Ferromagnetic resonance mode interactions in periodically perturbed films

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Ferromagnetic resonance linewidth measurements are reported for thin films of $Ni_{80}Fe_{20}$ deposited on substrates with 320 nm period grooves or parallel aperiodic scratches. These films are model systems for studying the effects of inhomogeneity on ferromagnetic resonance. With the grooved substrate, the ferromagnetic resonance spectra show that interactions split the resonant frequencies of interacting modes leading to two resonances for strong interactions and broadened resonances for weak interactions. The results obtained with the scratched substrate are in agreement with the two-magnon model of linewidth, showing sharply increased linewidth when the scratches are oriented to allow coupling to degenerate spinwave modes. The results are not in agreement with a simple model of linewidth as a direct measure of the spread in local resonance fields. [DOI: 10.1063/1.1456382]

I. INTRODUCTION

Ferromagnetic resonance (FMR) linewidth in thin films has been interpreted in many cases as a combination of intrinsic damping and a distribution of local resonance fields. This interpretation neglects the magnetostatic and exchange interactions between different parts of the material. The two magnon model of ferromagnetic resonance linewidth[1–7] includes these interactions in the dispersion relation for spinwaves[5,8–10] that are the normal modes of precession for a material with magnetostatic and exchange interactions.

The two magnon model is based on a Hamiltonian of the form

$$\frac{\mathcal{H}}{\hbar}=\omega_0 a_0^\dagger a_0+\sum_{\mathbf{k}} \omega_{\mathbf{k}} a_{\mathbf{k}}^\dagger a_{\mathbf{k}}+\sum_{\mathbf{k}} (A_{0\mathbf{k}} a_0 a_{\mathbf{k}}^\dagger + A_{0\mathbf{k}}^* a_0^\dagger a_{\mathbf{k}}), \tag{1}$$

where $a_{\mathbf{k}}^\dagger$ and $a_{\mathbf{k}}$ are the raising and lowering operators for the spinwave normal modes of a uniform film and the coefficients $A_{0\mathbf{k}}$ describe the strength of inhomogeneities that scatter the uniform precession into spinwave modes.

The damping rate of the uniform precession is given by

$$\Gamma=\frac{2\pi}{\hbar}\sum_{\mathbf{k}} |A_{0\mathbf{k}}|^2 \delta(\hbar\omega_0-\hbar\omega_{\mathbf{k}}). \tag{2}$$

In the description of mode interactions presented by the two-magnon model, interactions allow energy to ''leak'' from one mode to another, as long as the modes are degenerate.

One of the more important features of two-magnon scattering is that the number of degenerate modes that enter the sum in Eq. (2) can be adjusted experimentally. When the magnetization is rotated out of plane, the number of degenerate modes decreases, and the two-magnon damping rate is reduced.[4,5]

Following the suggestion of Arias and Mills,[6,7] we show in this article that it is also possible to adjust the two-magnon damping rate by using oriented inhomogeneities such as parallel grooves. For these inhomogeneities, the interaction coefficients $A_{0\mathbf{k}}$ are significant only for $\mathbf{k}$ perpendicular to the grooves, and therefore, the uniform precession is only coupled to spinwaves with wave vectors that are also perpendicular to the grooves.

For magnetization in plane, the dispersion relation $\omega_{\mathbf{k}}$ for the spinwaves is anisotropic.[5,8–10] This feature of the dispersion relation is illustrated in Fig. 1 where the in-plane wave vectors of degenerate modes are plotted for a 50 nm thick film of $Ni_{80}Fe_{20}$ with a 0.1 T field applied in plane. The degenerate spinwave modes have wave vectors within an angle ϕ_c of the magnetization direction; $\sin^2\phi_c=H/(H+M)$. Using $\mu_0 M_s=1$ T ($4\pi M_s=10$ kG) and an applied field of $\mu_0 H=0.1$ T (1000 Oe), the critical angle for this film is predicted to be $\phi_c=17.5°$.

As the magnetization is rotated in plane relative to the grooves, the perturbation wave vectors will coincide with degenerate mode wave vectors only for certain angles. Increasing the angle between the perturbation wave vectors and $\mathbf{M}$ beyond ϕ_c, will effectively turn off the two magnon scattering due to the grooves.

In this article, we explore the consequences of interactions between normal modes of magnetization precession using thin films on grooved substrates. In Sec. II, we describe the behavior of a film prepared to highlight interactions between pairs of modes. In Sec. III, we describe the behavior of a film prepared with interactions between a subset of the spinwave modes.

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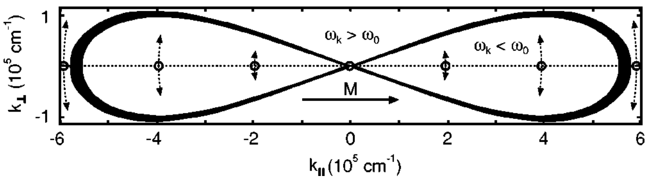

FIG. 1. Wave vectors of spin wave modes having frequencies within 84 MHz of the uniform precession frequency (9.28 GHz) calculated for a 50 nm thick film of $Ni_{80}Fe_{20}$ with an in-plane applied field of 0.1 T. Open circles indicate wave vectors associated with 320 nm periodic grooves, when the grooves are perpendicular to M. When the magnetization is normal to the film, the modes within 84 MHz of the main resonance are confined to $|k|<2400\ \mathrm{cm}^{-1}$.

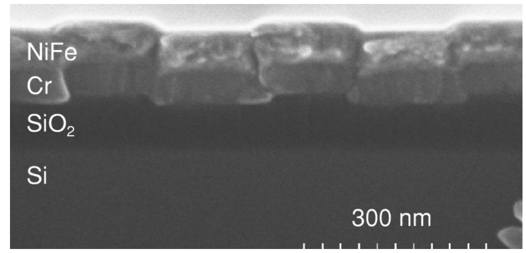

FIG. 2. Micrograph of the cleaved surface of a lithographically grooved substrate with 50 nm Cr and 50 nm $Ni_{80}Fe_{20}$.

II. COUPLING TO DISCRETE WAVE VECTORS

The two magnon model is an application of perturbation theory. To proceed beyond perturbation theory, which is limited to values of $A_{0\mathbf{k}}$ that are in some sense small, Eq. (1) would have to be diagonalized to find the mixtures of the uniform and spin wave modes of the unperturbed system that are the true eigenmodes of the perturbed system. Such a diagonalization is relatively trivial when the number of interacting modes is small.

Compared to the two-magnon model, the full solution for a very limited two-mode system gives a very different description of what happens when modes interact. For a system with only two modes labeled 0 and $\mathbf{k}_1$, diagonalization yields eigenfrequencies

$$\omega^{\pm}=\frac{\omega_0+\omega_{\mathbf{k}_1}}{2}\pm\sqrt{\left(\frac{\omega_0-\omega_{\mathbf{k}_1}}{2}\right)^2+|A_{0\mathbf{k}_1}|^2}. \tag{3}$$

For $\omega_0=\omega_{\mathbf{k}_1}$, frequencies of the new eigenmodes differ by $2|A_{0\mathbf{k}}|$. Rather than only allowing energy transfer as predicted by the two-magnon model, the interaction also separates the previously degenerate modes. Also, for $\omega_0=\omega_{\mathbf{k}_1}$ the eigenmodes of the diagonalized Hamiltonian are mixtures containing equal parts of the 0 and $\mathbf{k}_1$ modes for arbitrarily small values of $A_{0\mathbf{k}}$ This also contrasts with the two-magnon model where the uniform mode is essentially unchanged for small values of $A_{0\mathbf{k}}$.

If the interaction parameter is small compared to the intrinsic damping parameter, the diagonalized Hamiltonian describes a broadened peak consistent with overlapping resonances, but if the interaction parameter is large, we expect two peaks of equal amplitude, one for each of the new eigenmodes.

To generate inhomogeneities with discrete wave vectors, periodically grooved silicon substrates were produced using interference lithography, a technique that allows parallel lines to be produced over large areas.[11] A 320 nm period grating was used with a step height of 18 nm, smoothed somewhat by a 50 nm coating of Cr. On this substrate, a 50 nm $Ni_{80}Fe_{20}$ film and a 1.0 nm Al capping layer were deposited (see Fig. 2).

Starting with the magnetization and applied field oriented in-plane and perpendicular to the substrate grooves, we took ferromagnetic resonance (FMR) spectra for applied field angles out of the plane of the film and in the plane of the film.

As the applied field direction is rotated out of the plane, the resonance field increases (for constant frequency). Spin-wave modes with $\omega_{\mathbf{k}}<\omega_0$ appear as weak resonances on the high field side of the main resonance. As **M** is rotated out of plane, these modes will have $\omega_{\mathbf{k}}>\omega_0$, and will appear as weak resonances on the low field side of the main resonance. One such transition from $\omega_{\mathbf{k}}<\omega_0$ to $\omega_{\mathbf{k}}>\omega_0$ is shown in Fig. 3. Near 74°, the spectrum shows two separate modes with roughly equal amplitudes in at least qualitative agreement with the predictions of the diagonalized two-mode Hamiltonian.

As the applied field direction is rotated in plane, there is a similar transition from $\omega_{\mathbf{k}}<\omega_0$ to $\omega_{\mathbf{k}}>\omega_0$ (dashed arcs in Fig. 1), but the interaction parameter is apparently somewhat weaker. The inset to Fig. 3 shows the peak-to-peak FMR linewidth as a function of in-plane applied field angle. In the regions where the linewidth is increased, the resonances deviate from a symmetric Lorentzian shape. We attribute the asymmetry of this plot to an additional anisotropy arising from off-normal deposition of the $Ni_{80}Fe_{20}$. Again, the results are consistent with the predictions of the diagonalized two-mode Hamiltonian in the case where the $A_{0\mathbf{k}}$ in appropriate units is smaller than the intrinsic damping, so that the

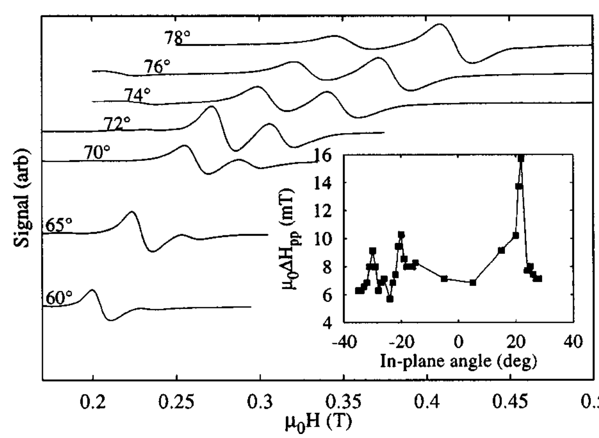

FIG. 3. Ferromagnetic resonance spectra for 50 nm Permalloy on a periodically grooved substrate for a series of angles out of plane showing interactions between the main resonance and a spin wave mode. Inset: FMR linewidth as a function of in-plane applied field angle. Linewidth increases are observed as spin wave modes interact with the main resonance.

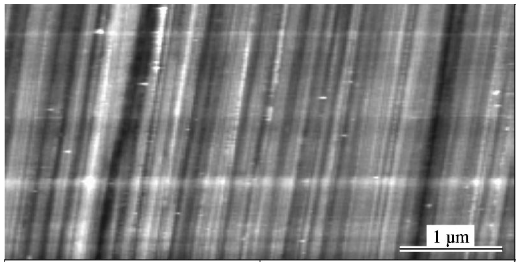

FIG. 4. Atomic force microscope image of the aperiodically grooved substrate. The gray scale spans 10 nm vertical displacement.

observed signal is at least qualitatively consistent with two overlapping resonances.

III. COUPLING TO PARALLEL WAVE VECTORS

In the previous section, we described how interactions between the uniform precession and single spinwave modes were not in good agreement with the two-magnon model. In this section, we describe experiments where the uniform precession is allowed to interact with many spinwaves with the restriction that the coupling is to spinwaves with parallel wave vectors.

Substrates with parallel, aperiodic grooves were produced by mechanical abrasion of a silicon wafer with a 0.25 μm diamond slurry. An atomic force microscope image of this substrate is shown in Fig. 4. Grooves average roughly 140 nm in spacing, but there is a distribution to the feature size. Surface roughness is 1.3 nm and the maximum peak to valley height is 9 nm. $Ni_{80}Fe_{20}$ was deposited normally to a thickness of 65 nm.

The FMR spectra of this sample consist of two peaks: a main resonance, and a weaker resonance appearing about 20 mT (200 Oe) lower in field for **M** in plane and about 43 mT (430 Oe) lower in field for **M** normal to the film. The origin of the weaker resonance is not clear, but because the low field peak is reproduced in a similar film deposited on an ungrooved oxide-coated substrate, we do not think it is associated with the substrate grooves.

The most striking feature in Fig. 5 is the increased linewidth observed in an angular span of roughly $\pm 15°$ centered around a direction perpendicular to the scratches. The angular dependence of the enhanced linewidth is in very good agreement with the the two-magnon model and the magnon dispersion relation. A positive field shift of the type predicted by Arias and Mills[6,7] is also evident.

IV. DISCUSSION

These experiments lead us to several points. First, the two magnon model does not appear to describe our results for a film deposited on periodic grooves where the uniform precession only interacts with a single spinwave. The features we observe in the spectra are much better described by a diagonalization of the perturbed Hamiltonian. Second, in an aperiodically scratched substrate, where a larger number of spinwaves are simultaneously coupled to the uniform precession, the two-magnon model describes the results quite nicely.

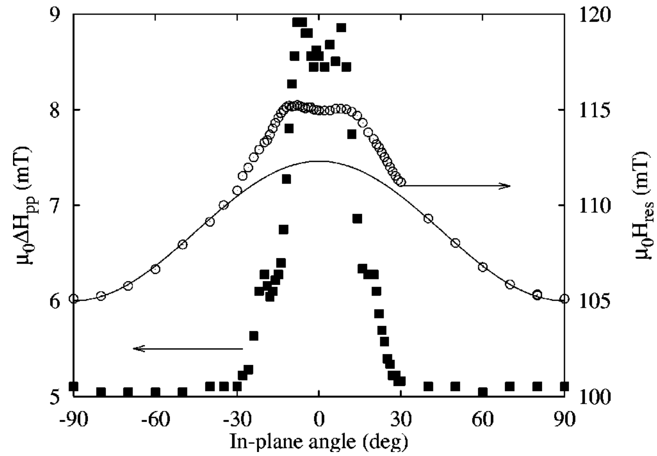

FIG. 5. Ferromagnetic resonance linewidth (solid squares) and resonance field (open circles) as a function of in-plane field direction for a $Ni_{80}Fe_{20}$ film on the substrate shown in Fig. 4. At $0°$, the magnetization is perpendicular to the scratches. The solid line is a cosine curve fit to the resonance fields outside the linewidth peak region.

Perhaps the most important result of these experiments is that neither the periodic grooves nor the aperiodic scratches produce linewidths that are proportional to a dispersion of the local internal field. The dispersion in the in-plane magnetostatic field should have an angular dependence proportional to $\cos^2 \phi$, and the dispersion in the out-of-plane magnetostatic field should have no angular dependence. Local field dispersion would predict linewidths with angular dependence no more complicated than $\cos^2 \phi$ for our samples. The close relationship between linewidth and the magnon dispersion relation in inhomogeneous films shows that interpretation of FMR linewidth directly as a dispersion in local resonance field is at best a dangerous practice.

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