality magnetic force images. The image contrast and SNR can be significantly improved in the magnetic force microscope imaging.

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