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 $1.1 \times 10^{-10}$ cm$^3$. Given a signal-to-noise ratio of 40, we estimate a magnetic moment sensitivity of $1.7 \times 10^{-16}$ A/m$^2$.

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

Magnetic resonance-force microscopy (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 (ESR) and nuclear magnetic resonance (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, 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 the 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 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 non-magnetic 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 $\mu$m 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 1/2 on/off duty cycle. We observe a maximum in the signal-to-noise ratio (SNR) at the 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 $\mu$m 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 $T_{FMR} = \mu_0 \Delta M \cdot H_T \cdot V_{film}$, where $\Delta M$ is the change in the magnetization due to the FMR precession, $V_{film}$ is the total mag-

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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 $\Delta M_z$, 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 $5^\circ$ 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 $5^\circ$ 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 $\phi$. For a beam with uniform torque applied along its axis, and with $t \ll w, l$,

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

Here, $E$ is Young’s modulus ($E = 1.3 \times 10^{11}$ N/m²); $n$ 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 $\phi$ can be estimated from our AFM detector sensitivity of $7.66 \times 10^{-4}$ 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 $\mu$m of the cantilever was coated with a NiFe film 30 nm thick, which corresponds to a total magnetic volume of $1.1 \times 10^{-10}$ cm³. 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 $180^\circ$ reverses the sign of the torque signal. This is expected, since the magnetization of the film changes by $180^\circ$, but the torque field $H_T$ remains the same. The absolute magnitudes of the peaks are close ($1.29 \times 10^{-14}$ Nm vs $1.38 \times 10^{-14}$ Nm) 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 $\sigma$ 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...
The dependence of $\Delta M_z$ on $H_1$ can be obtained from the imaginary part of the FMR susceptibility $\chi''$. At resonance, $m_{in}$ can be calculated by $|m_{in}|=H_1\chi''=H_1/2M_s/\Delta H$, and, therefore, the $\Delta M_z$ is given by $\langle \Delta M_z \rangle=H_1^2M_s/(\Delta H)^2$.

With the relations above, we can perform a self-consistency calculation. The torque as determined from geometrical parameters $T_G$ [see Eq. (1)] was $1.8 \times 10^{-15}$ N m. The torque $T_{\text{FMR}}$ as calculated from our FMR parameters was $1.3 \times 10^{-15}$ N m, with $M_s=732$ kA/m, $H_r=144$ 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 $\Delta M_z$, (b) our estimate of $\Delta H$ 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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A linear dependence of the torque corresponds to a non-linear dependence of the magnetization, since $\langle \Delta M_z \rangle=1/4 M_s \alpha^2$ for small FMR tilt angles $\alpha$ 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$^{11,12}$

$$\langle M_z \rangle = \langle \sqrt{\langle M_z^2 \rangle - \langle M_z^4 \rangle} \rangle = M_s - \left( \frac{m_{\text{in}}^2(t) + m_{\text{out}}^2(t)}{2M_s} \right),$$

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

$$\langle \Delta M_z \rangle = \frac{m_{\text{in}}^2}{4M_s} + \frac{|m_{\text{out}}|^2}{m_{\text{in}}^2}. \quad (3)$$

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

$$\frac{m_{\text{out}}}{m_{\text{in}}} = \frac{H_0}{H_0 + M_s}, \quad (4)$$

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

9. In this experiment, a micromechanical calorimeter sensor is used to detect FMR of thin magnetic films. The calorimetric sensor is a silicon AFM cantilever coated with a thin magnetic film onto one side. The cantilever bends at resonance, due to thermal absorption of the microwave power.