Extrinsic contributions to spin-wave damping and renormalization in thin $Ni_{50}Fe_{50}$ films

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Ferromagnetic resonance has been used to study the room-temperature linewidth and frequency shift of the $q=0$ spin-wave mode in thin films of NiFe sputtered on Si(100) substrates. The data on the variation of the linewidth and resonance field with film thickness are completely consistent with the extrinsic mechanism recently proposed by Arias and Mills based on momentum nonconserving two-magnon scattering off defects on the film surfaces.

I. INTRODUCTION

The manner in which the magnetization relaxes towards equilibrium is governed by the spin interactions and the detailed microscopic structure of a magnetic system. With device applications reaching the microwave frequency range, understanding the mechanisms responsible for the damping of the spin excitations becomes increasingly important. Thus, it is rather surprising that relatively little activity has been reported on the investigation of the ferromagnetic resonance (FMR) linewidth in magnetic thin films. One of the recent interesting advances in this area is the realization that the sample quality and interface roughness play an important role in the spin relaxation in ultrathin magnetic films. It has been observed[1–3] that in general the FMR linewidth increases substantially as the film thickness decreases below certain values. On the other hand, very recently Arias and Mills[4] made theoretical predictions for the extrinsic contribution to the FMR linewidth arising from two-magnon scattering processes. Two-magnon scattering is a well-known relaxation mechanism in bulk samples, both insulating[5,6] and metallic,[7] which has also been shown to be present in thin films.[8] According to Arias and Mills (AM), in magnetic films the sources of the scattering are defects and imperfections on the surfaces and interfaces. In ultrathin films this mechanism is predicted to give rise to a significant contribution to the linewidth, which adds to the Gilbert damping and other relaxation processes existing in conducting films. However, no quantitative comparison with experimental data has been established to our knowledge.

This paper reports an investigation of the FMR linewidths and resonance field shifts in thin films, specifically designed to verify the predictions of AM. Since the two-magnon scattering processes result in damping as well as renormalization of the magnon frequencies, if the proposed mechanisms are effective one expects consistency between the measured linewidths and resonance field shifts. The data were taken in thin films of $Ni_{50}Fe_{50}$ prepared by sputtering deposition. Although this alloy does not have exactly the same composition of permalloy, it has quite small crystal anisotropy and consequently small contributions to the linewidth arising from mechanisms other than the Gilbert damping. Analysis of the experimental data confirms that in ultrathin films there is a significant contribution to the magnon damping and frequency renormalization arising from surface roughness induced two-magnon scattering.

II. EXPERIMENTS

All measurements reported here were obtained at room temperature, using the standard ferromagnetic resonance technique, with fixed microwave frequency ω and swept external dc field H. With the field applied in the film plane, in isotropic films the resonance occurs at the frequency of the spin-wave mode with wave number $q\cong 0$ propagating along the film[4,8]

$$\omega_0=\gamma[H(H+4\pi M+H_s)]^{1/2}-\delta\omega_0, \tag{1}$$

where $\gamma=g\mu_B/\hbar$ is the gyromagnetic ratio, M is the saturation magnetization, $H_s=2K_s/Mt$ is the surface anisotropy field, t is the film thickness, and $\delta\omega_0$ is the frequency shift due to spin-wave energy renormalization processes. By measuring the field for resonance H_R at various frequencies and fitting Eq. (1) to data, one can obtain the values of the magnetic parameters and the frequency shift.

The samples were prepared by dc magnetron sputtering in a Balzers/Pfeiffer PLS500 system. Magnetic films of $Ni_{50}Fe_{50}$ were deposited on commercially available Si(100) after cleaning in ultrasound baths of acetone and ethanol for 10 min and drying in nitrogen flow. Neither a buffer layer on the substrate nor a cover layer on the magnetic film were used. The base pressure of the system prior to deposition was 2.0×10^{-7} Torr. The films were deposited in a 3.4×10^{-3} Torr argon atmosphere in the sputter-up configuration, with the substrate at a distance of 9 cm from the target. The purity of the NiFe target is 99.9% and that of the argon gas is 99.999%. The films were deposited on the substrate at a temperature of 130 °C and the deposition rate was 0.7 Å/s. This rate was calibrated by measuring the frequencies of volume spin-wave modes in thicker films using Brillouin light scattering and confirmed by measurements in a surface profiler. Eight samples were prepared with thicknesses in the range 27–158 Å.

The FMR data were taken with a home-made X-band spectrometer using a YIG-tuned sweep oscillator as the microwave source. Measurements were done at several frequencies by employing various TE_{102} rectangular microwave cavities with Q factor in the range 2500–3000 and an appropriate oscillator-cavity frequency stabilization circuit. The

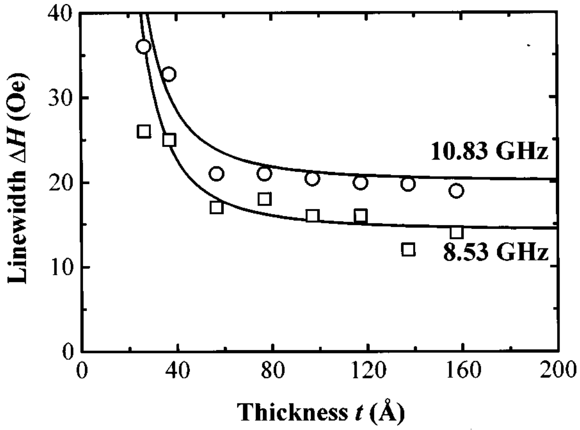

FIG. 1. Thickness dependence of the FMR linewidth in NiFe(t)/Si(100) measured at two frequencies, 8.53 GHz (squares) and 10.83 GHz (circles). The lines are fits with Eq. (2) plus a constant term, as described in the text.

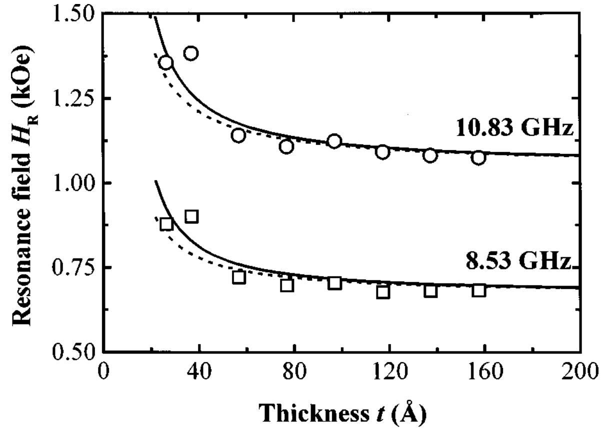

FIG. 2. Thickness dependence of the FMR in-plane resonance field in NiFe(t)/Si(100) measured at two frequencies, 8.53 GHz (squares) and 10.83 GHz (circles). The solid lines are fits with equations (1) and (4), as described in the text. Dashed lines represent the calculations with $r=0$ in Eq. (4) and all other parameters the same as in the fits.

sample was mounted on the tip of an external goniometer and introduced through a hole in the shorted end of the cavity so that it could be rotated in the plane to allow measurements of the in-plane resonance field H_R and linewidth as a function of the angle. The dc magnetic field was provided by a 9 in. electromagnet and was modulated with a 1.1 kHz ac component of a few oersteds using a pair of Helmholtz coils. The resonance field H_R and linewidth ΔH were determined by fitting the derivative of a Lorentzian line shape to the measured field spectrum. The FMR linewidth was characterized by the peak-to-peak field spacing ΔH.

In each sample the FMR spectrum was measured as a function of the in-plane angle. The angular variations of both the resonance field and linewidth displayed a small uniaxial anisotropy, so the values reported here are averages over the angular variations. The symbols in Fig. 1 represent the linewidths measured at 8.53 and 10.83 GHz as a function of the sample thickness. As in previous reports, the linewidth increases markedly with decreasing sample thickness below 50 Å. Thicker samples exhibit a thickness independent linewidth approaching 14 and 20 Oe at 8.53 and 10.83 GHz, respectively. These values are approximately proportional to the measuring frequencies and are attributed to the Gilbert damping. As we show next, the rise in the linewidth observed in thinner films are due to extrinsic mechanisms. Figure 2 shows the resonance field H_R measured at the same two frequencies as a function of the sample thickness. The increase in H_R with decreasing t is commonly observed in films with negative surface anisotropy.[9–11] It is usually attributed to the lowering of the FMR frequency (1) resulting solely from the reduction in the effective magnetization $4\pi M_{\text{eff}}=4\pi M-|H_s|$. Actually, as we show in the next section, part of the field shift results from the spin wave renormalization due to two-magnon scattering.

III. DISCUSSION

In this section we calculate the FMR linewidth and frequency shift, and show that the data are completely consistent with the theoretical predictions of AM.[4] According to their theory the low-wave number spin waves, such as the $q=0$ FMR mode, are scattered off defects and imperfections on the film surfaces and interfaces into degenerate volume modes propagating along the film. The momentum nonconserving two-magnon interactions resulting from the scattering contribute to damping as well as to the frequency renormalization of the incoming spin waves. Since the dominant energy contribution in the process is the surface anisotropy, the effects become more pronounced in ultrathin films.

The calculation is carried out assuming that the defects on the film surfaces consist of bumps and pits, in the shape of rectangular parallelepipeds having faces parallel and perpendicular to the film plane and randomly varying dimensions. Considering that in the experiments $H \ll 4\pi M$, the extrinsic contribution to the FMR linewidth given by Eq. (94) of AM can be written approximately as

$$\Delta H=\frac{2}{\sqrt{3}}\,\frac{16sH_s^2}{\pi D}\,\frac{H^{1/2}}{(H+4\pi M+H_s)^{1/2}},\qquad(2)$$

where D is the exchange stiffness constant and s is a geometrical factor characteristic of the surface roughness given by

$$s=pb^2\left(\left\langle\frac{a}{c}\right\rangle-1\right),\qquad(3)$$

p being the fraction of the surface covered by defects having average height (or depth) b and lateral dimensions a and c. Note that the prefactor $2/\sqrt{3}$ in Eq. (2) results from the fact that we measure the peak-to-peak linewidth. Since the surface anisotropy field H_s is inversely proportional to the sample thickness, Eq. (2) immediately shows that the extrinsic contribution to the linewidth increases as the film thickness decreases, as observed experimentally.[1,2] However, in order to confirm the predictions of AM quantitatively, it is necessary to correlate the variation of the linewidth with the resonance field shift. According to the AM theory, the roughness induced two-magnon interaction also renormalizes the spin wave energies, causing the FMR frequency to shift downwards. Since the microwave frequency is fixed, this produces an upward shift in the resonance field, which can be written approximately as[3]

$$\Delta H_R = r H_s^2, \tag{4}$$

where r is a renormalization factor given by

$$r = \frac{16s}{\pi D} \ln\left[\left(\frac{q_m}{q_0} \right)^{1/2} + \left(1 + \frac{q_m}{q_0} \right)^{1/2} \right] \tag{5}$$

with $q_0 = (2\pi M t/D)$ being a characteristic volume-mode wave number and $q_m = 1/\langle a \rangle$ a cutoff wave number determined by the transverse length scale of the surface defects. Note that although q_0 depends on the sample thickness, the logarithm function attenuates this dependence so that the field shift ΔH_R given by Eq. (4) varies approximately with H_s^2 and therefore as t^{-2}. Equations (1) and (4) show that the variation of the resonance field H_R with sample thickness results from the additive combination of the direct change in the effective magnetization with the magnon renormalization. Since the two contributions have different dependencies on the surface anisotropy field H_s, it is possible to extract the value of H_s for each sample from the field shift data. The solid lines in Fig. 2 represent a least square fit of Eqs. (1) and (4) to the field shift data obtained at the two frequencies, assuming that the surface anisotropy field is the same in both equations and varies as t^{-1}. From this fit one obtains the following parameters: $g = 2.0$, $4\pi M = 13.2$ kG, $r = 8\times10^{-6}$ Oe^{-1}, and $H_s = -(82/t)$ kOe Å^{-1}. This gives for the sample with $t = 27$ Å a surface anisotropy field $H_s = -3.1$ kOe. Approximately the same value for H_s was obtained by fitting the measured out-of-the plane angular dependence of the FMR resonance field with the appropriate equation.[10] In order to demonstrate the importance of the energy renormalization we show by the dashed lines in Fig. 2, the variation of the resonance fields calculated with $r = 0$ and the other parameters kept the same. It is worth noting that in the sample with $t = 27$ Å the renormalization contributes with 77 Oe to the field shift. The contribution of the Gilbert damping mechanism to the resonance field shift (Ref. 12), is of order 0.01 Oe, and for this reason is negligible compared with the field shifts predicted by the AM theory.

The values of H_s and $4\pi M$ thus determined may be used to fit the linewidth data. The curves in Fig. 1 represent fits to data of the extrinsic contribution (2) plus a constant term. Using for the exchange stiffness $D = 2\times10^{-9}$ Oe cm^2, the fit yields for the geometrical factor $s \approx 16$ Å^2. This value is compatible with realistic estimates for the geometry of the defects: $b = 8$ Å, $p = 0.5$, and $\langle a/c \rangle = 1.5$. Now, using in Eq. (5) the value of s obtained from the linewidth fit, and using $q_0 = 8\times10^{-5}$ cm^{-1} and $q_m = 1/(20$ Å$)$, one obtains for the renormalization factor $r = 7\times10^{-6}$ Oe^{-1}. This is in good agreement with the value 8×10^{-6} Oe^{-1} obtained from the fit of theory to the field shift data.

In conclusion, we have shown that the variations of the FMR linewidth and resonance field shift in thin films of NiFe with film thickness, are quantitatively consistent with the theoretical predictions of Arias and Mills (AM) (Ref. 4) based on two-magnon scattering processes resulting from the presence of defects on the film surfaces.

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[1] W. Stoecklein, S. S. P. Parkin, and J. C. Scott, Phys. Rev. B **38**, 6847 (1988).
[2] W. Platow, A. N. Anisimov, G. L. Dunifer, M. Farle, and K. Baberschke, Phys. Rev. B **58**, 5611 (1998).
[3] J. R. Fermin, A. Azevedo, F. M. de Aguiar, B. Li, and S. M. Rezende, J. Appl. Phys. **85**, 7316 (1999).
[4] R. Arias and D. L. Mills, Phys. Rev. B **60**, 7395 (1999).
[5] M. Sparks, R. Loudon, and C. Kittel, Phys. Rev. **122**, 791 (1961).
[6] M. J. Hurben and C. E. Patton, J. Appl. Phys. **83**, 4344 (1998), and references therein.
[7] B. Heinrich, J. F. Cochran, and R. Hasegawa, J. Appl. Phys. **57**, 3690 (1985).
[8] R. D. McMichael, M. D. Stiles, P. J. Chen, and W. F. Egelhoff, Jr., J. Appl. Phys. **83**, 7037 (1998).
[9] B. Heinrich, in *Ultrathin Magnetic Structures II*, edited by B. Heinrich and J. A. C. Bland (Springer, Berlin, 1994), Chap. 3.
[10] C. Chappert, K. Le Dang, P. Beauvillain, H. Hurdequint, and D. Renard, Phys. Rev. B **34**, 3192 (1986).
[11] Yu. V. Goryunov, N. N. Garif'yanov, G. G. Khaliullin, I. A. Garifullin, L. R. Tagirov, F. Schreiber, Th. Mühge, and H. Zabel, Phys. Rev. B **52**, 13 450 (1995).
[12] N. S. Almeida and D. L. Mills, Phys. Rev. B **53**, 12 232 (1996).