Ferromagnetic resonance force microscopy on microscopic cobalt single layer films

Z. Zhang\textsuperscript{a)} and P. C. Hammel\textsuperscript{b)}

Los Alamos National Laboratory, Los Alamos, New Mexico 87545

M. Midzor and M. L. Roukes
California Institute of Technology, Pasadena, California 91125

J. R. Childress\textsuperscript{c)}
University of Florida, Gainesville, Florida 32611

(Received 24 February 1998; accepted for publication 31 July 1998)

We report mechanical detection of ferromagnetic resonance (FMR) signals from microscopic Co single layer thin films using a magnetic resonance force microscope (MRFM). Variations in the magnetic anisotropy field and the inhomogeneity of were clearly observed in the FMR spectra of microscopic Co thin films 500 and 1000 Å thick and \( \sim 40 \times 200 \) \( \mu \text{m}^2 \) in lateral extent. This demonstrates the important potential that MRFM detection of FMR holds for microscopic characterization of spatial distribution of magnetic properties in magnetic layered materials and devices. © 1998 American Institute of Physics. [S0003-6951(98)01640-4]
For these measurements the earlier apparatus was modified in two respects: we employed a geometry in which the axis of the bar magnet is oriented perpendicular to the motion of the cantilever, in contrast to the conventional MRFM geometry where these are parallel, and we used microstrip resonator to generate the rf field (see inset, Fig. 1). The geometry, depicted in the inset to Fig. 2, was selected because the applied field is in the film plane enabling us to saturate the film with a modest magnetic field (of order hundreds of gauss). In contrast, for the parallel geometry, the magnetic field would be applied perpendicular to the film plane and the resonant field as a function of the position (x, z) of the sample with respect to the bar magnet, we distinguish the individual contributions of the electromagnet and the bar magnet to the total field at the film and determine the detailed spatial dependence of the x and z components of the field of the bar magnet. From these data the angle \( \phi_H \) was calculated. We find that the field gradient \( \partial B_{\text{total}}/\partial z \) due to the bar magnet at the Co sample is \( \sim 0.15 \text{ G/µm} \). For our Co film, which is \( \sim 200 \mu\text{m} \) long, this corresponds to a 30 G field difference across the film. Because the resonance line-width of the Co films (between 50 and 100 G) is greater than this, we are not able to distinguish resonance signals arising from different spatial locations in the microscopic Co film by means of the applied field gradient. The larger field gradient produced by reducing the diameter of the magnet will be necessary to improve the spatial resolution of the experiment.

Analysis of our MRFM spectra enabled us to determine magnetic properties of the microscopic ferromagnetic films; in particular, these spectra reveal the dependence of the magnetic anisotropy and the film quality on the deposition method and film thickness. The magnetic anisotropy of the film thickness.

Rather than a coil (used in previous FMR experiments), we used a microstrip resonator with a characteristic frequency near 8 GHz to provide the rf field. This increased the resonant field (applied in the film plane), \( H_{\text{res}} = \sqrt{(2/\pi M_s)^2 + (\omega/\gamma)^2 - 2\pi M_s} = (\omega/\gamma)^2/4\pi M_s \), to a value sufficient to saturate the Co film (\( \sim 100 \text{ G} \)). Unlike other microstrip designs in which the resonator is located at the end of the transmission line, the resonator (see inset, Fig. 1) is located beside the transmission line. This provides good coupling between the resonator and the incoming transmission line (\( -20 \text{ dB} \)) even with a fairly large gap (\( \sim 0.2 \text{ mm} \)).

Modulation of the z component of the Co spin magnetization was accomplished by modulating the amplitudes of both the external field \( B_0 \) and the rf power at two distinct frequencies whose difference was set equal to \( f_c \) (i.e., anharmonic modulation).3,12

Figure 1 shows MRFM spectra of the three Co single layer films. The spectra were taken by measuring the in-phase oscillation amplitude of the cantilever while sweeping the external magnetic field; increasing the applied field causes the position of the sensitive slice to move away from the source of the field gradient. When the sensitive slice intercepts the Co thin film, an increase in the cantilever vibration amplitude is observed. As in the YIG experiment, the MRFM signals from the Co films were so large that all spectra were taken at ambient pressure in order to reduce the \( Q \) factor, and thus the response, of the cantilever (\( Q \sim 15000 \) in vacuum; \( \sim 40 \) in air). Because the signal-to-noise ratio is proportional to \( \sqrt{Q} \), this result indicates that, in vacuum, the MRFM will be easily capable of detecting the FMR signal from Co films with similar lateral extent, but as thin as 20–50 Å. By measuring the frequency dependence of the resonant field as a function of the position (x, z) of the sample with respect to the bar magnet, we distinguish the individual contributions of the electromagnet and the bar magnet to the total field at the film and determine the detailed spatial dependence of the x and z components of the field of the bar magnet. From these data the angle \( \phi_H \) was calculated. We find that the field gradient \( \partial B_{\text{total}}/\partial z \) due to the bar magnet at the Co sample is \( \sim 0.15 \text{ G/µm} \). For our Co film, which is \( \sim 200 \mu\text{m} \) long, this corresponds to a 30 G field difference across the film. Because the resonance line-width of the Co films (between 50 and 100 G) is greater than this, we are not able to distinguish resonance signals arising from different spatial locations in the microscopic Co film by means of the applied field gradient. The larger field gradient produced by reducing the diameter of the magnet will be necessary to improve the spatial resolution of the experiment.

Analysis of our FMR spectra enabled us to determine magnetic properties of the microscopic ferromagnetic films; in particular, these spectra reveal the dependence of the magnetic anisotropy and the film quality on the deposition method and film thickness. The magnetic anisotropy of the
A sputtered film was determined by analysis of the dependence of the resonance field on \( \phi_H \). This angle is varied by displacing the Co film with respect to the bar magnet in either the \( x \) or \( z \) direction, thus changing the \( x \) and \( z \) components of the magnetic field applied to the film. This result is shown in Fig. 2. The solid curve in Fig. 2 is a theoretical prediction for the dependence from classical FMR theory assuming only a demagnetization field. In particular, no crystalline anisotropy is observed; this absence is an expected consequence of the demagnetization field. In particular, no crystalline anisotropy this dependence from classical FMR theory assuming only a demagnetization field. In particular, no crystalline anisotropy is observed; this absence is an expected consequence of the demagnetization field. In particular, no crystalline anisotropy is observed; this absence is an expected consequence of the demagnetization field.

Figure 1 shows the FMR spectra of the three films taken at constant angle \( \phi_H=33^\circ \). The resonant field position is larger in evaporated films indicating an additional anisotropy in these films. In particular, the effective demagnetization field, \( 4\pi M_{\text{eff}}=4\pi M_s-2K_u/M_s \) is different (where \( K_u \) is the uniaxial anisotropy energy density perpendicular to the film plane). This variation in \( K_u \) could arise from different residual stresses developed during the film deposition. Assuming that the saturation magnetization \( M_s \) for each of the Co films is the same as for bulk Co (\( \sim 1400 \text{ emu/cm}^3 \)), we find that \( 2K_u/M_s \sim 0 \) for the sputtered film, \( \sim 2.8 \text{ kG for the 1000 Å evaporated film, and \( \sim 4.9 \text{ kG for the 500 Å evaporated film. These results indicate that the evaporated samples develop larger stress than the sputtered sample, and that the stress decreases with increasing film thickness.} \)

A dependence of sample homogeneity on the deposition process is also evident in Fig. 1 from the variation of the FMR linewidth. The sputtered sample has a narrowest linewidth, about 45 G. The applied field gradient cannot explain this linewidth variation because the sputtered sample has the largest spatial extent along the \( z \) axis (the direction along which the field gradient is largest). Thus, the linewidth reflects the quality or homogeneity of the Co film itself, and these measurements indicate that sputtering produces a more homogeneous film than does thermal evaporation. Between the two evaporated samples, the 500 Å sample has the narrower resonance linewidth, possibly because a two stage evaporation was required for the 1000 Å film, or possibly indicating that the film quality degrades as it becomes thicker.

In conclusion, a MRFM has been successfully used to detect FMR signals from microscopic Co single layer thin films with unprecedented sensitivity. These signals were obtained from a perpendicular-geometry MRFM operating at a frequency of 8 GHz. These conditions ensured that for modest resonance fields the applied field component in the plane of the film was sufficient to saturate the film. The large signal intensity indicates that the sensitivity of the current MRFM is adequate to detect FMR signals from microscopic metallic ferromagnets as thin as 20 Å. In fact, this has been verified in our most recent experiments on 50 Å Co films. Although the field gradient in the present instrument is not large enough to distinguish FMR signals from different spatial locations in the film, our results demonstrate that MRFM detection of FMR has the sensitivity to enable microscopic studies of systems composed of thin film metallic ferromagnets. We have demonstrated, in particular, the ability to observe variations in magnetic anisotropy energy and film quality from one microscopic sample to another. In order to improve the spatial resolution, larger field gradients from smaller bar magnets are needed. Placing the magnetic probe on the cantilever is an essential step to enable experiments on samples prepared on well-characterized substrates. These improvements are presently underway.

The authors gratefully acknowledge fruitful discussions with Philip Wigen at Ohio State University and the support of the Center for Nonlinear Studies at Los Alamos National Laboratory. Work at Los Alamos was supported by the U.S. Department of Energy, Office of Basic Energy Sciences.