Exchange bias of NiO/NiFe: Linewidth broadening and anomalous spin-wave damping

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(Presented on 14 November 2002)

We studied sputtered NiO(150 nm)/NiFe exchange-biased films using Network Analyzer ferromagnetic resonance spectroscopy (NA-FMR) and Brillioin light scattering (BLS) techniques. The complex permeability spectra were obtained for NiO/NiFe films and were fitted to the Landau–Lifshitz–Gilbert equation to determine intrinsic and extrinsic contribution to Gilbert damping, in addition to other magnetic parameters. The exchange anisotropy (H_{EX}) was determined from the field variation data of NA-FMR resonance frequency (f_{res}) and BLS mode frequency (f_m). H_{EX} was observed to decreases as 1/thickness, from where we derive macroscopic interfacial exchange energy $J_E = 0.021$ erg/cm^2. Second, we investigated the relaxation mechanism in NiO/NiFe films from NA-FMR linewidth (Δf_{res}) for wave vector $k=0$ mode and from BLS mode linewidth (Δf_m) for $k \neq 0$ modes. Interestingly, we observed Δf_{res} to increase with increasing magnetic field but Δf_m was observed to decrease with increasing magnetic field. Therefore, it is confirmed that, the relaxation rate measured by FMR and BLS techniques is different. Δf_{res} was observed to increase with decreasing NiFe thickness and follows a t^{-2} fit function, from which we determine the local interfacial exchange energy $J_1 = 3.3$ erg/cm^2.
[DOI: 10.1063/1.1557964]

The phenomena of exchange bias (EB), discovered 4 decades ago by Meiklejohn and Bean,[1] is primarily due to the interaction between ferromagnetic (F) and antiferromagnetic (AF) films at their interface. The effect produces a shift of the hysteresis loop in addition to an enhanced coercivity. The model by Mauri *et al.*[2] assumes the formation of a domain wall in the antiferromagnet parallel to the interface. Malozemoff[3] interpreted exchange bias in terms of random exchange fields due to interface roughness. The recent reviews[4,5] outlined many theoretical and experimental approaches to this problem. There are many uncertainties including the origin of exchange bias,[3–5] relaxation phenomenon, and line broadening,[6,7] etc. which require more research to gain better understanding.

Ferromagnetic resonance (FMR) is a very sensitive technique which can be used to study exchange-biased structures. In addition to using the FMR frequency (f_{res}) to determine H_{EX}, the frequency linewidth (Δf_{res}) is a direct measure of the relaxation rate of the uniform precession and the structural quality of the EB films. The relaxation rate ($\tau_m = 1/2\pi\Delta f_{res}$) is a direct measure of the coupling energy at the interface. The line broadening studied recently by various workers,[6–9] is attributed to the local variation of exchange field at the F/AF interface due to relaxation via a two-magnon scattering process.

However, no quantitative analysis of intrinsic and extrinsic contribution to Gilbert damping has been done so far on the EB system. This article deals with an evaluation of the Gilbert damping parameters from linewidth data from network analyzer ferromagnetic resonance (NA-FMR) spectroscopy.

We deposited polycrystalline NiO/NiFe exchange bias films on Si substrates using a dc magnetron sputtering system with a base pressure of 10^{-8} Torr. The films were deposited with a small external magnetic field in the sample plane to induce a uniaxial anisotropy (H_U) in the NiFe layer and to define the direction of the EB axis. Permalloy and NiO were deposited at a rate of 1 Å/s. First the NiO film was grown and the thickness was kept constant at 150 nm for all the films. The NiFe film was grown on NiO with thickness (t_{Py}) of 2.5, 10, 15, 25, 30, 35, 40, 45, and 50 nm. At the end, 5 nm of Cu was grown to cover the NiFe layer.

In the NA-FMR technique, we used a vector network analyzer (HP-8720B) to measure the complex **S** parameters of the EB films. The film was placed across a coaxial receptacle to produce an electric short circuit between the center ($d_1 = 0.135$ cm) and outer ($d_2 = 0.4$ cm) conductors of the 50 Ω transmission line. The rf excitation cell was designed for a cutoff frequency $f_C = 2c/\{\pi(d_2+d_1)\sqrt{\varepsilon_r}\} = 28$ GHz (c is velocity of light, ε_r is Teflon dielectric constant) and characteristic impedance $Z = \{60/\sqrt{\varepsilon_r}\}\ln(d_2/d_1) = 50\ \Omega$. The complex S parameters ($\mathbf{S}_{11}$) were measured over a continuous frequency range of 1 MHz–10 GHz. In this configuration, h_{RF} is aligned perpendicular to the EB axis and causes the magnetization to precess. From the S-parameters we obtain the permeability $\mu(\omega) = \mu'(\omega) + j\mu''(\omega) = 1 + \Delta Z/(j\mu_0 \mathrm{L} t_{Py}\omega)$, where $\Delta Z = Z_S$ (sample on substrate)–$\mathbf{Z}_S$ (only substrate) with $\mathbf{Z}_\mathbf{S} = Z_0[(1+\mathbf{S}_{11})/(1-\mathbf{S}_{11})]$. Z_0 is the free space impedance and $L = \ln(d_2/d_1)$. To determine H_{EX} we applied different magnetic fields (H) along and opposite to the EB axis for each frequency sweep.

For the Brillouin light scattering (BLS) experiment, we used a laser light at a 45° angle of incidence on the sample and the backscattered light was collected by a computer controlled (2×3) pass tandem Fabry–Pérot interferometer.[6] The

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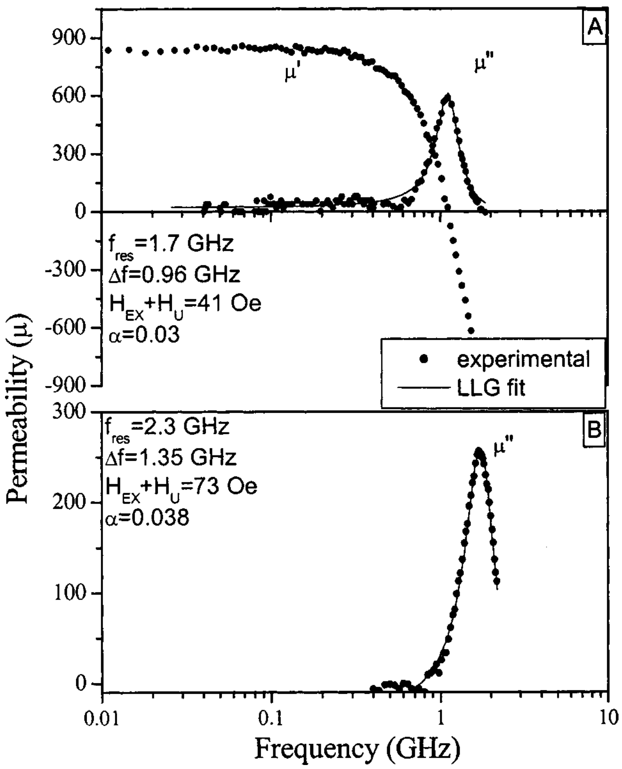

FIG. 1. Real and imaginary permeability for exchange-biased NiO(150 nm)/NiFe(15 nm) [part (A)], NiO(150 nm)/NiFe(10 nm) [part (B)] films. The solid lines are fit to LLG equation.

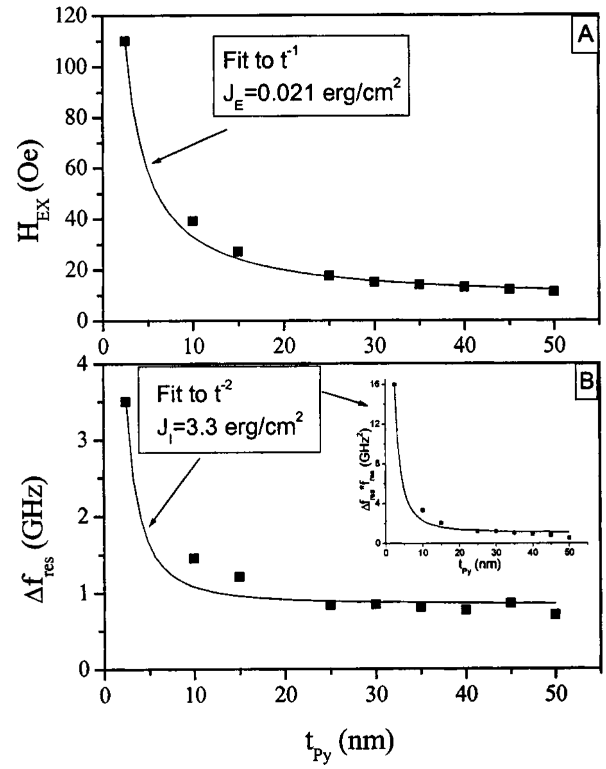

FIG. 2. Thickness dependence of exchange anisotropy [part (A)] and frequency linewidth [part (B)] in NiO(150 nm)/NiFe(t). The lines are fit to t^{-1} and t^{-2} functions to determine J_E and J_I from H_{EX} and Δf_{res} data, respectively. The inset to part (B) is a plot of normalized linewidth ($\Delta f^*_{res} f_{res}$) with t_{Py} also showing a fit to t^{-2} function.

surface modes (f_m) (for Stokes and anti Stokes) were observed with a magnetic field applied parallel and antiparallel to the EB axis.

Figure 1 shows the real (μ') and the imaginary (μ'') parts of the complex permeability (μ) versus frequency at $H=0$ for the EB films with NiFe thicknesses of 15 nm [part (A)] and 10 nm [part (B)]. Figure 1(A) shows μ' crosses zero with a sign change at 1.7 GHz where μ'' shows a maximum. This frequency corresponds to the resonance frequency. Figure 1(B) shows a maximum of μ'' at 2.3 GHz. The solid lines for the μ'' curve were derived from the Landau–Lifshitz–Gilbert (LLG) equation of motion, taking into account the demagnetizing, the anisotropy parameters, etc. We obtain

$$\mu''=\frac{\gamma 4\pi M_S\omega\alpha[\gamma^2(4\pi M_S+H_{\mathrm{eff}})^2(1+\alpha^2)+\omega^2]}{[\omega_r^2(1+\alpha^2)-\omega^2]^2+[\alpha\omega\gamma(4\pi M_S+2H_{\mathrm{eff}})]^2}. \quad (1)$$

The parameters used in Eq. (1) are the gyromagnetic ratio [$\gamma=1.76\times 10^7$ Hz/Oe], the saturation magnetization of NiFe ($4\pi M_S=10$ kOe), $\omega_r=2\pi f_{res}=[\gamma\{(4\pi M_S+H_{EX}+H_U)(H_{EX}+H_U)\}^{1/2}]$, $\Delta\omega=2\pi\Delta f_{res}=[\alpha\gamma(4\pi M_S+2H_{EX}+2H_U)]$, and $H_{eff}=H_{EX}+H_U$. The four parameters derived from the fit are f_{res}, Δf_{res}, $H_{eff}=H_{EX}+H_U$ and the Gilbert damping parameter α. The shift in the resonance frequency for different thicknesses of Permalloy, t_{Py}, is due to different values of H_{EX}. According to Arias–Mills,[9] the two-magnon contribution to the linewidth is zero as $f\rightarrow 0$ (hence $H=0$). This is because as $H\rightarrow 0$, the phase space available to the final state spin waves becomes increasingly smaller. Therefore, α obtained at zero frequency ($\alpha=0.018$ for 50 nm to $\alpha=0.043$ for 2.5 nm) is the intrinsic Gilbert damping (α_{int}). The broadening of Δf_{res} and hence higher α_{int} for thinner NiFe film (2.5 nm) may be due to thickness fluctuations in NiFe.[9]

The exchange anisotropy (H_{EX}) was obtained from NA-FMR resonance frequency (f_{res}) and from the BLS mode frequency (f_m) data and fit with the torque equation.[7,8] Figures 2(A) and 2(B) show H_{EX} and Δf_{res} ($H=0.3$ kOe) versus t_{Py}, respectively. Both H_{EX} and Δf_{res} decrease with increasing t_{Py}. The decrease of H_{EX} is best fit to t^{-1} and Δf_{res} to t^{-2} functions and is shown as solid lines in the figures. The linear dependence of H_{EX} to t^{-1} indicates the interfacial origin of the observed exchange bias field and yields a coupling energy[3,4,8] at the NiO/NiFe interface ($J_E=H_{EX}M_St_{Py}$) of 0.021 erg/cm^2.

Δf_{res} decreases substantially below 20 nm NiFe in the EB films [see inset in Fig. 2(B)]. Since Δf_{res} changes with f_{res} for different t_{Py} at a fixed magnetic field, we normalized it (by multiplying by f_{res}) and fit the result to a t^{-2} function. Following the Arias–Mills[9] theory, we relate Δf_{res} to the local interfacial exchange energy (J_I) of an EB system by

$$\Delta f_{res}=K(J_I/K_S t)^2 \Rightarrow \Delta f_{res}\propto t^{-2}, \quad (2)$$

where the parameter K deals with surface defects (parameters used are close to those in Ref. 8). The thicker samples exhibit a thickness independent linewidth (~0.8 GHz) which is attributed to the intrinsic linewidth. The rise in Δf_{res} for thinner samples can be claimed to be due to an extrinsic mecha-

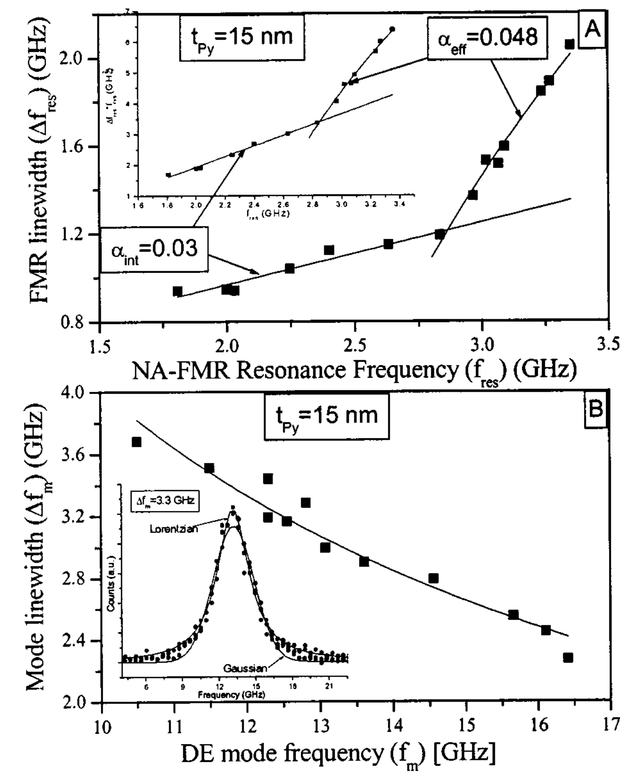

FIG. 3. (A) NA-FMR resonance linewidth and (B) BLS mode linewidth as a function of FMR frequency (f_{res}) and BLS mode frequency (f_m), respectively. The solid lines to parts (A) and (B) are fits to Eqs. (3) and (4), respectively.

nism, dominated by two-magnon scattering. The BLS linewidth also follows a t^{-2} fit. Therefore, NA-FMR ($k=0$ magnons) and BLS ($k\neq 0$ magnons) linewidth data are consistently explained[7–9] by the two-magnon scattering processes. The fit yields $J_I=3.3$ erg/cm^2 and is 2 orders of magnitude larger than J_E, the macroscopic exchange energy.

Figure 3 shows the frequency variation of the NA-FMR linewidth [Δf_{res}: part (A)] and the BLS mode linewidth [Δf_m: part (B)]. Δf_{res} is observed to increase with the increase of f_{res}, whereas Δf_m decreases with increasing f_m. A marked slope change of Δf_{res} versus f_{res} above 2.75 GHz was also observed. The increase of Δf_{res} is attributed to intrinsic and extrinsic contributions. The intrinsic contribution (Δf_{int}) comes from damping, whereas, the extrinsic linewidth (Δf_{ext}) is associated with the magnetic inhomogeneities within the material (surface and interface roughness) and the anisotropic dispersion. The linewidth is modeled theoretically by considering the recent Arias–Mills theory.[9] We relate Γ [Eq. (55) of Ref. 9] to Δf_{res}, for the NA-FMR data analysis and obtain

$$\Delta f_{res}=(\gamma\alpha/2\pi)(2H+4\pi M_S+2H_{eff})+(\Gamma/4\pi f_{res}). \quad (3)$$

The Δf^{int} is the first term of Eq. (3) and increases as f_{res} increases. The $\Delta f^{ext}=\Gamma^{ext}(H)\sin^{-1}[H/(H+4\pi M_S+H_{eff})]^{1/2}$ (second term) is more complicated with increasing frequency (note the f_{res} term in denominator). Therefore, we plotted normalized f_{res} (i.e., $\Delta f^*_{res} f_{res}$) with f_{res} [Fig. 3(A) inset]. The effective Gilbert damping ($\alpha_{eff}=\alpha_{int}+\alpha_{ext}$) was obtained from the fitting of high frequency side Δf_{res} data to Eq. (3), where two-magnon scattering provides the dominant contribution. The fitting of the first term of Eq. (3) to the low frequency side data for Δf_{res} gives the intrinsic Gilbert damping (α_{int}) with negligible contribution from two-magnon scattering. The fitting of $\Delta f^*_{res} f_{res}$ to Eq. (3) also yields almost the same values. The value of α_{ext} increased from 0.008 for 50 nm NiFe film to 0.03 for 2.5 nm thick NiFe film. The thinner NiFe EB films have a much higher α_{ext} than the thicker films. This is another indication of strong two-magnon contribution to the extrinsic damping mechanism.

Interestingly, the BLS linewidth data shows completely opposite behavior to the resonance frequency [see Fig. 3(B)]. The magnon mode linewidth (Δf_m) decreases with the increase of mode frequency. The main possibilities to explain this behavior are as follows: (i) the thickness of the ferromagnet and antiferromagnet fluctuate spatially. Since the EB field varies as l/t_{Py} this leads to an increase in linewidth. This results in a Gaussian line shape for the magnon modes in the BLS spectrum. (ii) The increased damping of spinwaves at the $F/$AF interface is due to the dragging of some AF spins by the excited F spins. This results in a Lorentzian line shape. The inset to Fig. 3(B) shows a magnon mode lineshape and the fitting to Lorentzian and Gaussian curves. Our BLS line shapes are closer to the Lorentzian form at the peak. The falling edges and the wings are mixture of both Lorentzian and Gaussian line shapes. Hence, the broadening is a mixture of both mechanisms. The symmetric lineshape of the magnon mode confirms that the broadening due to the sampling of magnon modes for a finite q range, i.e., $(\partial f_m/\partial q)$, is negligible ($\sim$0.02 GHz).

The decrease of Δf_m with the increase of f_m can be explained quantitatively by considering the Arias–Mills theory[9] using Rezende *et al.*'s approach.[8] Magnon linewidth for $k>0$ mode can be expressed as

$$\Delta f_m=\lfloor(\gamma^2 p\langle A_d\rangle \times\langle\cos^2\theta\rangle 4\pi M_S\zeta)/(2\pi D f_m)\rfloor[(J_I)/(M_S t_{Py})]^2. \quad (4)$$

The parameters p, A_d, θ, and ζ are related to the geometry of a rectangular defect. D is the exchange stiffness of NiFe. By fitting the data of Δf_m versus f_m to Eq. (4) [the solid line in Fig. 3(B)], we obtain the local interfacial exchange energy $J_I=2.89$ erg/cm^2. This is close to the NA-FMR value (3.3 erg/cm^2).

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