Ferromagnetic resonance detection with a torsion-mode atomic-force microscope

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We have developed a ferromagnetic resonance (FMR) instrument based on a torsion-mode atomic-force microscope (AFM). The instrument measures the torque on a magnetized thin film in a static out-of-plane field perpendicular to the film surface. The magnetic film is deposited onto an AFM microcantilever. FMR measurements are performed at a fixed microwave frequency of 9.15 GHz with a sweeping in-plane field. At the FMR condition, the change in the average in-plane magnetization of the film is at a maximum corresponding to a maximum change in the torque on the AFM cantilever. Our instrument is capable of measuring fluctuations of in-plane magnetization of 63.3 A/m of NiFe film samples with a total volume of 1.1×10^{-10} cm^3. Given a signal-to-noise ratio of 40, we estimate a magnetic moment sensitivity of 1.7×10^{-16} A/m^2. [S0003-6951(00)04109-7]

Ferromagnetic resonance (FMR) is an important experimental method for characterizing magnetic materials. Magnetic quantities such as the Landé g factor, the FMR linewidth ΔH, the anisotropy field H_k, and the magnetization M, can be obtained from FMR measurements.[1] FMR instruments are relatively sensitive tools, but are not easily modified to obtain spatially resolved information on a microscopic scale.

Magnetic resonance-force microscopy[2] (MRFM) was developed to overcome these limitations by combining the principles of atomic-force microscopy (AFM) and of magnetic resonance imaging (MRI). The first results were obtained by using electron-spin resonance[3] (ESR) and nuclear magnetic resonance[4] (NMR) samples. These experiments have been performed in vacuum to improve instrument sensitivity for high-resolution imaging since the magnetic moments of ESR and NMR samples are relatively small. MRFM with FMR samples, on the other hand, can be performed under ambient conditions due to the much larger magnetic moments of microscopic ferromagnetic samples.

In this letter, we present a method for FMR spectroscopy with a torsion-mode atomic-force microscope. This method is fundamentally different from MRFM with FMR samples that use deflection-mode AFM to measure magnetic forces versus magnetic torques,[5,6] as is the case described here. A substantial gain in torque sensitivity is obtained by integrating a micrometer-sized sample directly with an AFM cantilever and by operating at its torsional resonance frequency. In addition, it is possible to apply large torque fields and, thus, generate large torque signals in our experiment due to fact that magnetization is kept in the plane of the sample by its shape anisotropy.

Our AFM head is equipped with a laser-beam-bounce detection scheme[7] having a four-quadrant-diode detector array. This allows for measuring both torsion and deflection of a micromachined cantilever. The head of the AFM is nonmagnetic and fits into an electromagnet providing the in-plane sweep field H_0 up to 1.2 T. Figure 1 shows the experimental configuration. The microwaves are coupled into the microstrip resonator from an adjacent microstripline through a gap 30 μm wide. The resonator was fabricated using photolithography on a commercially available epoxy–ceramic substrate with a dielectric constant of 9.7. The resonator is 6 mm long and 0.5 mm wide, and has a resonant frequency of 9.15 GHz. Experiments are performed in air.

An oscillator signal adjusted to match the torsional resonance frequency f_T of the cantilever is used to modulate the amplitude of the microwave (RF) field H_1 and is also used as the reference for the lock-in amplifier. We modulate the RF field with a square pulse having a $\frac{1}{2}$-on/off duty cycle. We observe a maximum in the signal-to-noise ratio (SNR) at the $\frac{1}{4}$ duty cycle. At higher duty cycles we believe that thermal heating can dominate the torque signal. A SmCo permanent magnet close to the cantilever provides the necessary torque field H_T. The cantilever's torque signal is input to a lock-in amplifier with a time constant of 200 ms. One side of each of the cantilevers was coated with 30-nm-thick thermally evaporated nickel–iron (NiFe) films. In addition, the cantilevers were shadow masked so that only 50–70 μm of the ends were coated with NiFe. The cantilevers had dimensions of length $l=449\,\mu$m, width $w=49\,\mu$m, and thickness $t=2.5\,\mu$m.

Figure 1 shows the orientation of the cantilever versus the torque field H_T, sweep field H_0, and the RF field H_1. The NiFe films are saturated by the sweep field H_0 in the plane of the film and perpendicular to the axis of the cantilever. The microwave field H_1 has the proper orientation perpendicular to H_0 necessary for FMR. The contributions to the torque signal depend on the local angle that H_1 makes with the plane of the film as well as the local magnitude of H_1 as a function of position along the cantilever. The cantilever is tilted at 14° to accommodate the laser-beam-bounce detection system.

The torque resulting from the FMR experiment is $T_{\mathrm{FMR}}=\mu_0\Delta M_z H_T V_{\mathrm{film}}$, where ΔM_z is the change in the magnetization due to the FMR precession, V_{film} is the total mag-

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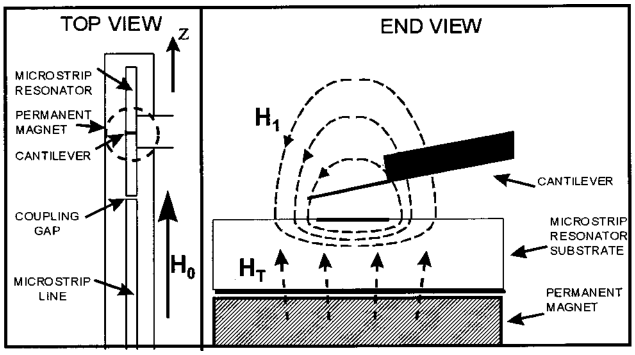

FIG. 1. Experimental configuration. The NiFe-coated cantilever is positioned above the microstrip resonator that provides the microwave field H_1. A permanent SmCo magnet provides the static torque field H_T. The in-plane sweep field H_0 is generated by an electromagnet (not visible in the figure).

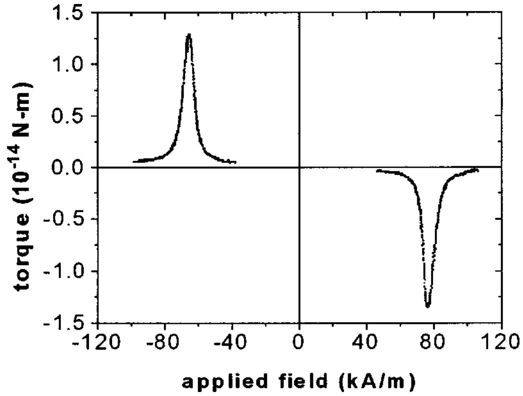

FIG. 2. Cantilever torque response vs sweep field H_0 for a NiFe film. The peak positions depend on the sign of H_0 (−65.7 kA/m vs 77.1 kA/m) shifted due to the local in-plane field from the permanent magnet.

netic volume, and H_T is the torque field. The magnetization of the NiFe film is kept in the plane of the film due to the demagnetization field and the sweep field H_0, which is also in the plane. (H_T is always perpendicular to ΔM_z, and the NiFe film is always saturated; $H_0 > H_c$.) We can define a limit for the applied torque field H_T as the field strength at which the in-the-plane magnetization will be rotated by 5° into the out-of-plane orientation. For H_T below this limit, we estimate that the in-plane magnetic moment is within 1% of its true value. The in-plane and out-of-plane anisotropy fields for the given ferromagnetic material determines this field strength. We find that for polycrystalline NiFe films thicker than 10 nm, shape anisotropy dominates and out-of-plane fields on the order of 700 kA/m are necessary to rotate the magnetization 5° out of plane. Note that the measured saturation magnetization of our film is 732 kA/m and we would expect the magnetization to substantially rotate out of plane for fields above 700 kA/m.

We can compute the torque from the geometrical parameters of the microcantilever, based on our estimate of the torsion angle ϕ. For a beam with uniform torque applied along its axis, and with $t \ll w$,[8]

$$\phi = \frac{6(1+n)l}{E(wt^3)} * T_G. \tag{1}$$

Here, E is Young's modulus ($E = 1.3\times 10^{11}\ \mathrm{N/m^2}$); n is Poisson's ratio ($n = 0.28$); and l, w, and t are the length, width, and thickness of the microlever, respectively. The torsion angle ϕ can be estimated from our AFM detector sensitivity of 7.66×10^{-4} rad/V.

The cantilever torque as a function of applied bias field H_0 is shown in Fig. 2. Here, the input power to the resonator was 75 mW. About 68 μm of the cantilever was coated with a NiFe film 30 nm thick, which corresponds to a total magnetic volume of $1.1\times 10^{-10}\ \mathrm{cm^3}$. Prior to the FMR measurements, we swept the frequency of the ac current in a small torque coil that was put in place of the SmCo magnet in order to find the torsional resonance frequency f_T of the cantilever. The torsional frequency f_T was 250.3 kHz.

Figure 2 shows that changing the direction of the sweep field by 180° reverses the sign of the torque signal. This is expected, since the magnetization of the film changes by 180°, but the torque field H_T remains the same. The absolute magnitudes of the peaks are close (1.29×10^{-14} N m vs 1.38×10^{-14} N m) for both orientations of the sweep field, and the full widths at half maximum (FWHM) are also in good agreement (7.8 kA/m vs 7.5 kA/m). However, the absolute values of the peak positions are different (65.7 kA/m vs 77.1 kA/m). The shift of the peak position can be explained by a local in-plane component of the torque field H_T of the SmCo magnet. An in-plane component would give rise to a local additional magnetic field in the direction of the sweep field H_0, therefore, shifting the FMR peak positions.

The shift in the FMR peak positions can be used to determine the value of the local magnetic field at the end of the cantilever, since the correct peak position of 77.4 kA/m is known from calorimetric FMR measurements on the same sample in the same instrument with the SmCo magnet removed.[9] We have already demonstrated magnetic-field mapping with an ESR sample in a previous paper.[10] In the present configuration, we should be able to perform spatially resolved FMR field maps as well.

To demonstrate the gain in sensitivity by operating at the torsional resonance frequency of the cantilever, we have obtained the peak heights from Lorentzian fits for measurements at different oscillator frequencies. Figure 3 shows the torque response of the cantilever as a function of oscillator frequency. The error bars represent the σ of the data. Note that the input power to the microstrip resonator was decreased from 75 mW (Fig. 2) to 25 mW (Fig. 3). The torsional resonance frequency was 250.3 kHz and the FWHM

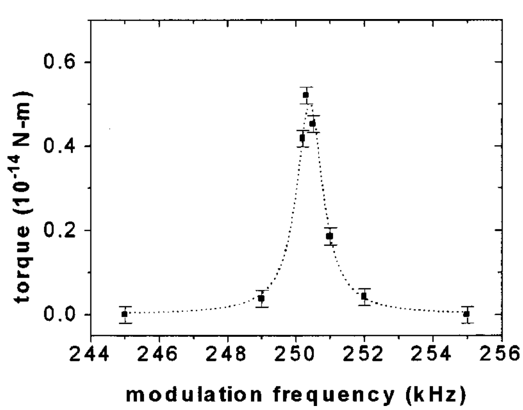

FIG. 3. Cantilever torque response vs modulation frequency at FMR. The increase in SNR is fitted to the Lorentzian (dotted line).

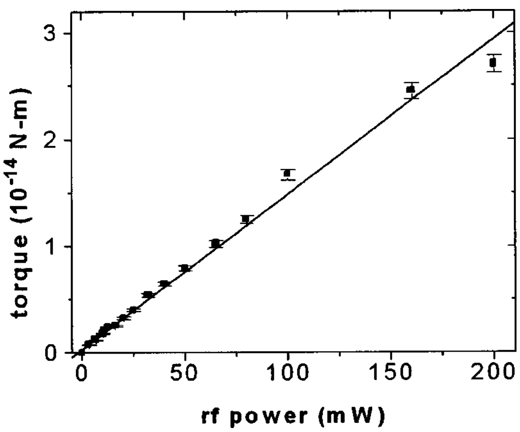

FIG. 4. Cantilever torque response vs input power to the microstrip resonator.

was 0.9 kHz based on a Lorentzian fit, corresponding to mechanical quality factor Q of 278. Theoretically, the SNR should be increased by approximately $Q^{1/2}$ or by a factor of 16.7. This is in good agreement with our experimental results, which showed improvement by a factor of 16.

Figure 4 shows the dependence of the FMR torque signal on microwave power. The torque increases linearly with microwave power. We could not observe a change in the linear dependence due to saturation for a microwave input power up to 75 mW. Above 75 mW, the data points deviate slightly from the linear fit, but we believe this does not indicate saturation effects, since the FMR linewidth does not increase above 50 mW. The FMR linewidth ΔH was 9.6 kA/m for microwave power levels from 3.2 to 40 mW, whereas for microwave power levels from 50 to 200 mW, the linewidth was 10.4 kA/m. This small change in the linewidth indicates that there is no significant heating from the microwave field in our experiment.

A linear dependence of the torque corresponds to a nonlinear dependence of the magnetization, since $\langle \Delta M_z \rangle = 1/4\, M_s \alpha^2$ for small FMR tilt angles α away from the z axis in the plane of the film.

For thin magnetic films, the time average of the z component of the magnetization M_z at resonance is[11,12]

$$\langle M_z \rangle = \left\langle \sqrt{M_s^2 - |m_{\rm in}^2(t)| - |m_{\rm out}^2(t)|} \right\rangle \approx M_s - \left\langle \frac{|m_{\rm in}^2(t)| + |m_{\rm out}^2(t)|}{2M_s} \right\rangle, \tag{2}$$

where M_s is the saturation magnetization, $m_{\rm in}$ is the in-plane component of the dynamic magnetization, and $m_{\rm out}$ is the out-of-plane component of the dynamic magnetization. $\langle \Delta M_z \rangle$ is given by

$$\langle \Delta M_z \rangle = \frac{|m_{\rm in}^2|}{4M_s} \left(1 + \left| \frac{m_{\rm out}}{m_{\rm in}} \right|^2 \right). \tag{3}$$

For thin magnetic films, we can neglect the second term of Eq. (2) given that

$$\left| \frac{m_{\rm out}}{m_{\rm in}} \right| = \frac{H_0}{H_0 + M_s}, \tag{4}$$

and the in-plane bias field $H_0 \ll M_s$.

The dependence of ΔM_z on H_1 can be obtained from the imaginary part of the FMR susceptibility χ''. At resonance, $m_{\rm in}$ can be calculated by $|m_{\rm in}| \cong H_1 \chi'' = H_1\, 2M_s/\Delta H$, and, therefore, the ΔM_z is given by $\langle \Delta M_z \rangle = H_1^2\, M_s/(\Delta H)^2$.

With the relations above, we can perform a self-consistency calculation. The torque as determined from geometrical parameters T_G [see Eq. (1)] was 1.8×10^{-15} N m. The torque $T_{\rm FMR}$ as calculated from our FMR parameters was 1.3×10^{-15} N m, with $M_s = 732$ kA/m, $H_T = 144$ kA/m, $H_1 = 53$ A/m (based on our estimate for a microwave input power of 10 mW), and the linewidth $\Delta H = 5.7$ kA/m (based on tuned-cavity FMR measurements of similar samples). The torque values as determined from geometrical parameters and from FMR parameters are in agreement. The differences between the two calculations for torque are well within the uncertainties associated (a) with our assumptions for calculating ΔM_z, (b) our estimate of ΔH from a tuned-cavity FMR spectrometer measurement performed on a similar NiFe film, and (c) our estimate of H_1 that is sensitive to the precise positioning of the cantilever relative to the microstrip resonator.

In conclusion, we have demonstrated FMR detection with a torsion-mode AFM. A large out-of-plane torque field can be used to significantly enhance the torque signal on thin-film samples with large-shape anisotropy energy. In addition, by modulating the microwave field at the torsional resonance frequency of the cantilever, we obtained an increase by a factor of 16 in the SNR at ambient conditions. Future experiments will explore the ultimate limit of the number of spins that are necessary to provide a measurable torque signal.

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