Observation of ferromagnetic resonance in a microscopic sample using magnetic resonance force microscopy

Z. Zhang and P. C. Hammel[a)]
Los Alamos National Laboratory, Los Alamos, New Mexico 87545

P. E. Wigen
Department of Physics, The Ohio State University, Columbus, Ohio 43210

(Received 12 December 1995; accepted for publication 25 January 1996)

We report the observation of a ferromagnetic resonance signal arising from a microscopic ($\sim 20\ \mu\text{m} \times 40\ \mu\text{m}$) particle of thin ($3\mu$m) yttrium iron garnet film using magnetic resonance force microscopy (MRFM). The large signal intensity in the resonance spectra suggests that MRFM could become a powerful microscopic ferromagnetic resonance technique with a micron or sub-micron resolution. We also observe a very strong nonresonance signal which occurs in the field regime where the sample magnetization readily reorients in response to the modulation of the magnetic field. This signal will be the main noise source in applications where a magnet is mounted on the cantilever. © *1996 American Institute of Physics.* [S0003-6951(96)00914-X]

Magnetic multilayer devices[1] display a variety of interesting and technologically important properties such as giant magnetoresistance. It is important to understand how the performance of such devices is influenced by microscopic spatial variations in properties like interface quality and interlayer exchange coupling. Conventional ferromagnetic resonance (FMR) is a powerful technique for characterizing magnetic anisotropy and exchange energies of magnetic materials. However, due to limited sensitivity, a macroscopic sample is required, and only average properties of the entire sample can be measured. Employing magnetic resonance force microscopy (MRFM) we have observed a strong FMR signal from a microscopic, thin film ferromagnet. This demonstration opens the possibility of microscopic (sub-micron resolution) FMR studies in a variety of magnetic materials, including the technologically important magnetic multilayer systems.

MRFM, based on mechanical detection of magnetic resonance signals, promises substantial improvements in both signal sensitivity and spatial resolution in magnetic resonance imaging.[2–4] The resonance signal is detected by monitoring the oscillation amplitude of a micro-mechanical cantilever with either a sample or a small magnet mounted on it.[2–6] The large field gradient $\partial B/\partial z$ from a small permanent magnet generates the coupling between the spin magnetization $\mathscr{M}$ in the sample under study and the mechanical oscillator: $F = \mathscr{M}_z(\partial B/\partial z)\ (\vec{B} \| \vec{z})$. The field gradient plays a second role: it defines a thin shell ("sensitive slice") of constant field in the sample where the Larmor frequency, $\omega_L = 2\pi\gamma H$ (H is the applied field and γ the gyromagnetic ratio) of the spins matches the frequency of oscillation of the applied rf field (H_1). Selective sensitivity to spins in this slice is achieved because only these spins are manipulated by the applied rf field in such a way that their magnetic moment $\mathscr{M}_z$ varies at the cantilever frequency f_c thus producing a time varying force which drives the cantilever. Demonstrations to date[3,7,5] of MRFM have employed paramagnetic samples; as we report here it can also be employed as a microscopic probe of magnetically ordered materials. We expect that the limit of the spatial resolution will be the magnetic correlation length (of order 0.01–0.1 μm for most magnetic materials).

Our results on a single crystal yttrium iron garnet (YIG) thin film also provide essential insight for the development of a general MRFM instrument. In order to apply the ultrahigh, 3-D spatial resolution of MRFM to samples of arbitrary size and shape, the bar magnet will need to be mounted on the cantilever. However, all of the experimental data reported in the literature[3,7,5] have been taken with the *sample* on the cantilever. Understanding the large and unwanted direct coupling between the magnet and various time dependent, applied fields is a major concern in developing an instrument with the magnet on the oscillator. All processes which cause $\mathscr{M}_z$ to vary at f_c will appear as MRFM signal. We have observed such a large nonresonance signal in the YIG MRFM experiment: as we discuss below it arises from domain wall motion in response to time varying fields.

The MRFM setup was as previously described.[5,6] A small (approximately 20 $\mu\text{m} \times 40\ \mu$m, not exactly rectangular) YIG film 3 μm thick was mounted on the cantilever with the 20 μm dimension aligned parallel to the bias field and field gradient. The resonance frequency f_c and Q-value of the loaded cantilever at ambient pressure (where the MRFM experiment was performed) were 5.26 kHz and 41, respectively. Anharmonic modulation,[7] i.e., modulation of both the bias field H and the rf field H_1 at two frequencies whose difference (or sum) equals f_c, was used to generate the time varying force on the cantilever at f_c. In this experiment, H_1 ($\sim$2 G) was 100% amplitude modulated at a frequency f_1 of 41.27 kHz, and H was modulated at a frequency $f_B = 36.01$ kHz with an amplitude of $H_B^m = 4.1$ G. In the experiments we report here the frequency of the applied rf field H_1 varied between 700 and 1000 MHz.

A typical spectrum is shown in Fig. 1. The measurements were performed at ambient pressure to avoid producing excessively *large* oscillation amplitudes. The signal to noise ratio[2,3] S/N can be improved dramatically (S/N

[a)]Author to whom correspondence should be addressed. Electronic mail: pch@rayleigh.lanl.gov

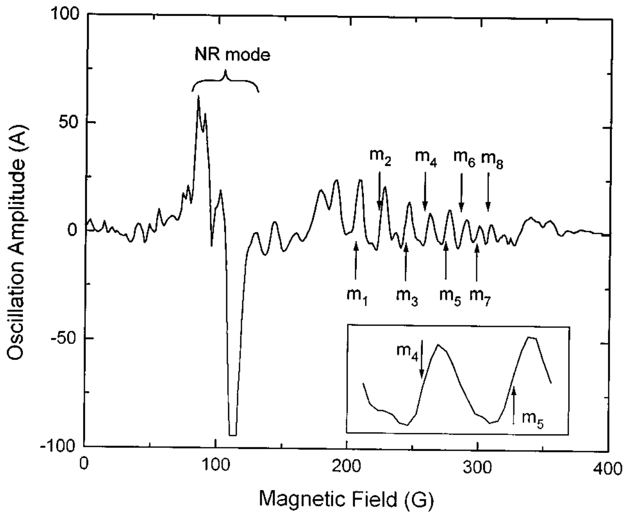

FIG. 1. An experimental MRFM spectrum of a single crystal YIG film which shows the nonresonance (NR) mode and a family of magneto-static modes (labeled as m_1, m_2, . . .). The centers of these magneto-static modes are indicated by the arrows as shown in the inset. The rf frequency is 825 MHz and the rf power, which corresponds to a field of 2 G, is 100% amplitude modulated at 41.27 kHz. The bias field is ramped at 1.5 G/s and modulated with a frequency of 36.01 kHz and an amplitude of 4 G.

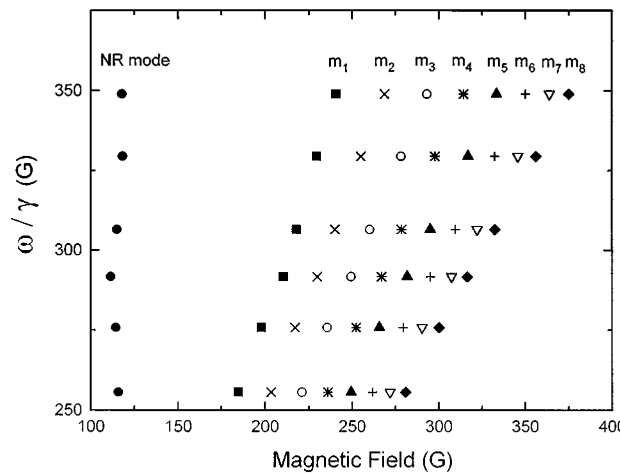

FIG. 2. The center fields of the MRFM signals (both the NR mode and the magneto-static modes) at various rf frequencies (given in units of $2\pi f_{rf}/\gamma$, where $\gamma/2\pi = 2.83$ MHz/G for YIG).

$\propto \sqrt{Q}$) by reducing the pressure which increases the Q of the present cantilevers by three orders of magnitude thus providing the sensitivity to detect the signal from much smaller sample volumes. The strongest signal was observed at a field of $\sim$110 G with an extremely asymmetrical derivative lineshape. The out-of-phase MRFM spectrum also showed a large signal at this field value. The value of the magnetic field at which this signal was observed is independent of the rf frequency, indicating that this mode is not related to the resonance behavior of the spins in the YIG sample. Direct evidence that this is a nonresonant behavior is obtained from the fact that this mode is observed in the absence of any rf field, when the bias field is modulated at $f_c/2$ (using half frequency modulation[3]).

On the high field side of this mode, we observe a family of resonance modes (at least 8) whose elements we label m_1, m_2, . . . (Fig. 1). The field separation between adjacent modes is about 10 to 20 G and decreases with increasing mode number. With increasing rf frequency, the entire family of modes moves to higher field, away from the nonresonance (NR) mode, as shown in Fig. 2. In addition, the field separations between the resonance modes increases at higher rf frequencies.

The field gradient at the YIG sample is $\sim$0.5 G/μm, corresponding to a $\sim$10 G difference across the film. This is much less than the field range ($\sim$100 G) spanned by the magneto-static modes. Thus the field gradient is insufficient to distinguish various regions of the sample and the observed modes are related to the resonance behavior of the entire YIG film.

The MRFM experiment is sensitive to any variation in the component of the magnetic moment parallel to the field gradient, regardless of whether this occurs as a consequence of resonant coupling of the rf excitation to the spins in the x-y plane (resonance modes) or through the change of the orientation of the sample magnetization due to variations in the bias field (NR modes). The latter occurs when the value of the applied field is close to but less than the value necessary to saturate the sample magnetization. Figure 3 shows the internal demagnetization field $H_d(0,0,z)$ of a $40\times 20\times 3\ \mu\text{m}^3$ rectangular YIG sample experiencing applied fields of various magnitudes oriented parallel to the z-axis (the 20μm-axis). An applied field $H > 2\pi M_s = 880$ G (where $M_s = 140$ emu/cm^3 is the saturation magnetization of YIG) is required to fully saturate the film (curve (a)). Since all of the modes shown in Fig. 1 occur below 400 G, the YIG sample is far from saturation. Accordingly, we are interested in $|H_{d,\hat{z}}(0,0,z)|$ in an applied field $H^{(b)}$ insufficient to saturate the film (i.e. $H < 2\pi M_s$); curve (b) in Fig. 3 is a schematic drawing of $|H_{d,\hat{z}}(0,0,z)|$ under these conditions. The magnetization will only be saturated in the region of the sample where $H^{(b)} > |H_{d,\hat{z}}|$, thus only in the region $|z| < z_s$. Outside this region, the domains will rearrange themselves in such a way that, to first order, the de-

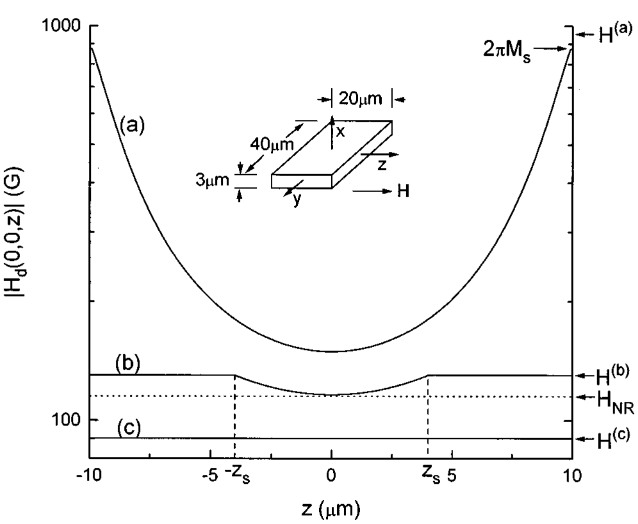

FIG. 3. An illustration of the internal demagnetization field $|H_{d\hat{z}}|$ as a function of position along the z-axis when the film is (a) fully saturated at $H^{(a)}$ (exact calculation); (b) partially saturated at $H^{(b)}$; (c) fully unsaturated at $H^{(c)}$. The bias field is parallel to the z-axis and the sample dimensions are as shown in the inset.

magnetization field cancels the applied field. Since the magnetized moment of the sample is smaller in this case, $|H_{d,\hat{z}}(0,0,z)|$ in the saturated region (i.e. $|z|\leqslant z_s$) is smaller than that in curve (a). Further decrease of the applied field will diminish the saturated region until it disappears when the applied field is below a critical value H_{NR} as shown in Fig. 3. Because $\partial H_{d,\hat{z}}/\partial z=0$ at the center of the sample, a small field modulation around H_{NR} will cause a substantial change in the saturated volume of the sample, and thus create a large variation in the magnetized moment along the applied field orientation. The observed field value of the NR mode $H_{NR}\simeq 110$ G agrees well with our estimates of the minimum field necessary to saturate the center of the sample.

We turn now to the resonance modes we observe. These are magneto-static modes first calculated by Damon and Eshbach[8] (DE) for an infinite thin film system. The application of DE theory in our case is complicated by the small size and irregular shape of our sample. As is observed in conventional FMR experiments on large area films[9] (which are well described by DE theory) we find that the higher order modes (indicated by decreasing mode intensity) correspond to higher fields. These modes correspond to discrete standing wave vectors k_z (where $\vec{z}\|\vec{B}$) which describe the spatial variation of the phase and amplitude of the precessing electron spin magnetization. Using DE theory, we estimate that the field separation between the first and the third k_z modes (the second k_z mode does not couple to the rf field) is 25 G, close to the 20 G shown in Fig. 2. This separation varies with rf frequency supporting the argument that the film is not fully saturated at resonance. In contrast to DE's prediction, we find that the magneto-static modes are not equally separated (Fig. 2); this is a consequence of the irregular shape of our sample.

In conclusion, extremely strong FMR signals were observed from a microscopic sample of single crystal YIG film using MRFM. This indicates that MRFM has the potential to study a large variety of magnetic materials with very high sensitivity. By increasing the field gradient associated with the probe magnet, we expect it will be possible to conduct microscopic FMR experiments with micron or sub-micron resolution. By applying the bias field in the film plane, we were able to separate the magneto-static modes from the nonresonance mode. The behavior of the magneto-static modes can be qualitatively understood using DE theory. The NR mode arises from the changes in the component of the spin magnetization oriented parallel to the bias field. This will be a source of substantial ''noise'' in MRFM spectra obtained with the magnet located on the cantilever. Thus, in order to achieve satisfactory results in MRFM experiments employing this geometry, it will be necessary to carefully align the magnet with respect to the applied field to ensure that the NR mode does not occur in the field range to be studied.

One of us (Z.Z.) acknowledges the support of the Center for Nonlinear Studies at Los Alamos National Laboratory. Work at Los Alamos performed under the auspices of the United States Department of Energy.

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