Einstein–de Haas effect in a NiFe film deposited on a microcantilever

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(Received 31 May 2006; accepted 27 July 2006; published online 18 September 2006)

A method is presented for determining the magnetomechanical ratio g' in a thin ferromagnetic film deposited on a microcantilever via measurement of the Einstein–de Haas effect. An alternating magnetic field applied in the plane of the cantilever and perpendicular to its length induces bending oscillations of the cantilever that are measured with a fiber optic interferometer. Measurement of g' provides complementary information about the g factor in ferromagnetic films that is not directly available from other characterization techniques. For a 50 nm $Ni_{80}Fe_{20}$ film deposited on a silicon nitride cantilever, g' is measured to be 1.83 ± 0.10.
[DOI: 10.1063/1.2355445]

An understanding of magnetization dynamics is necessary for the development and optimization of materials for spin electronics and magnetic data storage. Several tools that operate in the microwave regime, such as pulsed inductive microwave magnetometry[1] (PIMM), have been developed for quantitative characterization of magnetization dynamics in thin films. Frequency data from PIMM (Refs. 2 and 3) and other resonant techniques[4,5] are fit to the Kittel equation[6] with the g factor and components of the effective field as fitting parameters. It is highly desirable to find an independent method for determining the g factor. Ideally, such an independent method will not involve microwave radiation, as nonresonant interactions of microwaves with the system may distort results, particularly in multilayers. This letter describes a method for indirectly measuring the g factor by first obtaining the magnetomechanical ratio g' from gyromagnetic experiments.

Gyromagnetic effects in macroscopic bodies were observed in the early decades of the previous century[7] and fall into two categories: the Barnett effect[8] (magnetization induced by rotation) and the Einstein–de Haas effect[9] (rotation induced by change in magnetization). More recently, phenomena reminiscent of the Einstein–de Haas effect have been observed in Bose-Einstein condensates[10] and the Einstein–de Haas effect has been suggested as the mechanism for induced rotation of soft magnetic amorphous wires.[11] In the original experiment by Einstein and de Haas, the rotation of a macroscopic iron cylinder suspended by a glass wire was induced by applying an alternating magnetic field along the central axis of the cylinder.[9] Here, we present a method for measuring the Einstein–de Haas effect in a microscale system: a 50 nm NiFe film deposited on a microcantilever. In describing gyromagnetic effects, the magnetomechanical ratio g' is defined as

$$g' = \frac{2m_e}{e}\frac{\mu}{J_{\mathrm{tot}}}, \tag{1}$$

where m_e is the electron rest mass, e is the electron charge, μ is the magnetic moment, and J_{tot} is the total angular momentum. Note that Eq. (1) differs from the definition of the g factor associated with ferromagnetic resonance in that the term J_{tot} in Eq. (1) includes contributions from both the spin and orbital angular momenta while the analogous angular momentum term in the definition of the g factor includes only the spin angular momentum.[12] It can be shown that

$$2 - g' = g - 2, \tag{2}$$

if only the first order effect of the spin-orbit interaction is considered.[12,13] Even when Eq. (2) does not strictly hold, determination of g' provides complementary information about magnetization dynamics in the film.

The definition of the magnetomechanical ratio reflects the fact that changes in magnetic moment μ are accompanied by changes in angular momentum J_{tot}. In order to conserve angular momentum, changes in J_{tot} are compensated by changes in the angular momentum of the macroscopic magnetized body. Here, the in-plane magnetic moment of a NiFe film deposited on a microcantilever is driven by an alternating magnetic field that is in the plane of the film and perpendicular to the length of the microcantilever. The resulting torque bends the cantilever and has a maximum magnitude of

$$T_0 = \frac{2m_e\omega}{eg'}\Delta\mu, \tag{3}$$

where ω is the driving frequency of the alternating magnetic field and $\Delta\mu$ is the change in the magnetic moment of the film.

Following Ref. 14, the torque in Eq. (3) acting along the entire length of the cantilever beam is modeled as a forced, damped harmonic oscillator, with an equivalent force acting on an effective point mass at the free end of the rectangular cantilever beam. The amplitude z_0 of the resulting cantilever deflection is

$$z_0 = \frac{F_0/m_{\mathrm{mod}}\omega}{\sqrt{(\omega_0^2 - \omega^2)^2/\omega^2 + \omega_0^2/Q^2}}, \tag{4}$$

where

$$F_0 = \frac{4m_e}{l_c e g'}\Delta\mu\omega, \tag{5}$$

m_{mod} is the modal mass of the beam, $\omega_0 = 2\pi f_0$ is the resonant frequency of the beam, Q is the quality factor, and l_c is the length of the cantilever. For a rectangular beam cantilever, the modal mass is 0.24 times the mass of the canti-

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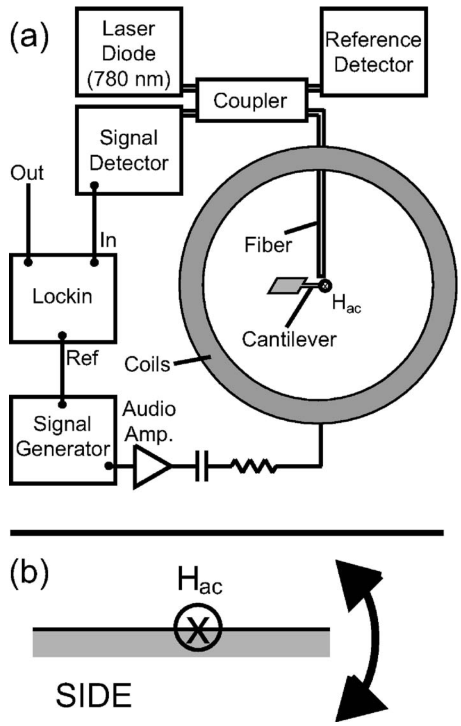

FIG. 1. (a) Apparatus for measurement of the Einstein–de Haas effect in a ferromagnetic film deposited on a microcantilever. (b) Side view of cantilever. The alternating magnetic field (H_{ac}) goes in and out of the page, as drawn. The resulting bending motion is indicated by black arrows.

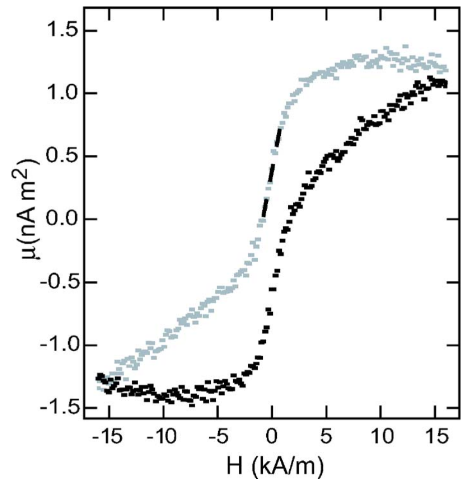

FIG. 2. Alternating gradient magnetometry of the film is shown. Black points correspond to the increasing field and gray points to the decreasing field. The dashed line is a linear fit to the region between −800 and 800 A/m and has a slope of $(4.57\pm0.21)\times10^{-13}$ m^3. Here, the linear fit is done on the curve corresponding to decreasing field; a linear fit to the increasing field (not shown) gives a consistent value of the slope.

lever, which we calculate from the nominal dimensions and density of the cantilever.[14,15]

Figure 1 shows a schematic of the measurement of the Einstein–de Haas effect in a NiFe film deposited on a microcantilever. Helmholtz coils were driven by a signal generator to produce the alternating magnetic field. A variable capacitor ($\sim$0.01 μF) was placed in series with the coils in order to produce a tank circuit with a tunable resonant frequency near the mechanical resonance of the cantilever (10–20 kHz). In order to maintain constant magnetic field amplitude during swept-frequency measurements, the magnetic field amplitude as a function of the frequency and amplitude of the current in the driving coil were calibrated with a pickup coil at the cantilever position. A 50 nm film of $Ni_{80}Fe_{20}$ was deposited onto a 200 μm $\times$ 20 μm $\times$ 600 nm commercial silicon nitride cantilever. The cantilever was positioned such that the tip was at the center axis of the coils. The deflection of the cantilever was measured by the use of a fiber optic interferometer with the end of the fiber positioned tens of micrometers above the tip of the cantilever. The output of the signal photodetector in the interferometer served as the input to a lock-in amplifier while the signal from the generator that drove the alternating field served as the reference for the lock-in detection. To reduce mechanical noise, the apparatus was mounted on an active vibration isolation stage. The temperature of the fiber chuck was regulated with a feedback loop in order to prevent drift of the fiber position due to thermal expansion of the chuck. To maximize sensitivity, the setpoint of the thermal feedback loop was chosen to coincide with the steepest portion of an interference fringe. All measurements were carried out under ambient pressure and temperature.

In order to determine $\Delta\mu$, the NiFe film was characterized by the use of an alternating gradient magnetometer (AGM) as shown in Fig. 2. The coercive field (about 2.5 kA/m) is not unusual for NiFe films of this size and shape deposited on cantilevers and reflects the shape anisotropy in the film. The linear fit to the region between −800 and 800 A/m shown in Fig. 2 corresponds to a susceptibility of 4.57×10^{-13} m^3. $\Delta\mu$ was determined by multiplying the susceptibility times the amplitude of the alternating magnetic field which is known from the pickup coil calibration. In this calculation, the initial ac susceptibility (up to 20 kHz) is approximated by the susceptibility measured with the AGM. Note that during the experiments, the magnetic moment of the film was not driven over the full hysteresis loop shown in Fig. 2, but rather over minor loops corresponding to alternating field amplitudes between 125 and 450 A/m.

Measurements of the root mean square (rms) cantilever deflection amplitude as a function of field frequency are shown in Fig. 3. The data were fit to Eq. (4), giving f_0=13 180 Hz, Q=24, and g'=1.82. Note that when a permanent magnet was used to saturate the in-plane magnetiza-

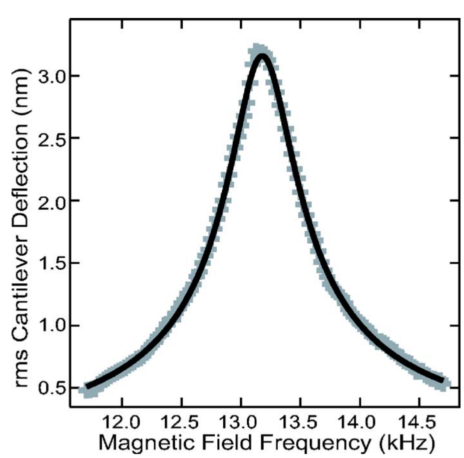

FIG. 3. Root mean square (rms) cantilever deflection is shown as a function of the frequency of the applied magnetic field [gray "plus" signs are measured data; solid black line is a fit of Eq. (4)]. The amplitude of the applied magnetic field (H) is 367 A/m, resulting in a change in magnetic moment of the film ($\Delta\mu$) of 0.335 ± 0.012 nA m^2.

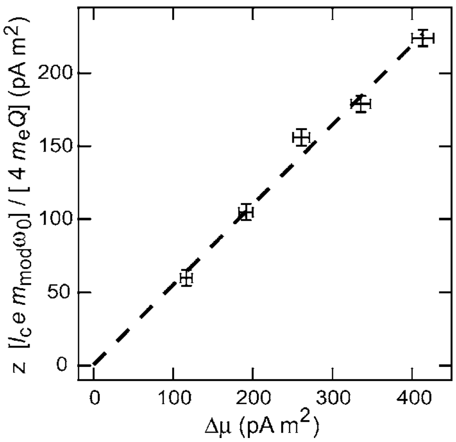

FIG. 4. Maximum rms deflection of the cantilever (i.e., deflection at mechanical resonance) is shown as a function of the change in the magnetic moment of the film. The vertical axis has been scaled so that the slope of a linear fit is $1/g'$. With $l_c=200\ \mu$m, $m_{mod}=1.86\times10^{-12}$ kg, $f_0=13\,180$ Hz, and $Q=24$, the fit gives $g'=1.83$.

tion, the effect disappeared as is expected when $\Delta\mu$ is zero. In order to obtain a more accurate value of g' and to estimate the uncertainty, additional measurements of the cantilever deflection were made for several different amplitudes of the driving field. Figure 4 shows the maximum cantilever deflection as a function of the change in magnetic moment. The linear fit shown in Fig. 4 (dashed line) corresponds to $g'=1.83\pm0.10$. By way of comparison, g' in bulk Permalloy is 1.91.[12]

The sources of this uncertainty in the measurement include: uncertainty in the measured change in the magnetic moment, lack of a direct measurement of the cantilever dimensions, and mass, as well as uncertainty in the measured cantilever deflection. The uncertainty in the measured deflection arises from changing distance between the fiber and the cantilever due to thermal drift. Although a thermal feedback loop is used to stabilize the position of the fiber, drift around the setpoint is still observed. Additionally, several potential sources of spurious signals exist, including bending of the cantilever due to magnetostriction in the film. However, the transverse magnetostriction constant is particularly small in $Ni_{80}Fe_{20}$ ($\lambda<10^{-6}$),[16,17] resulting in a deflection of the cantilever that is much less than observed here. Another potential source of spurious signal is the possibility that there will be a component of the magnetic moment of the film that is not parallel to the applied magnetic field, thus producing an additional torque. The absence of large background magnetic fields insured that the film's magnetization was in plane. Thus, to avoid this problem the cantilever was mounted on a goniometer and the orientation of the cantilever was adjusted so that the driving field was parallel to the magnetic moment of the film.

The experiments described here provide a proof of concept for the determination of g' in thin ferromagnetic films deposited on microcantilevers. In the future, this method may be improved in a number of ways. For example, the uncertainty in the magnetic moment may be reduced by integrating the film into a torsional oscillator and performing microcantilever torque magnetometry.[18] Also, uncertainty in the deflection may be reduced by operating the system in vacuum which will thermally isolate the fiber chuck and reduce thermal drift. Additionally, direct measurements of the cantilever dimensions and mass are desirable.

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