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Ferromagnetic resonance linewidth in thin films coupled to NiO

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Abstract

The out-of-plane angular dependence of the ferromagnetic resonance linewidth, ΔH, has been measured for thin magnetic films coupled to NiO and for uncoupled control films. In the control films, ΔH is described by nearly angle-independent damping parameters. In the NiO-coupled films, however, the damping was found to depend strongly on magnetization orientation, with linewidth values comparable to the control samples at normal orientation, but several times larger when the magnetization lies in plane. The additional linewidth in the NiO-coupled films follows the angular dependence of the number of nearly degenerate spin wave modes, in agreement with the predictions of a two-magnon scattering model of damping which incorporates a spin wave dispersion relation suitable for ultra-thin films.

I. INTRODUCTION

Increased ferromagnetic resonance linewidth[1,2] is a part of the complex phenomenology of exchange anisotropy that includes shifted hysteresis loops[3], rotational hysteresis[4] and shifts in the Brillouin scattering frequency[5] and ferromagnetic resonance (FMR) field[1,2,6]. Explanations of the increased linewidth in ferromagnet/antiferromagnet bilayers have been based on a dispersion of resonance fields due to dispersion of the exchange bias[1,2]. This

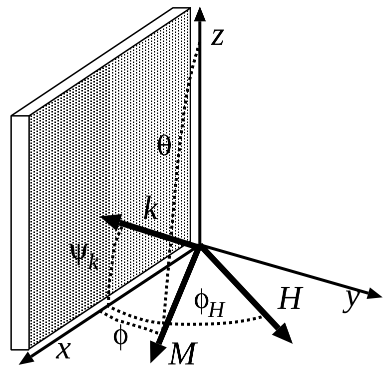

FIG. 1. Coordinate system used in to describe the orientation of **M**, **H**, and **k** with respect to the film.

paper presents, for the first time, measurements of the FMR linewidth, ΔH, as a function of the magnetization orientation from in-plane to film normal. These results are compared with the predictions of a two-magnon model of FMR damping.

II. EXPERIMENTAL

The samples in this study were deposited by DC magnetron sputtering in 0.25 Pa (2 mTorr) Ar. The base pressure before depositing a film was approximately 10^{-6} Pa (10^{-8} Torr) of which 90% was hydrogen. The films consisted of $Ni_{80}Fe_{20}$, Co, and $Co_{30}Ni_{35}Fe_{35}$ deposited on 50 nm NiO and capped with Au or Ta, and the magnetic film thickness ranged from 4.0 nm to 10.0 nm. These films were deposited in a field which set the direction of the exchange anisotropy field, $\mathbf{H}_{\rm ex}$. The corresponding control films were deposited with 2.0 nm layers of Ta separating the magnetic films from the NiO.

Ferromagnetic resonance spectra were taken using an X-band spectrometer operating at 9.78 GHz. The samples were mounted on the side of a quartz rod passing through the center of the TE_{102} microwave cavity, and sample orientation was controlled by a goniometer with a precision of $\pm 0.12°$. Samples were mounted with $\mathbf{H}_{\rm ex}$ directed parallel to the rotation axis, along the z direction (see Fig. 1) so that the applied field, **H** was always perpendicular to $\mathbf{H}_{\rm ex}$. Resonance fields and peak-to-peak field linewidths of 10 nm thick $Ni_{80}Fe_{20}$ films on NiO and on Ta are shown in Fig. 2.

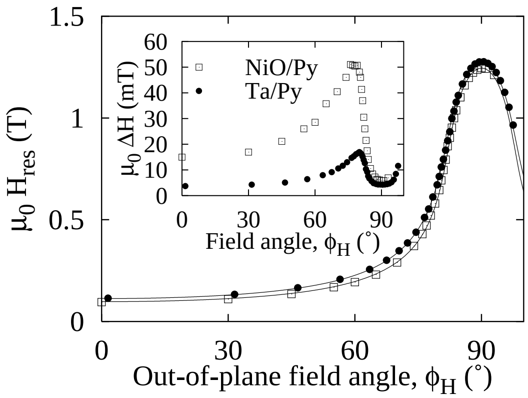

FIG. 2. Resonance fields and linewidths (inset) for 10 nm thick films of $Ni_{80}Fe_{20}$ on NiO and on Ta. The solid lines are fits to the $H_{\rm res}$ data.

The free energy, $\mathcal{F}$, of the magnetization is modeled by

$$\mathcal{F} = K_u \sin^2\theta \sin^2\phi + K_a \sin^2\theta \cos^2\phi$$
$$-\mu_0 \mathbf{M}\cdot\mathbf{H} - \mu_0\mathbf{M}\cdot\mathbf{H}_{\rm ex} - \mu_0\mathbf{M}\cdot\mathbf{H}_{\rm ra} \tag{1}$$

where K_u and K_a are uniaxial anisotropies with hard axes directed along the y and x directions respectively. $\mathbf{H}$ is the applied field and $\mathbf{H}_{\rm ra}$ is a rotatable anisotropy field, $\mathbf{H}_{\rm ra} \parallel \mathbf{M}$, included to model an isotropic negative resonance field shift[6]. The angles are defined in Fig. 1. The resonance condition is given by

$$(\omega/\gamma)^2 = (M^2 \sin^2\theta)^{-1}[\mathcal{F}_{\theta\theta}\mathcal{F}_{\phi\phi} - \mathcal{F}^2_{\theta\phi}] \tag{2}$$

where the subscripts indicate partial derivatives, evaluated at values of θ and ϕ which minimize $\mathcal{F}$, and $\gamma = g\mu_b/\hbar \approx 1.76 \times 10^{11} T^{-1}s^{-1}$.

The $H_{\rm res}$ data was fit using an orthogonal least-squares algorithm[7] to obtain values for the parameters in (1). The fit parameters are then used to calculate ϕ and values of $d\omega/dH$ corresponding to each data point.

While the measurements were made by sweeping H at fixed ω, theoretical linewidth calculations are simpler at fixed H. To make comparisons with theoretical results, values for $\Delta\omega$ are obtained from the ΔH data using $\Delta\omega = (d\omega/dH)\Delta H$ where $d\omega/dH$ is calculated numerically using parameters obtained from the $H_{\rm res}$ fit described above. Plots of $\Delta\omega/\gamma$ vs.

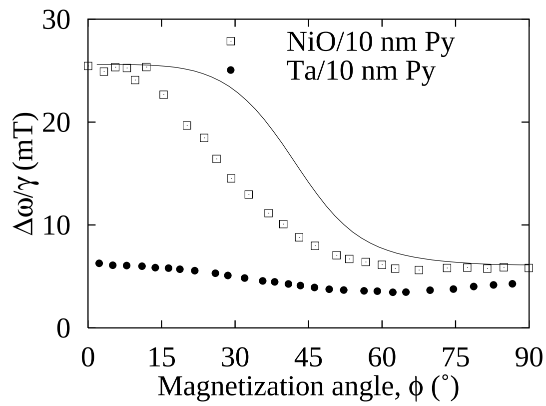

FIG. 3. Frequency linewidth, $\Delta\omega/\gamma$ for 10 nm thick $Ni_{80}Fe_{20}$ films on NiO and Ta plotted as a function of magnetization orientation. The solid line

ϕ for the 10 nm thick $Ni_{80}Fe_{20}$ samples are shown in Fig. 3. There is a smooth increase in $\Delta\omega$ in the NiO coupled film as $\mathbf{M}$ is rotated from the sample normal (90°) to in-plane (0°). In contrast, $\Delta\omega$ does not depend strongly on ϕ for the $Ni_{80}Fe_{20}$ film on Ta . Other films with different thicknesses and compositions described above were measured, and the results show very similar linewidth behavior.

III. TWO-MAGNON THEORY

The ferromagnetic film is modeled as a $N_x \times N_y \times N_z$ rectangular array of spins with lattice parameter a. The thickness of the film, d, is given by $d = N_y a$. The coordinate system used to describe the orientation of $\mathbf{M}$, $\mathbf{H}$, and the spin wave propagation vector, $\mathbf{k}$, is shown in Fig. 1.

In a uniform film, the normal modes can be described as a uniform precession mode, which couples to the microwave excitation field, and a manifold of spin wave modes which are not directly excited. Nonuniformities will induce coupling between the normal modes, leading to a broadening of the resonance.

The two-magnon model of FMR damping[8–10] treats nonuniformities as perturbations. The scattering rate, $\lambda_{0,k}$, of uniform precession, or $k = 0$, magnons into other, $k \neq 0$ spin wave mode is

$$\lambda_{0,k} = \frac{2\pi}{\hbar} \sum_k |A_k|^2 \delta(\hbar\omega_0 - \hbar\omega_k), \tag{3}$$

where A_k is the coefficient of the perturbation Hamiltonian term which couples the uniform precession and spin wave modes. As λ represents the rate of decay of a population of $k = 0$ magnons, it also represents a contribution to the frequency linewidth, $\Delta\omega = \lambda + \delta\omega_0$, of continuously driven uniform precession.

If the inhomogeneity is restricted to the interface, the perturbation Hamiltonian can be modeled as an exchange bias or anisotropy field, $H_p(\mathbf{r})$, acting on the first layer of atoms in the ferromagnet. This field varies randomly from grain to grain along the interface, but is correlated over a distance, ξ, corresponding to a grain size. The expectation value of $|A_k^2|$ is calculated using $A_k = \frac{\gamma\hbar\mu_0}{\sqrt{N}} H_p(\mathbf{k})$[9] under the assumption that $<H_p(\mathbf{r})H_p(\mathbf{r}')>\approx<H_p^2>$ $\exp[-|\mathbf{r} - \mathbf{r}'|/\xi]$.

$$\lambda = \frac{2\pi\gamma^2\mu_0^2 <H_p^2>}{N_x N_z d^2} \sum_k \frac{2\pi\xi^2}{[1 - (k\xi)^2]^{3/2}} \frac{\delta\omega_k/\pi}{[\delta\omega_k^2 + (\omega_0 - \omega_k)^2]} \tag{4}$$

In this expression, the δ-function in (3) has been replaced by a Lorentzian with $\delta\omega_k$ chosen to represent the intrinsic spinwave linewidth.

The spinwave dispersion relation, $\omega_k = \omega(k, \psi_k, H, \phi_h, M, \phi, d)$, is the source of angular dependence in (4). It is derived assuming uniform precession through the thickness of the film because in the thickness range of interest, spinwaves with components of $\mathbf{k}$ perpendicular to the plane of the film will have $\omega_k > \omega_o$ and will not count in the sum. Starting with $d\mathbf{M}/dt = -|\gamma|\mathbf{M} \times \mathbf{H}$ and using magnetostatic fields given by

$$H_y^D(\mathbf{k}) = -NkM_y(\mathbf{k}) \tag{5}$$

$$H_{x,z}^D(\mathbf{k}) = -\mathbf{k}[M_x(\mathbf{k})k_x + M_z(\mathbf{k})k_z](1 - N_k)/|k|^2 \tag{6}$$

where $N_k = [1 - \exp(-kd)]/kd$,[11] the resulting dispersion relation is

$$\begin{aligned}(\omega_k/\mu_0\gamma)^2 = &\left[H_\mathrm{i} + Dk^2 + M(1 - N_k)\sin^2\psi_k\right] \\ &\times \left[H_\mathrm{i} + Dk^2 + MN_k\cos^2\phi \right.\\ &\left. + M(1 - N_k)\sin^2\phi\cos^2\psi_k\right] \\ &- \left[M(1 - N_k)\cos\psi_k\sin\psi_k\sin\phi\right]^2,\end{aligned} \tag{7}$$

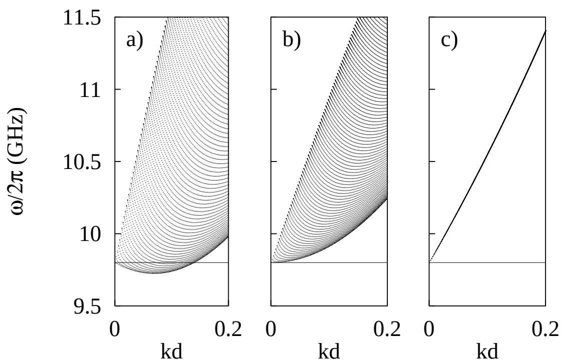

FIG. 4. Spin wave manifolds calculated for a 10 nm thick $Ni_{80}Fe_{20}$ film with a) $\mathbf{M}$ oriented in the plane of the film, b) at $\phi = 45°$, and c) normal to the film. The applied field is set to give $\omega_0/2\pi = 9.8$ GHz in each case.

where H_i is the internal static magnetic field, D is the spin wave dispersion constant, and the angles are defined in Fig. 1. Spinwave manifolds calculated from (7) are shown in Fig. 4.

The solid line in Fig. 3 is the result of the two-magnon theory for a 10 nm film of $Ni_{80}Fe_{20}$ assuming that $\xi = 40$ nm, which is a typical grain size for these films. To match the experimental data at 0°and 90°, the value of $\mu_0 H_p a/d$ was adjusted to 35 mT and an intrinsic linewidth $\delta\omega_0 = \delta\omega_k = 5$ mT was used.

It is helpful to think about the result in (4) in terms of two parts: the terms outside the summation having to do with the strength of the scattering of spin waves, and the summation over magnon wavevectors which is essentially a weighted count of the number of spin wave modes having wavevectors matching the spatial fluctuations of the perturbing field and with frequencies close enough to ω_0 to accept the scattered energy. The angular dependence of $\Delta\omega$ is contained entirely within the mode counting terms through ω_k and thickness dependence is shared by the mode counting and the scattering strength terms.

The quantity $\Delta\omega d^2/(H_p^2 a^2)$ contains only the thickness dependence of the mode counting, with the explicit $1/d^2$ thickness dependence of the scattering strength factored out. This quantity is plotted in Fig. 5 as a function of inverse film thickness for $Ni_{80}Fe_{20}$ films with $\mathbf{M}$ in plane ($\phi = 0$).

The thickness dependence of the two-magnon model, with an explicit $1/d^2$ dependence in the scattering strength and a $1/d$ thickness dependence in the mode counting does not agree well with published results[1,2] which show the linewidth increasing linearly with $1/d$ for $d > 10$ nm and decreasing for a thinner sample. The $1/d^2$ dependence of the scattering strength can be eliminated if the perturbing field is assumed to act on spins throughout the thickness of the sample, rather than on the surface spins. It is interesting to note that the thickness dependence of the mode counting part alone, without the implicit thickness dependence of the scattering strength, is very similar to that of previously published results (see ref. 2, Fig. 5).

IV. CONCLUSIONS

The experimental results show consistently that for magnetic films deposited on NiO, the FMR linewidth is several times larger for **M** in plane than for **M** normal to the film, and that the frequency linewidth changes smoothly as a function of magnetization orientation. In agreement with the two-magnon model, these results are consistent with a proportionality between the frequency linewidth and the number of nearly degenerate spin wave modes.

If the perturbation is restricted to the interface, the two magnon model predicts an explicit $1/d^2$ dependence multiplying the $\sim 1/d$ dependence of the mode counting. This result is not supported by previous experimental data[1,2]. However, if the perturbation is allowed to act throughout the thickness of the film, there is no explicit thickness dependence

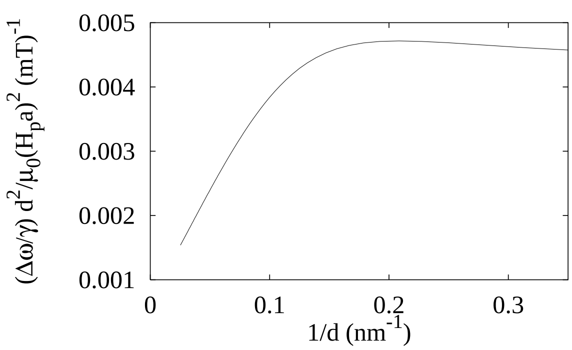

FIG. 5. Thickness dependence of the number of degenerate spinwaves calculated for a $Ni_{80}Fe_{20}$ film at 34 GHz, using $\mu_0 \delta\omega_k/\gamma = 10$ mT and $\xi = 40$ nm.

and the agreement with experiment is quite good.

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