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Magnetic Response Versus Lift Height of Thin Ferromagnetic Films

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The interaction between a magnetic force microscope (MFM) tip and ferromagnetic films of Ni, $Co_{90}Fe_{10}$ and Py with in-plane magnetization has been investigated. The measured interaction, due to the magnetizing of the films by the MFM tip field, was determined by the phase shift of the cantilever response. The tip-film separation or lift height dependent phase shift was found to be independent of the saturation magnetization of the ferromagnetic film. The result is identical for all three films and micromagnetic simulations give similar results. The reason is at a given tip-sample separation the tip induced magnetization of the film creates a demagnetization field which is equal in magnitude to the tip field at that separation.

***Index Terms*—Magnetic films, magnetic force microscopy.**

I. Introduction

In typical operation a magnetic force microscope (MFM) provides a means of examining the magnetic structure of microscopic samples by sensing the emerging magnetic field gradients from a specimen [1], [2]. This sensing is accomplished through the influence of the specimen's field gradients on a magnetic tip located on the end of a silicon cantilever. In general the alteration of the magnetic structure by the MFM magnetic tip is not desirable although one can use it to quantify the moment of the tip [3], [4] or make microscopic susceptibility measurements [5]. In the case of a uniform in-plane magnetization as in a polycrystalline magnetic thin film one would expect to image a constant signal over the film; an image without structure. This constant signal is not a null signal, however, but consists of the interaction of the MFM tip with the magnetization induced in the film by the tip's magnetic field. This signal should be uniform everywhere over the film. We have measured the induced signal by imaging various magnetic thin films with in-plane magnetization as a function of the separation between the MFM tip and specimen usually referred to as lift-height. We find the signal as a function of lift height is independent of the saturation magnetization of the ferromagnet.

In what follows we briefly describe the operation of a MFM relevant to the present discussion. This is followed by our sample preparation and results. A summary of this work is presented at the end.

II. Theory

As has been shown [4], the signal a MFM detects is determined by the interaction energy, E_{int}, of the magnetic tip with the sample. Considering the tip field interacting with the sample [6], the energy is given by

$$E_{\text{int}} = -\int_{Sample} \mu_o \vec{M}_{Sample} \bullet \vec{H}_{Tip} dV \tag{1}$$

where M_{Sample} is the magnetization of the sample and H_{Tip} is the magnetic field from the tip. In our case the energy can be thought of as the field from the tip altering the magnetization in the specimen [4], i.e., $\vec{M}_{Sample} = \chi_{Sample}\vec{H}_{Tip}$

For the operation of a MFM, the usual technique is to measure the phase shift between an applied driving force at a frequency close to the cantilever resonant frequency and the cantilever response. In this case the magnetic signal is this phase shift $(\Delta\phi)$ between the drive and the cantilever response. The phase shift's relation to the energy is given by

$$\Delta\phi = \frac{Q}{k}\frac{\partial F_{\text{int}}}{\partial z} = \frac{Q}{k}\frac{\partial^2 E_{\text{int}}}{\partial z^2} \tag{2}$$

where Q is the quality factor and k is the spring constant of the cantilever. Thus for our experimental situation, the MFM tip magnetizes the specimen and the MFM images correspond to the second derivative of the energy of the attraction between the induced magnetization and the MFM tip.

III. Sample Preparation

For our experiments we made samples consisting of pairs of ferromagnetic films on a non-magnetic substrate. By keeping the thickness of the films small the demagnetization energy of our films constrains the magnetization to lie in the sample plane. The tip of our MFM cantilever is magnetized perpendicular to the plane of the film. Thus the detected signal is due to the deflection of part of the magnetization from lying in the xy-plane to parallel with the z-axis.

Our samples consisted of 40 nm thick films of $Co_{90}Fe_{10}$ and either Permalloy or Ni with a 5 nm cap of Tantalum sputtered onto Si substrates. Standard lithographic processes were

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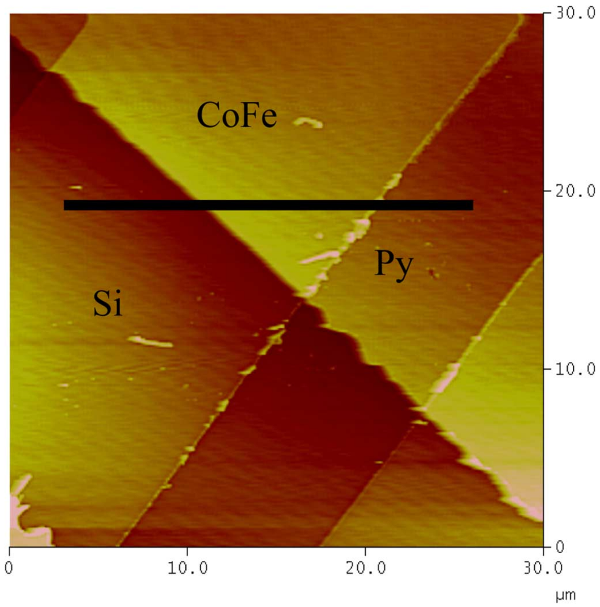

Fig. 1. Topographic image of a sample consisting of CoFe and Py. The black line indicates a scan line which would include the substrate and both magnetic films.

used to pattern and shield the films for ion milling to the substrate in certain regions, leaving a metal mesa and substrate valley. Before lift-off a second ferromagnetic film and Ta cap were deposited filling up the milled valleys. Lift-off was then performed, leaving the substrate and two lithographically defined metals next to each other. A second patterning and milling process left both metal mesas next to a substrate valley as shown in Fig. 1. With this patterning the imaging of the samples could be aligned such that a single scan line included a region of both films and the non-magnetic substrate as shown by the line in Fig. 1; the scan over the non-magnetic substrate provided the value of zero $\Delta\phi$. For the imaging, we used a Dimension 3000 Scanning Probe Microscope, operating in tapping and lift mode using standard MFM tips.

IV. Result and Conclusions

Results for two different samples are shown in Fig. 2. Fig. 2(a) is a plot of $\Delta\phi$ versus lift height for a sample with both Py and $Co_{90}Fe_{10}$ while 2(b) is a similar plot for Ni and $Co_{90}Fe_{10}$. One will immediately notice that for a given sample $\Delta\phi$ is the same for both magnetic materials at the same lift height although the saturation magnetizations differ considerably between the ferromagnetic materials ($Co_{90}Fe_{10} = 1430$, Py $= 800$, Ni $=$ $485\ \mathrm{emu/cm^3}$).[1]

We also performed micromagnetic calculations using the LLG [7] software for the geometry and magnetic parameters appropriate to the experimental situation. In the simulations the magnetic tip was modeled with a high uniaxial anisotropy to

[1]In this figure one should also notice the difference in $\Delta\phi$ for the $Co_{90}Fe_{10}$ in A and B for the two samples at the same lift height. This variation in $\Delta\phi$ from sample to sample is not fully understood but was, in part, responsible for the development of samples where two magnetic films could be measured in a single scan.

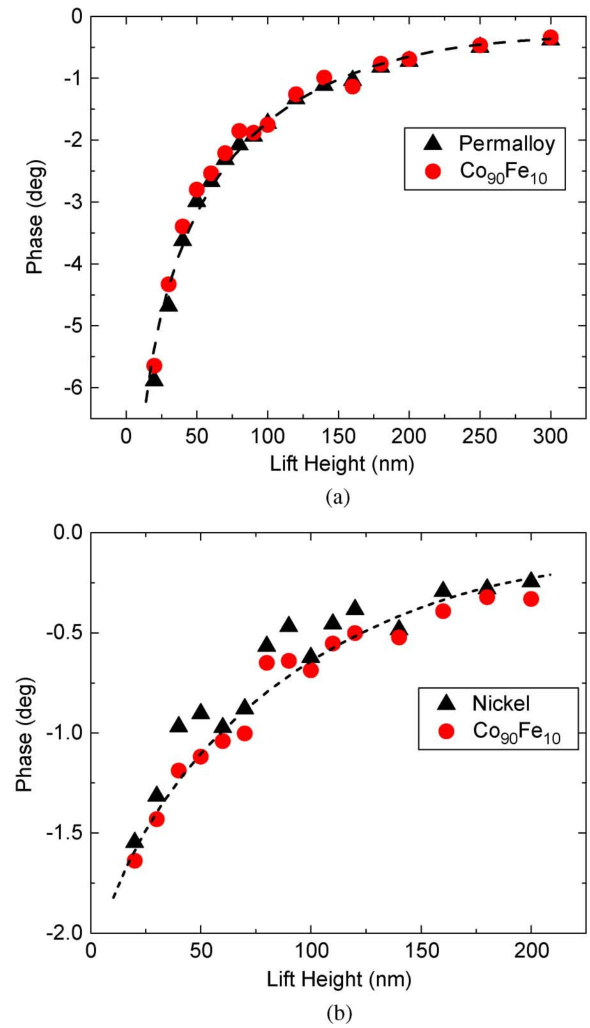

Fig. 2. Measurements of $\Delta\phi$ or phase versus lift height for Permalloy/$Co_{90}Fe_{10}$ sample (a), and a nickel/$Co_{90}Fe_{10}$ sample (b). Each plot shows the detected phase is identical illustrating that the phase detected is independent of film magnetization. The dashed lines serve as guides for the eye.

hold the magnetization perpendicular to the plane of the film and placed at various heights above the plane of a uniformly magnetized (in-plane) ferromagnetic film with an appropriate value for the saturation magnetization of the materials being investigated. The simulation relaxes the system from the initial tip-film conditions and calculates the total energy of the system. By simulating a series of spatially close separations two finite derivatives could be taken which is related to the phase shift in (2). Fig. 3 is a plot of the second derivative of the calculated energy as a function of the simulated tip lift height. As can be seen from the data in Figs. 2 and 3 the experimental data and the simulation data are qualitatively in agreement. It is difficult to make them quantitatively in agreement given the lack of specific knowledge needed to determine an absolute phase. We have, however, linearly scaled both the lift height and phase angle of the simulation data and get a reasonable agreement with the experimental data.

In summary, for a given tip we find a universal curve for the MFM signal versus lift height; this curve is independent of the saturation magnetization of a film. This universal behavior can

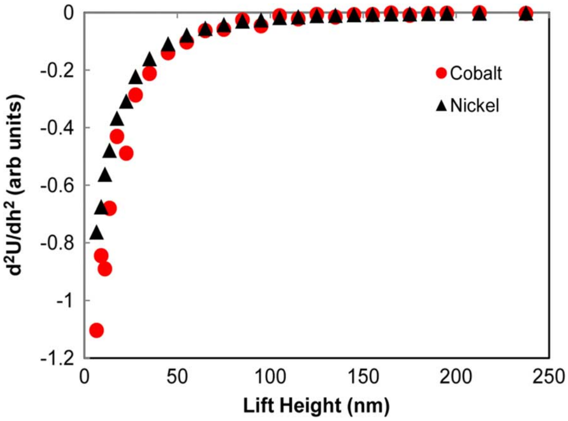

Fig. 3. Simulated response of the micromagnetic tip interacting with thin films of nickel and cobalt. The second derivative of the energy as a function of tip lift height is comparable to the measured experimental response.

be explained as follows. The magnetization of the sample induced by the tip creates a demagnetizing field. This demagnetizing field must be equal and opposite to the tip magnetic field. Thus, independent of the saturation magnetization of the film, the alteration of the magnetization of the sample is limited by the applied field; exactly what would be seen in a hysteresis loop measurement perpendicular to the plane of a magnetic film, i.e., the shear in the loop or field dependent magnetization is given by the demagnetization field of the film.

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