MFM Study: the Air Damping Effect on Magnetic Imaging of CoNbZr Thin Film

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Abstract This paper studies the CoNbZr soft magnetic thin film by magnetic force microscopy (MFM). By measuring in atmosphere circumstance, the magnetic force images display some clear dark dots which are corresponding to the clusters in the topography images well. Then the dark dots disappear in magnetic force images, scanning in high vacuum. This indicates that the dark dots are caused by air damping between the vibrating tip and the sample. An interpretation for the above observation is given.

Key words air damping effect; magnetic force microscopy; topography; magnetic imaging

Magnetic force microscopy (MFM) has become one of the most widely used techniques for imaging surface magnetic stay field distributions [1]. This is due to the minimal sample preparation and the relative ease with which high quality sub-100-nm resolution images may be obtained under normal laboratory conditions. With the new widely available commercial microscopes and magnetic tips, images with 50 nm resolution are quite routine [2].

The MFM operates by mainly sensing the magnetic force between a cantilevered probe and the sample surface. In the dynamic mode, which is favored because of its high resolution, the cantilever is oscillated at or close to its resonance frequency and scanned over the sample surface. The force gradient due to the interaction force between the tip and sample surface causes the modification of the spring constant of the cantilever and change of its resonance frequency [3]. For low amplitudes, the problem can be treated as a harmonic oscillator with the frequency:

\[ f = \frac{1}{2\pi} \sqrt{\frac{c - \frac{\partial F}{\partial z}}{m}} \]  (1)

where \( m \) is the effective mass of tip and cantilever and \( c \) is the cantilever constant [4]. From this we can see that the force derivative \( \frac{\partial F}{\partial z} \) changes the cantilever resonant frequency to

\[ f = f_0 \sqrt{1 - \frac{\frac{\partial F}{\partial z}}{c}} \]  (2)

where \( f_0 \) is the free resonance frequency of the cantilever in the case of no tip sample interaction.

The resonance frequency and quality factor \( Q \), which affects the responsiveness, are determined by the mechanical and geometrical properties of the cantilevers and controlled by the forces from gas or fluid surrounding the cantilever. Normally, the MFM operates in atmosphere and subjects to the air damping effect among the sample surface, the tip and the cantilever [5].

In this article, by the experiment in high vacuum circumstance, we show that the dark dots in the magnetic force images of the CoNbZr thin film is caused by the air damping phenomena.

1 Experiment

A Seiko SPA300-HV was used in its MFM trace mode configuration. Trace mode employed interleave technology [6], in which the probe firstly worked in constant-force tapping mode to attain the topography of one scan line, and then it was lifted by the so called trace distance and followed the orbit of the first scan in dynamic mode to gain the magnetic interaction signal on the same scan line. This would remove the topographical influence on the MFM image in great extent. The trace distance is the distance between the sample surface and the tip apex when the tip reaches the bottom of each swing in lifted scan. The experiment used a silicon nitride cantilever (40 N/m, 125 \( \mu \)m long, resonance frequency 300 kHz) with the
tip deposited magnetic coat. The vacuum experiment used a rotary vane pump together with a turbo molecular pump to achieve $3 \times 10^{-4}$ Pa vacuum. The sample for experiment was a CoNbZr soft magnetic thin film and the magnetic field above the surface was low.

Fig.1 The topography image and the MFM images attained in atmosphere condition at different trace distances

2 Results and Discussions

Fig.1 (a) shows the topography image of the area of $20 \mu m \times 20 \mu m$ on the sample surface scanned in atmosphere. Fig.1(b) to Fig.1(f) shows the MFM images of the same area with various trace distances of 30 nm, 45 nm, 70 nm, 100 nm, 500 nm, respectively. There is a negative phase shift at each of the most apparent cluster positions, which indicates attractive interaction. This is different from that by Koch et al.\cite{7} in which the phase shift was positive at each cluster position. However, the phase intensity of the phase shift is also directly related to the cluster height. The higher the cluster height is, the larger the negative phase shift is comparing with average flat. As the trace distance increases from 30 nm to 45 nm (in Fig.1(b), and (c)), the phase shift is better consistent with the contour of the clusters, and there are lots of much smaller clusters corresponding phase shift appeared in the MFM images. While the trace distance is greater than 100 nm, even to 500 nm, the contours and positions of dark dots are still well corresponding to the cluster. This shows that the dark dots are not caused by magnetic interaction or electrostatic forces since as trace distance increases greatly the intensity of these forces will decrease acutely, especially for soft magnetic thin film. Furthermore, the dark dots are also not due to the Van der Waals forces, which can be ignored in such high trace distance\cite{4}. The weak stripes in the MFM images are due to the interference between the laser beam reflected from the sample surface and the back of the cantilever.

Fig.2 shows the MFM images of the same area in Fig.1 but gained in high vacuum of $3 \times 10^{-4}$ Pa. In the same trace distance with the experiment in atmosphere, all of the dark dots disappear. This shows further that the dark dots appeared in atmosphere condition should be caused by air damping between the tip and the sample surface and even between cantilever and the sample surface.

Fig.3 The sectional images obtained in atmosphere
Fig. 3 shows the sectional images obtained in atmosphere, Fig. 3(a) is the sectional topographical image correspond to the real line A-B in Fig. 1(a) and Fig. 3(b) is the sectional MFM phase image of the same region. The arrow lines denote the corresponding positions in two images. The side slope is presumed to be caused by the air cushion between the tip side and the cluster side. The hollow in the middle of the sides may be due to the comparatively weaker air effect between the crests of the probe and cluster. As a result, the dark dot is formed because of the negative phase shift in the center.

3 Conclusions

The presented experiment comparing the MFM images under atmosphere condition with high vacuum condition has proved the air damping effect in MFM images. There are so many dark dots consistent with clusters in the topography image well and the phase shift is directly related to the cluster height. However, it would be unnoticed if only part of the phase shift is in that case. Moreover, if air induced forces are coupling with the magnetic forces of the clusters, the MFM image in atmosphere condition could be distorted and the quantitative analysis becomes unreliable. The further investigation of the exact model to explain the sectional image of the dark dots is expected.

References


Brief Introduction to Author(s)

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