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Citation of published version:

Nazaretski, E., et al. (2007): Temperature-dependent Magnetic Resonance Force Microscopy Studies of a Thin Permalloy Film, *Journal of Applied Physics,* 101(7). https://doi.org/10.1063/1.2715761

Temperature-dependent magnetic resonance force microscopy studies of a thin Permalloy film

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(Received 13 September 2006; accepted 28 January 2007; published online 13 April 2007)

We used magnetic resonance force microscopy (MRFM) to study a 50 nm thick continuous Permalloy film. We mechanically measured the ferromagnetic resonance signal in the temperature range between 10 and 70 K in the presence of a static magnetic field applied normal to the surface of the film. The measurements show a decrease of the ferromagnetic resonance field with increasing temperature. We attribute this behavior to the temperature-dependent changes of the saturation magnetization. Our experiments demonstrate the potential of MRFM to perform quantitative ferromagnetic resonance measurements as a function of temperature. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2715761]

I. INTRODUCTION

Ferromagnetic resonance (FMR) has proven to be a powerful tool for characterization of ferromagnetic materials and, in particular, thin magnetic films.[1] Currently, the rapidly growing magnetic-data-storage industry envisions disk drives with up to 1 $\mathrm{Tbit/in^2}$ storage density[2] and data transfer rates approach 1 Gbit/s.[3] Further increase of the storage density requires a thorough understanding of the underlying magnetization properties and dynamics of all magnetic components used in hard drives. For example, crucial components of hard drives are the read heads, which utilize thin ferromagnetic films in multilayer structures and FMR can be used to study the exchange anisotropy governing the behavior of the exchange coupled ferromagnetic layer.[4,5] Conventional FMR techniques require samples with a surface area on the order of a few $\mathrm{mm^2}$ to obtain signals of adequate strength in the *X* band, and do not provide information about spatial variations of the magnetic properties in magnetic films. To obtain spatial information other techniques such as time-resolved Kerr microscopy,[6,7] locally resolved thermally modulated FMR technique,[8] or x-ray spatially resolved FMR technique[9] have to be used.

Zhang *et al.*[10] used magnetic resonance force microscopy (MRFM) to investigate ferromagnetic resonance on a microscopic scale. MRFM is based on detection of the magnetic force originating from the interaction between the spins in a sample and a permanent magnet mounted on a high-quality-factor micromechanical cantilever.[11] In their recent work, Rugar *et al.* demonstrated the unprecedented sensitivity of MRFM via detection of a force signal originating from a single electron spin.[12] Analogous to magnetic resonance imaging, MRFM experiments are performed in the presence of a strong magnetic field gradient, thus resonant conditions are satisfied only in a narrow region of a sample, known as the sensitive slice. By scanning the sensitive slice both across the surface and perpendicular to it, the three-dimensional (3D) spatial distribution of the magnetization can be mapped in a paramagnetic sample, thus allowing imaging.[13]

To date, MRFM measurements on ferromagnetic films were performed either at room or liquid helium temperatures, and MRFM has been used to perform temperature-dependent study on the exchange biased CoO/Co bilayers.[14] In this paper, the MRFM experiments on a thin Permalloy film are reported. The studies were conducted in the temperature range between 10 and 70 K, demonstrating the potential of MRFM to study temperature-dependent phenomena in ferromagnets.

II. EXPERIMENT

The MRFM apparatus used in this work is a low temperature microscope equipped with a homebuilt temperature regulation stage, capable of taking data in the 4–100 K range in vacuum. The schematic of the experiment is shown in Fig. 1. A double scanning stage (3D Attocube positioner[15] and a piezotube) allows coarse and fine scanning over the sample. To generate the field gradient, we used a 3.5 μm diameter $Nd_2Fe_{14}B$ spherical magnetic particle attached to a

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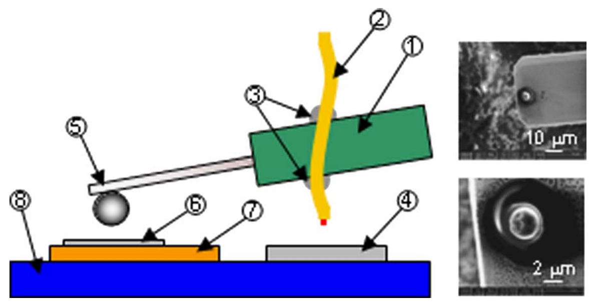

FIG. 1. (Color online) Schematic representation of the MRFM experiment. (1) Scanning stage, (2) optical fiber for the probe-sample distance control interferometer, (3) Torrseal glue, (4) reference mirror, (5) Veeco Instruments cantilever with the magnetic tip, (6) Permalloy sample, (7) stripline resonator, and (8) G10 substrate. (a) and (b) show the SEM micrographs of the cantilever tip.

cantilever (Veeco Instruments, dimensions: $420 \times 30 \times 2\ \mu m^3$, spring constant: 0.1 N/m, and nominal resonance frequency: 10 kHz). The scanning electron microscopy (SEM) micrographs of the cantilever tip are shown in Fig. 1. A fiber-optic interferometer was used to read out the vertical displacement of the cantilever[16] and the wavelength of the laser used was 1550 nm. Special attention was paid to maintaining a constant cantilever-sample spacing as a function of temperature. A second fiber-optic interferometer has been installed on the scanning stage, thus making it possible to measure the distance between the cantilever and the surface of a sample. The cantilever-sample distance was adjusted at every experimental temperature in order to compensate for the relative displacement of the cantilever from the stage caused by thermal expansion. A more detailed description of the microscope can be found elsewhere.[17]

The polycrystalline 50 nm thick Permalloy ($Ni_{80}Fe_{20}$) film was deposited on a 100 μm Si wafer on top of a 20 nm thick Ti adhesive layer. Permalloy was capped with a 20 nm thick Ti film to protect it from oxidation. An approximately 2 mm^2 sample was placed in the H_1 field region, produced by a stripline resonator operated in the X band. The external field was oriented perpendicular to the film plane.

III. RESULTS AND DISCUSSION

The MRFM force signals from the Permalloy film were obtained with the cantilever-sample spacing of approximately 9 μm, corresponding to a field gradient of ≈ 0.5 mT/μm at the surface of the sample. The gradient value was determined from the position of the leading edge with respect to the bulk MRFM force signal for various cantilever-sample distances, analogous to the procedure used by Hammel *et al.*[18] for a Diphenylpicrylhydrazyl (DPPH) film. The magnetic moment of the tip was measured using the cantilever magnetometry method[19] and the value of $\mu = (2.4 \pm 0.2) \times 10^{-11}$ J/T was obtained, which agrees within error margins with the calculations based on the SEM image of the tip. The saturation magnetization $\mu_0 M_s$ for $Nd_2Fe_{14}B$ magnetic particles was measured to be 1.3 T and used for calculations of the magnetic moments of the tip. To couple the cantilever to the in-resonance spins, the microwave field H_1 was amplitude modulated with a modulation depth of 70% at a frequency close to the resonance frequency of the cantilever of ≈ 10 kHz. The quality factor of the cantilever varied from $\approx 35\,000$ (far away from the sample) to ≈ 1000 (in close proximity to the film), depending on the tip-to-sample spacing, in accord with previously reported observations.[20] For the particular spacing of ≈ 9 μm used in our measurements the Q value changed as a function of temperature from ≈ 3000 at 70 K to ≈ 8000 at 10 K.

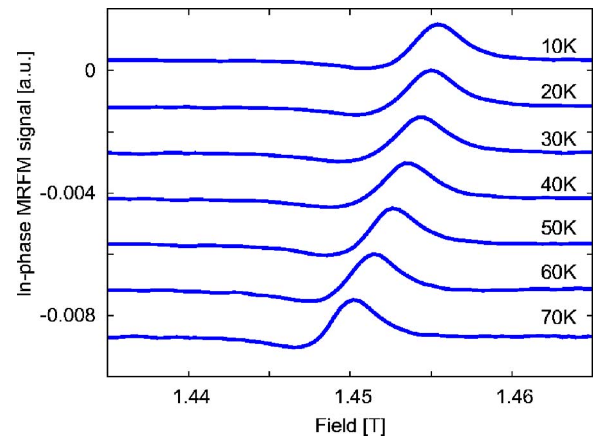

FIG. 2. (Color online) Temperature dependence of the ferromagnetic resonance line in a 50 nm Permalloy film. Spectra were scaled by the maximum amplitudes for display purposes and offset by 0.0015 a.u. each for clarity. Experimental parameters: cantilever-sample spacing ≈ 9 μm and rf of 9.4 GHz.

The FMR frequency for a film is given by the Kittel equation[21] and, in the limit of an infinite thin film for external field perpendicular to the film plain, can be written as

$$\omega_0 = \gamma (H_0 - \mu_0 M_s), \tag{1}$$

where γ is the gyromagnetic ratio, H_0 is the external field, and M_s is the saturation magnetization. We neglect the contribution of the anisotropy field to the resonance field because it is typically small and is less than a few millitesla.[22] The measured value of $\gamma = 28.9 \pm 0.5$ GHz/T between 9.35 and 11 GHz, which corresponds to a Lande factor $g = 2.07 \pm 0.03$, is in good agreement with $g = 2.08 \pm 0.01$ reported earlier by Seavey and Tannenwald.[23] It is important to mention that contrary to conventional cavity based FMR techniques where the FMR frequency is determined by the microwave resonant cavity and is not tunable, the stripline resonator used in MRFM experiments allowed us to record FMR spectra in the frequency range between 9.35 and 11 GHz. Implementation of tapered microstripline resonators or coplanar waveguides[24,25] would further increase the microwave frequency range.

Figure 2 shows the field dependence of the MRFM force signal at various sample temperatures between 10 and 70 K. The resonance field shifts toward lower values with increased temperature. To quantify the influence of the temperature dependence of the magnetization on the resonance field the temperature-dependent superconducting quantum interference device (SQUID) measurements of the saturation magnetization of the Permalloy film were performed. Twelve stacked samples of ≈ 9 mm^2 each were used to obtain a signal of sufficient strength and stability. Figure 3 shows mag-

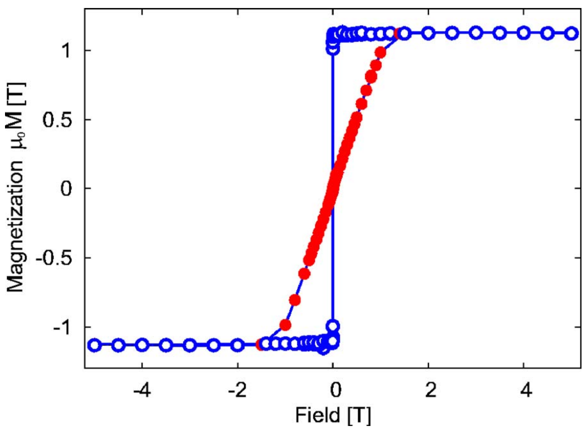

FIG. 3. (Color online) SQUID measurements of the magnetization in perpendicular (solid symbols) and parallel (open symbols) geometries. Data were taken at $T=30$ K.

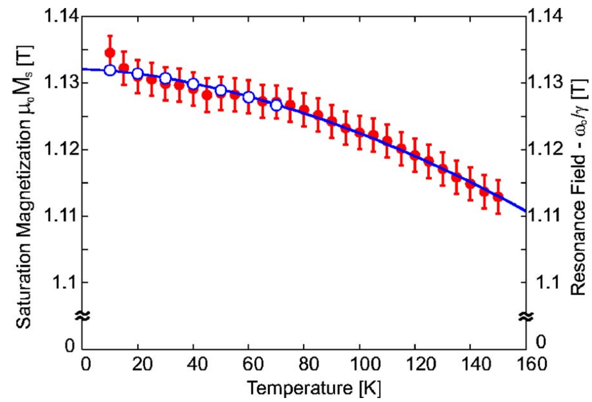

FIG. 4. (Color online) The evolution of the saturation magnetization measured with the SQUID magnetometer (solid symbols, left Y axis). The solid line is the best fit using Eq. (3) with the fitting parameters $\mu_0 M_s(0) = 1.13\pm0.06$ T, $\beta=(5.5\pm2.1)\times10^{-6}$ K$^{-3/2}$, and $\beta_1=(3.0\pm1.7)\times10^{-7}$ K^{-2}. The right Y axis (open circles) depicts the MRFM resonance field less ω_0/γ (0.324 T) vs temperature. The error bars for the MRFM points do not exceed the size of the symbols.

netization curves taken at $T=30$ K, with the film plane perpendicular and parallel to the magnetic field. For the perpendicular orientation the saturation field (equal to the internal field along the normal to the film plane) was obtained (1.130 ± 0.005 T) and compared to the internal field calculated from 30 K MRFM spectra (1.129 ± 0.012 T). Both fields agree within error margins indicating consistency of SQUID and MRFM data.

According to spin-wave theory,[26] the temperature dependence of the saturation magnetization, to a first approximation, is given by the Bloch equation

$$\frac{M_s(T)}{M_s(0)} = 1 - \beta T^{3/2}, \tag{2}$$

where $M_s(0)$ is the saturation magnetization at 0 K, and β is the constant. However, Bloch's law does not take into account the itinerant nature of spins in metallic ferromagnets which introduce an additional $\beta_1 T^2$ term and saturation magnetization is expressed as follows:[27]

$$\frac{M_s(T)}{M_s(0)} = 1 - \beta T^{3/2} - \beta_1 T^2, \tag{3}$$

where β and β_1 are constants. By fitting the experimental points to Eq. (3), the values of $M_s(0)$, β, and β_1 were determined to be $\mu_0 M_s(0)=1.13\pm0.06$ T, $\beta=(5.5\pm2.1)\times10^{-6}$ K$^{-3/2}$, and $\beta_1=(3.0\pm1.7)\times10^{-7}$ K^{-2}, respectively, with the change of the saturation magnetization M_s between 10 and 70 K of $\approx5.1\pm1.2$ mT. The large error bar in $\mu_0 M_s(0)$ is due to uncertainty in the mass estimates of a Permalloy film. It is important to mention that the $\beta T^{3/2}$ term in Eq. (3) contributes a factor of 2 more to the changes of M_s over the observed temperature range as opposed to the $\beta_1 T^2$ term. From Eq. (1) the dependence of the ferromagnetic resonance field on $M_s(T)$ was obtained. A 5.2 ± 0.2 mT shift in the MRFM resonance position was measured between 10 and 70 K (see Fig. 4, open symbols), in agreement with the observed 5.1 ± 1.2 mT shift measured by SQUID (Fig. 4, solid symbols). As it is seen in Fig. 4, the correlation between the two sets of data is very good.

The MRFM force signal was recorded as a function of distance between the sample and the cantilever. In close proximity to the sample (spacing less than a micron, i.e., under conditions of high field gradients) the MRFM response signal-to-noise ratio approached 1000, providing enough sensitivity to study films of subnanometer thickness. The MRFM signal vanished at a cantilever-sample spacing as large as ≈70 μm.

The MRFM cantilever was moved across one sample by a few hundred microns and temperature-dependent measurements were repeated at two new locations. A decrease of the resonance field with increasing temperature was always observed. The magnitude of the resonance field shift as a function of position varied randomly between 4.8 ± 0.2 and 5.2 ± 0.2 mT and its spatial variation did not exceed the size of empty symbols shown in Fig. 4. Our observations, namely, decrease of the resonance field with increasing temperature, agree with the results of conventional FMR experiments performed in Permalloy films in perpendicular geometry.[28,29]

IV. SUMMARY

In summary, MRFM has been used to detect FMR signals from a 50 nm thick Permalloy film in the temperature range between 10 and 70 K. The large signal-to-noise ratio (≈1000 in close proximity to the sample) indicates that the sensitivity of our MRFM apparatus is adequate for detection of FMR signals from subnanometer thick ferromagnetic films. We attribute the decrease of the resonance field with increasing temperature to the change of the saturation magnetization $M_s(T)$. With our experiments we have demonstrated the ability of MRFM to study quantitatively temperature-dependent effects in ferromagnetic films.

ACKNOWLEDGMENTS

The authors gratefully acknowledge stimulating discussions with Dr. I. Martin at Los Alamos. This work was performed at Los Alamos National Laboratory and supported by the US Department of Energy, Center for Integrated Nanotechnologies, at Los Alamos National Laboratory (Contract

No. W-7405-ENG-36) and Sandia National Laboratories (Contract No. DE-AC04-94AL85000). The work at OSU was supported by the US Department of Energy through grant No. DE-FG02-03ER46054. This work was partially supported by the Office of Naval Research through the Institute for Nanoscience at Naval Research Laboratory.

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