Relaxation in epitaxial Fe films measured by ferromagnetic resonance

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We have measured the ferromagnetic resonance (FMR) frequency and field linewidths of thin epitaxial Fe films (grown using molecular beam epitaxy) using network-analyzer FMR and conventional FMR. From the linewidths, we determined quantitatively the intrinsic and extrinsic contribution to the Gilbert damping. The observed broadening of the linewidth for thinner Fe films is consistent with the two-magnon scattering mechanism proposed by Arias and Mills. The decrease of the linewidth as a function of film thickness is fit to a power law. This fit allows a determination of the intrinsic contribution to the linewidth. We find a frequency width = 0.147 GHz and field linewidth = 47 Oe. © *2004 American Institute of Physics.* [DOI: 10.1063/1.1689760]

INTRODUCTION

There has recently been renewed interest in studying the ferromagnetic resonance (FMR) linewidth[1–4] of magnetic thin films because of their technological relevance for magnetic recording at the nanosecond time scale. Magnetic thin films and multilayers have been the subject of much interest due to their fundamental differences in magnetic and electronic properties from their bulk counterparts. The thin film properties are greatly influenced by the presence of interfaces. The recent magnetoelectronic and spintronic devices in the nanosecond time regime are based on the unique properties of thin magnetic films. Therefore it is important to understand the relaxation[1–4] of magnetization, which is governed by spin interactions, and depends on the quality and structure of the interfaces. The magnetization dynamics of a magnetic film can be described by the Landau–Lifshitz–Gilbert equation, involving a Gilbert damping[1–5] constant α. The observed enhancement of α in ultrathin films over their bulk counterparts, below a certain film thickness,[1–4] was successfully explained theoretically[5] by two-magnon scattering mechanism.

In this investigation, we have measured the FMR frequency (Δf_{res}) and field (ΔH) linewidths of thin epitaxial Fe films using network-analyzer FMR (NA-FMR) by the flip-chip method and by conventional FMR techniques, respectively. The observed anomalous broadening of the linewidth and hence increased effective Gilbert damping (α_{eff}) for thinner Fe films, can be explained by a two-magnon scattering mechanism proposed by Arias and Mills (AM).[5] From Δf_{res} and ΔH, we determined quantitatively the intrinsic (α_{int}) and extrinsic (α_{ext}) contribution to effective Gilbert damping (α_{eff}).

EXPERIMENT

Epitaxial Fe films of 4–30 nm in thickness were grown by molecular beam epitaxy on GaAs(100) substrates with a background pressure better than 10^{-9} mbar. First, a 150 nm thick Ag(100) buffer layer was grown on top of a 1 nm seed layer of Fe. The Fe films were grown on top of the Ag and were protected by a thin cover layer of ZnSe. The Fe deposition rate was maintained at 0.01 nm/s. The samples were characterized by Auger electron spectroscopy, low energy electron diffraction, and reflection high energy electron diffraction. The coercivity (H_C) of the Fe films was determined by the magneto-optic Kerr effect hysteresis loops and found to be between 8 and 10 Oe, respectively.

The NA-FMR measurements were done with a Vector Network Analyzer (HP model 8510C) along with a Cascade microprobe station. NISTCAL software was used to obtain the complex scattering matrix (S parameters) of the thin film subtracting out the effect of the connections. The sample was mounted on top of an Ag coplaner waveguide (CPW), by employing the flip-chip technique. We characterized the Ag CPW transmission lines at frequencies from 0.5 to 20 GHz using the NIST MULTICAL software for through-short-line calibration process. The longest and the shortest lines used for the calibration were 0.71 and 0.25 cm to cover the entire frequency range of interest. We have also used a 24 GHz FMR system to study the resonance as a function of in-plane field angle. The peak-to-peak linewidth (ΔH) was measured from the differential FMR signal.

RESULTS AND DISCUSSION

Figure 1 shows the Network Analyzer spectrum for 4 and 10 nm thick Fe films at a fixed magnetic field 0.3 kOe. This field is well above the saturated state (coercivity 10 Oe) of the sample. The graph shows the thickness-dependent resonance frequency (f_{res}) and frequency linewidth (Δf_{res}) values. At 0.3 kOe, f_{res} shifted upward from 12.3 to 13.2 GHz, for a change from a 4 nm thick film to a 10 nm thick film. On the other hand Δf_{res} decreased from 0.46 to 0.23 GHz, for 4–10 nm film. It should be noted that above 12 nm of Fe, Δf_{res} as well as f_{res} are independent of thickness. Therefore, the ~1 GHz frequency shift for the thinnest sample studied here could be consistent with the magnon renormalization process arises due to two-magnon scattering. According to AM theory,[5] the downward shift of f_{res} for

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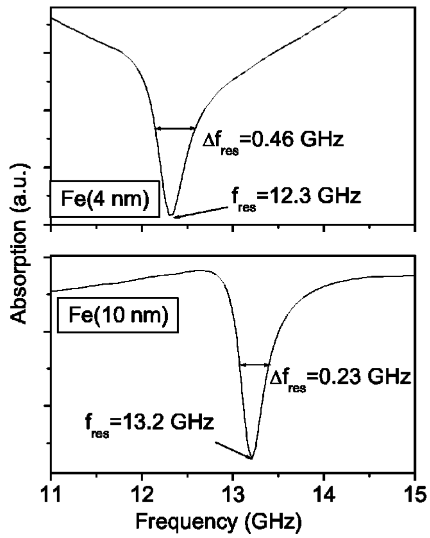

FIG. 1. NA-FMR spectrum showing the frequency linewidth as well as resonance frequency for Fe 4 nm (upper panel) and 10 nm (lower panel) films. The vertical scale is linear.

thinner Fe films is due to the roughness induced two-magnon scattering. However other effects, surface anisotropies for example, can also lead to the same outcome. The results of conventional FMR resonance field (H_{res}) and field linewidth (ΔH) are shown in Fig. 2. This figure shows a downward shift of H_{res} from 2.42 to 2.2 kOe and a decrease of ΔH from 105 to 65 Oe for 4–10 nm film. In conventional FMR, at a fixed frequency, the downward shift of f_{res} causes an upward shift of H_{res} for the thinner Fe films.

The changes in Δf_{res} and ΔH for various Fe film thicknesses are shown in Fig. 3 as solid points in log–log plots. Both ΔH and Δf_{res} decrease with increasing Fe film thickness. According to the AM theory,[5] the uniform precession $k=0$ mode can scatter off the defects and imperfections on the surfaces/interfaces into degenerate volume modes propagating along the film surface. For thinner samples, the broadening of the linewidth due to the increased damping and downward shift of the resonance frequency arises due to momentum nonconserving two-magnon interactions. Rewriting Eq. (91) of the AM theory[5] in terms of intrinsic and extrinsic contributions to the frequency and field linewidth we obtain

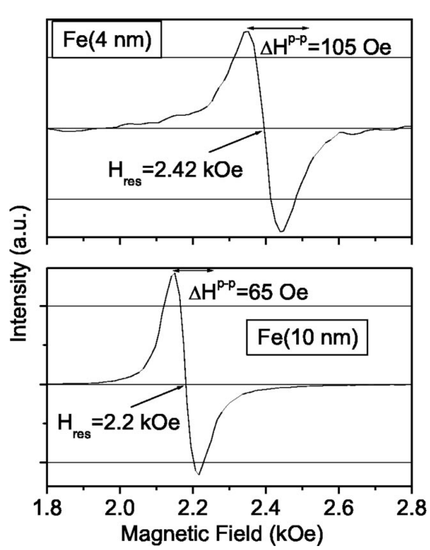

FIG. 2. Conventional in-plane FMR spectrum showing the FMR peak-to-peak linewidth and resonance field along easy directions for Fe 4 nm (upper panel) and 10 nm (lower panel) films.

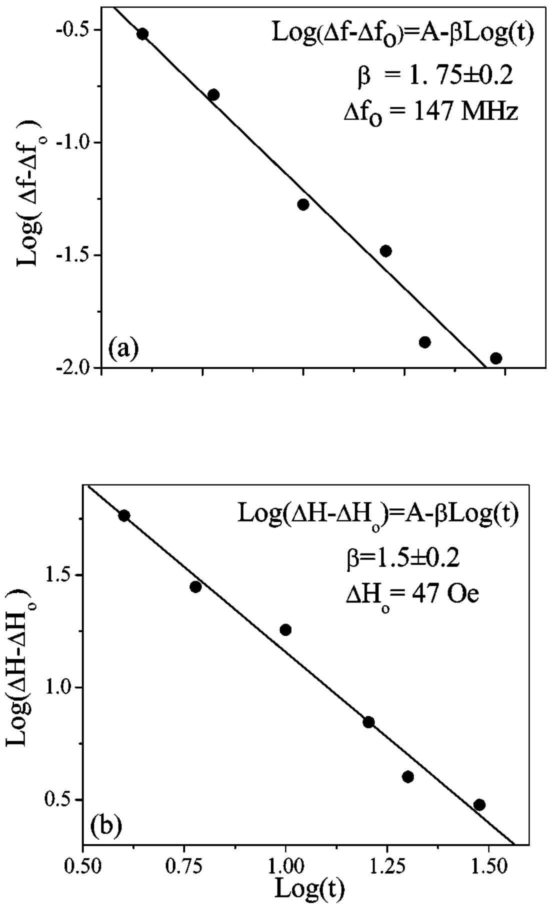

FIG. 3. Fe thickness dependence of NA-FMR frequency (upper panel) and field linewidth. Solid line represent the best fit.

$$\Delta f_{\mathrm{res}}=(\gamma\alpha/2\pi)(2H+4\pi M_S+2H_K)+(\Gamma/4\pi f_{\mathrm{res}})$$
$$=\Delta f^{\mathrm{int}}+\Delta f^{\mathrm{ext}}, \tag{1}$$

and

$$\Delta H=1.16(\alpha\omega/\gamma)+\lfloor\Gamma/(\gamma^2(2H+H_K+4\pi M_S))\rfloor$$
$$=\Delta H^{\mathrm{int}}+\Delta H^{\mathrm{ext}}, \tag{2}$$

where

$$\Gamma=(16sH_K^2\gamma^2/\pi D)\sqrt{H(2H+4\pi M_S+H_K)}. \tag{3}$$

The parameter Γ is related to a geometrical factor s and stiffness constant D. The factor s is related to the surface defect of a rectangular parallelepiped having faces parallel and perpendicular to the film plane. The first term of both Eqs. (1) and (2) is the intrinsic contribution to the linewidth, whereas and the second term is the extrinsic contribution. Inspection of Eqs. (1) and (2), especially the second term, indicates that the extrinsic contribution to linewidth increases as the film thickness decreases. In order to confirm the two-magnon contribution to linewidth broadening proposed by

Arias–Mills, it is necessary to separate the intrinsic and extrinsic contributions from both linewidths (frequency and field) and compare them quantitatively. The second term, which is the extrinsic contribution to the linewidth, is directly proportional to the square of the anisotropy. One expects the effective anisotropy constant has two contributions, i.e., $K_{\mathrm{eff}}=K_{\mathrm{bulk}}+K_{\mathrm{surface}}/\mathrm{thickness}$. For an ultrathin film the surface part often dominates. The films we deal with are somewhat thicker and it is not immediately obvious that a l/thickness term dominates. From our in-plane angular FMR measurements, we are able to determine the anisotropy field and find that a l/thickness behavior is appropriate below 10 nm. In this case the linewidth should be inversely proportional to square of sample thickness. Therefore, a fit of a t^{-2} function to both Δf_{res} and ΔH is consistent with a two-magnon contribution to linewidth, at least for the thinner films. We note that other forms for the thickness dependence have also been proposed. A t^{-1} behavior[6] should occur if the scattering centers are localized at the surface and directly remove energy from the spin system instead of just scattering the spin waves. A t^{-3} behavior has also been proposed for thicker films[7] using a two-magnon approach. We note that the applicability of the two-magnon theory versus a nonperturbative approach has recently been discussed.[8]

To determine the power law connecting linewidth to thickness and the thickness independent linewidth we have made a series of log–log plots assuming the correct power law is $\Delta H-\Delta H_0=A/t^{\beta}$. A similar formula holds for Δf. The best fits are shown in Fig. 3. We find a thickness independent linewidth $\Delta f_0=0.147$ GHz and $\Delta H_0=47$ Oe as the intrinsic contributions. The best fits also give $\beta=1.5\pm0.2$ for ΔH and $\beta=1.75\pm0.2$ for Δf. The quantitative conversion of Δf_0 obtained from the fit to ΔH_0, yields similar values for the intrinsic damping parameter (α_{int}) and gives $\alpha_{\mathrm{int}}=0.003$ from the frequency linewidth and $\alpha_{\mathrm{int}}=0.0043$ for the field linewidth. Since the β parameters are close to 2 it suggest the contribution to linewidth broadening proposed by Arias and Mills[5] is a reasonable explanation for the data.

The experiments in this study have the magnetic field in the plane of the sample. It has been pointed out[2] that an out-of-plane magnetic field, if sufficiently large, can drag the magnetization out of plane and eventually result in the disappearance of the two-magnon scattering mechanism. Unfortunately we were not able to test this because our experimental setup does not allow for the large fields (over 2 T) required.

CONCLUSION

In conclusion, we have shown that variation of the FMR linewidths as a function of film thickness in thin films of epitaxial Fe are qualitatively and quantitatively consistent with the two-magnon predictions of Arias and Mills. The downward resonance frequency shift for thinner Fe films is also an indication that the two-magnon scattering process results from defects and imperfections on the sample surface.

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