Angular momentum and energy transferred through ferromagnetic resonance

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We show that ferromagnetic resonance (FMR) selectively transfers angular momentum and energy from a microwave field to the lattice as measurable torque and heat. The expected torque and absorbed power are derived classically in terms of Landau–Lifshitz dynamics, including demagnetizing field effects. The torque is also described as a photon absorption process, in which the absorbed photons carry both energy and angular momentum. FMR data are shown for a thin NiFe film deposited on a micromechanical cantilever detector that measures both torque and heat under nearly identical conditions. [DOI: 10.1063/1.1361095]

We describe the transfer of both angular momentum and energy to the spin system when electromagnetic radiation drives magnetic resonance. Through damping of the spin precession, these quantities are transferred to the lattice, where the angular momentum manifests itself as a torque on the sample and the dissipation of energy results in heating of the sample. Both of these effects can be used as a means of detecting magnetic resonance.

The torque induced in electron paramagnetic resonance (EPR) was first measured using a quartz fiber torsional pendulum,[1–5] and more recently using micromechanical cantilevers.[6] Calorimetric techniques have been used to measure absorbed power in EPR,[7] nuclear magnetic resonance (NMR),[8] and ferromagnetic resonance (FMR).[9] FMR torque was considered in Ref. 10. However, the predictions have not been experimentally verified. Here, we report on the first measurement of the torque produced by the absorption of microwaves in FMR. Our measurements are based on a micromechanical detector that senses both the torque and the absorbed power, allowing a comparison of the two effects.

In their analysis of the EPR torque detected in the experiments described in Refs. 1–6, the authors assume that only σ^+ circularly polarized photons, matching the spin precession, are absorbed. Under this assumption, each absorbed photon contributes a quantum $\hbar\omega$ of energy and $\hbar$ of angular momentum, so that the absorbed power is directly related to the torque by $P=\omega T$. However, as we show here, in the presence of magnetic anisotropies, the elliptical precession of the magnetization allows absorption of different amounts of both σ^+ and σ^- circular polarizations. The corresponding transfers of $+\hbar$ and $-\hbar$ angular momenta to the sample partly cancel, whereas the energy contributions sum. Thus, in contrast to EPR and NMR experiments, in which the sample may be regarded as gyrotropic, the relation $P=\omega T$ does not hold for FMR experiments, where magnetic anisotropies can dominate the response.

Consider a magnetic material saturated by a uniform bias field H_0 directed along the z axis (see Fig. 1). The response of the magnetization to a perturbing field applied perpendicular to the bias field is described in terms of Polder's susceptibility tensor,

$$\begin{bmatrix} m_x \\ m_y \end{bmatrix} = \begin{bmatrix} \chi_{xx} & -i\kappa \\ i\kappa & \chi_{yy} \end{bmatrix} \begin{bmatrix} h_x \\ h_y \end{bmatrix}. \tag{1}$$

For sinusoidal excitation, this describes a rotating component of the magnetization in the $x-y$ plane. In the case of a dissipative medium, the susceptibilities χ and κ are complex, and result in a time lag between the microwave field h and the rotating magnetization m, shown schematically in Fig. 2. This lag implies both a dissipation of energy from the field and a torque due to the angle between the microwave field and the dynamic magnetization.

With the magnetic excitation restricted to the x direction (i.e., $h_y=0$), the dissipation is determined by the imaginary part of χ_{xx}, which produces the component of m directed parallel to, but temporally out of phase with, the driving field. For a sinusoidal excitation with angular frequency ω, the average power dissipated is

$$P=\tfrac{1}{2}\mu_0\omega\chi''_{xx}h_x^2V, \tag{2}$$

where $\mu_0=4\pi\times10^{-7}$ H/m is the permeability of free space, χ''_{xx} is the imaginary part of χ_{xx}, and V is the sample volume.

The off-diagonal elements in the susceptibility tensor indicate that, due to the precessional motion of the spins, a

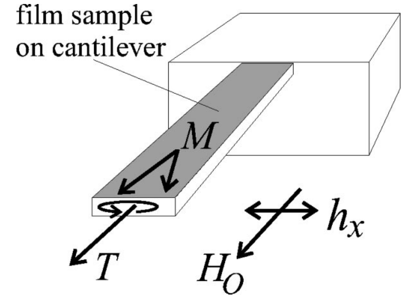

FIG. 1. Orientation of the bias field H_0 and microwave field h_x with respect to the cantilever. The magnetization of the film precesses in an elliptical orbit around H_0. Damping of this motion results in a torque vector T directed along the cantilever axis.

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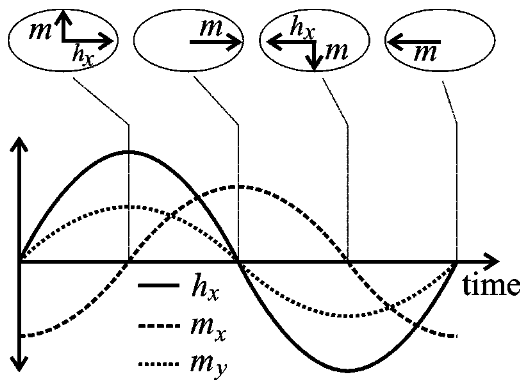

FIG. 2. Damping causes the precession of the magnetization m to lag the oscillating microwave magnetic field h_x. A component of m_x is out of phase with h_x, and results in absorption of energy from the microwave field. The component of m_y that is in phase with h_x is perpendicular to this field, and results in a torque. The case shown here is for a 90° lag, which occurs near resonance.

field in the x direction induces a magnetization in the perpendicular y direction. The component of m that is temporally in phase with, but perpendicular to, the driving field results in a torque $T=m\times h$ with an average value

$$T=\tfrac{1}{2}\mu_0\kappa'' h_x^2 V, \tag{3}$$

where κ'' is the imaginary part of κ. The torque acts along the z axis parallel to H_0. The elements of the susceptibility tensor can be calculated in terms of Landau–Lifshitz dynamics.[11] Assuming small precessional angles and neglecting eddy current effects,

$$\chi_{xx}=\frac{\omega_m(\omega_y+i\alpha\omega)}{\omega_x\omega_y-\omega^2+i\alpha\omega(\omega_x+\omega_y)}, \tag{4}$$

$$\kappa=\frac{-\omega_m\omega}{\omega_x\omega_y-\omega^2+i\alpha\omega(\omega_x+\omega_y)}, \tag{5}$$

where α is the Landau–Lifshitz damping parameter. The sample shape is accounted for by the demagnetizing factors $N_{x,y,z}$ using

$$\omega_m=\gamma M_s, \tag{6}$$

$$\omega_{x,y}=\gamma[H_0+M_s(N_{x,y}-N_z)]. \tag{7}$$

Here, M_s is the saturation magnetization and γ is the gyromagnetic constant. Effects of bulk and surface anisotropies may be incorporated in a similar fashion.[12] For a sample driven at resonance ($\omega^2=\omega_x\omega_y$) by an oscillating magnetic field in the x direction, Eqs. (2)–(5) reduce to

$$P_{\rm res}=\frac{\mu_0}{2}\,\frac{\omega_m\omega_y}{\alpha(\omega_x+\omega_y)}\,h_x^2V, \tag{8}$$

$$T_{\rm res}=\frac{\mu_0}{2}\,\frac{\omega_m}{\alpha(\omega_x+\omega_y)}\,h_x^2V. \tag{9}$$

Thus, when shape anisotropy is considered, the relationship between the absorbed power and torque becomes

$$P_{\rm res}=\omega_y T_{\rm res}=\omega_{\rm res}\sqrt{\omega_y/\omega_x}\,T_{\rm res}, \tag{10}$$

rather than $P_{\rm res}=\omega_{\rm res}T_{\rm res}$, as indicated for gyrotropic ($\omega_x=\omega_y$) media. The excess factor $\sqrt{\omega_y/\omega_x}$ is the ellipticity of the spin precession under the influence of the demagnetizing fields. For a thin film oriented in the x–z plane ($N_x=N_z=0$, $N_y=1$), this can be written as

$$P_{\rm res}=\omega_{\rm res}\sqrt{1+M_s/H_0}\,T_{\rm res}. \tag{11}$$

The normal modes which diagonalize the susceptibility tensor in Eq. (1) are elliptically polarized,[13] with $h_y=\pm i\sqrt{\omega_y/\omega_x}h_x$. Near resonance, absorption of the elliptical mode with circulation direction matching the precession is dominant. Thus, stimulation of FMR in a sample with anisotropy is characterized by the absorption of elliptically polarized radiation consisting of both, σ^+ and σ^- photons. For the ellipticity given previously, the ratio of σ^+ to σ^- photons is

$$\frac{n^+}{n^-}=\frac{\sqrt{\omega_y/\omega_x}+1}{\sqrt{\omega_y/\omega_x}-1}. \tag{12}$$

The absorbed radiation carries an average angular momentum per photon of

$$\frac{n^+\hbar-n^-\hbar}{n^++n^-}=\frac{\hbar}{\sqrt{\omega_y/\omega_x}}, \tag{13}$$

and an energy of $\hbar\omega$ per photon. This is consistent with Eq. (10).

In the steady state, the torque on the magnetic moments is balanced by the torque induced on the lattice through the damping mechanisms, and the average power absorbed by the spin system is transferred to the lattice as heat. We measure both the absorbed energy and torque in the same apparatus.[9,14,15] The detection is based on the mechanical response of a micromachined Si cantilever, 450 μm in length, 50 μm wide, and 2.5 μm thick. A magnetic thin film is deposited onto one side of the cantilever by thermal evaporation. The cantilever is mounted approximately 50 μm above the center of a 500 μm wide microstrip resonator driven at 9.15 GHz. The current in the stripline produces an oscillating magnetic field transverse to the cantilever, and in the plane of the film. The bias field H_0 is oriented parallel to the cantilever, so that the FMR precession and resultant torque act about the axis of the cantilever. Note that the source of this torque and the direction with respect to the fields is different from that measured in Ref. 15.

Due to the different thermal expansion coefficients of the specimen and cantilever, the combination also functions as a bimaterial calorimeter. The absorbed power results in a deflection of the cantilever tip. Both the deflection and torsion of the cantilever are measured using a laser beam reflected from the surface of the cantilever onto a four-quadrant photodiode detector. The microwave source is amplitude modulated to obtain an oscillating mechanical response of the cantilever. The response is detected by means of a lock-in amplifier synchronized with the modulating signal.

For calorimetric detection, the microwave source was pulse modulated at 1 kHz. The thermal response time of the cantilever is about 1 ms. At higher modulation frequencies, the calorimetry signal is strongly attenuated. For torque measurements, the modulation frequency is matched to the torsional resonant frequency of the cantilever (~250 kHz). The quality factor of the torsional resonance mode is approxi-

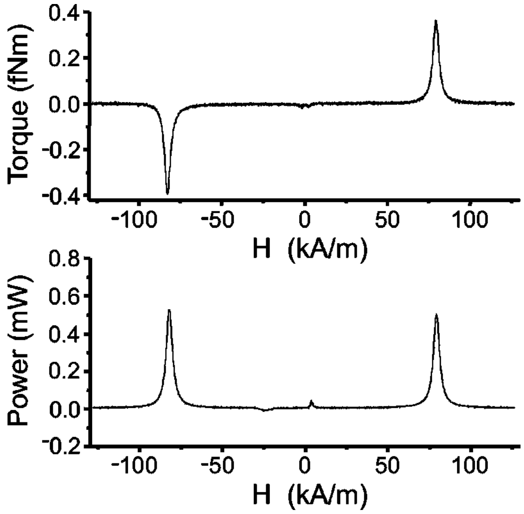

FIG. 3. Torque and absorbed power as a function of bias field at a fixed microwave frequency of 9.15 GHz. The top plot is the signal measured from the torsion of the cantilever. The sign of the torque reverses for opposite directions of the bias field. The bottom plot is the signal measured from the deflection of the cantilever.

mately 250, giving rise to a substantial gain in torque sensitivity. Experiments were performed in air at room temperature.

Figure 3 shows the FMR resonance spectra as a function of the bias field for a 30-nm-thick $Ni_{0.8}Fe_{0.2}$ film. For this sample, we expect surface and bulk anisotropies to be insignificant compared to the shape anisotropy. The upper graph shows the torque on the sample as determined from the cantilever torsion. Note that when the bias field is reversed, the torque acts in the opposite direction. The clockwise (or counterclockwise) precession of the spins in the presence of a positive (or negative) bias field produces a clockwise (or counterclockwise) torque along the cantilever axis. The lower graph shows the absorbed power as determined from the cantilever deflection.

As a verification of the squared dependence on h_x in Eqs. (2) and (3), we plot in Fig. 4 the magnitude of the absorbed power and torque at resonance as a function of the microwave power applied to the stripline. For the thin film sample with an in-plane microwave field, eddy current losses

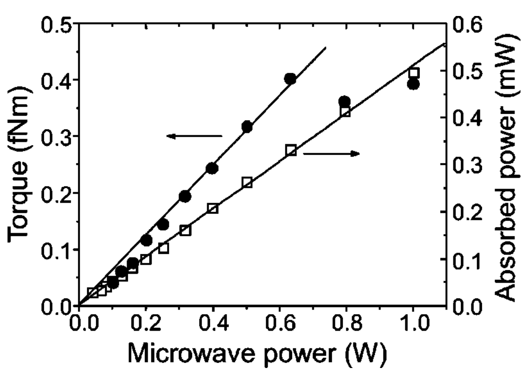

FIG. 4. Peak resonant torque (●) and absorbed power (□) vs microwave input power. The response is linear in accordance with Eqs. (2) and (3). The reduction in the torque signal at high power is due to a thermally induced change in mechanical properties of the cantilever.

are insignificant. The linear behavior indicates that, as required by the model assumptions, only small precessional angles are excited by the microwave field. The departure from linear behavior for the torque at high power is due to a heat-induced change in the mechanical resonance of the cantilever, rather than a nonlinear magnetic effect. This error is not seen in the power measurements because they are not performed at the mechanical resonance frequency.

For the thin-film geometry, Eq. (11) can be written as

$$P_{\mathrm{res}}/T_{\mathrm{res}}=\omega_{\mathrm{res}}^2/\gamma H_0 . \tag{14}$$

This measure is independent of M_s as well as sample volume, strength of the microwave field, and α. With $\omega_{\mathrm{res}}/2\pi=9.15\,\mathrm{GHz}$, $H_0=82.1\,\mathrm{kA/m}$, and $\gamma=2.31\times10^8\,\mathrm{m/kA\,s}$, Eq. (14) predicts $P/T=1.74\times10^{11}\,\mathrm{Hz}$ at resonance, compared to the experimentally determined value of $8.28\times10^{11}\,\mathrm{Hz}$. In the current experiment, the power and torque were derived from the estimated mechanical response of the cantilever based on its dimensions and material properties. Uncertainty in these parameters accounts for the deviation from the expected value. Additional structures patterned onto the cantilever[16] would allow for calibration of the P/T response.

We have derived an expression for the energy and angular momentum absorbed from the photons stimulating spin resonance in ferromagnetic samples. The transfer of this energy and angular momentum to the lattice results in the generation of heat and torque, which we have detected using the mechanical response of micromachined cantilevers. Micromechanical detection allows FMR spectra to be obtained from samples much smaller than those used in traditional microwave cavity experiments. We have shown measurements on samples as small as $2.2\times10^{-11}\,\mathrm{cm}^3$, and expect that several orders of magnitude improvement in sensitivity are still possible.[17] The torque is independent of resonant frequency [Eq. (9)] whereas the absorbed power measured in traditional experiments decreases with frequency.

[1] G. Alzetta and A. Gozzini, in *Proceedings of the XII Colloque Ampere* (North Holland, Amsterdam, 1964), p. 82.
[2] A. Gozzini, in Ref. 1, p. 209.
[3] E. Arimondo, Nuovo Cimento B **52**, 379 (1967).
[4] G. Alzetta, E. Arimondo, C. Ascoli, and A. Gozzini, Nuovo Cimento B **52**, 392 (1967).
[5] G. Alzetta, E. Arimondo, and C. Ascoli, Nuovo Cimento B **54**, 107 (1968).
[6] C. Ascoli, P. Baschieri, C. Frediani, L. Lenci, M. Martinelli, G. Alzetta, R. M. Celli, and L. Pardi, Appl. Phys. Lett. **69**, 3920 (1996).
[7] J. Schmidt and I. Solomon, J. Appl. Phys. **37**, 3719 (1996).
[8] W. S. Moore and T. M. Al-Sharbati, J. Phys. D **6**, 367 (1973).
[9] J. Moreland, M. Löhndorf, P. Kabos, and R. D. McMichael, Rev. Sci. Instrum. **71**, 3099 (2000).
[10] O. Benda, IEEE Trans. Magn. **5**, 921 (1969).
[11] C. E. Patton, in *Magnetic Oxides*, edited by D. J. Craik (Wiley, London, 1975), Chap. 10.
[12] B. Heinrich and J. F. Cochran, Adv. Phys. **42**, 523 (1993).
[13] C. Vittoria, *Microwave Properties of Magnetic Films* (World Scientific, Singapore, 1993).
[14] M. Löhndorf, J. Moreland, P. Kabos, and N. Rizzo, J. Appl. Phys. **87**, 5995 (2000).
[15] M. Löhndorf, J. Moreland, and P. Kabos, Appl. Phys. Lett. **76**, 1176 (2000).
[16] M. Willemin, C. Rossel, J. Brugger, M. H. Dspont, H. Rothuizen, P. Vettiger, J. Hofer, and H. Keller, J. Appl. Phys. **83**, 1163 (1998).
[17] J. Moreland, P. Kabos, A. Jander, M. Löhndorf, R. D. McMichael, and C.-G. Lee, Proc. SPIE **4176**, 84 (2000).