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Magnetostriction and angular dependence of ferromagnetic resonance linewidth in Tb-doped $Ni_{0.8}Fe_{0.2}$ thin films

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We present the dependence of the magnetostriction in $Ni_{0.8}Fe_{0.2}$ films on Tb and Gd doping concentration and compare with the measured doping dependence of the high-frequency damping. While the magnetostriction and the high-frequency damping are correlated, the dependence is complicated. In particular, the high-frequency damping parameter α increases rapidly ($\alpha = 0.008-0.84$) with a modest increase in the magnetostriction ($\lambda_s = -0.6\times10^{-6}$ to 5.7×10^{-6}) for Tb doping concentrations up to 10%. For Gd doping, the high-frequency damping changes slowly (α=0.008–0.02) as the doping concentration is increased to 10%, whereas the increase in magnetostriction is similar to that observed in the Tb-doped films. Further, it is possible to achieve low magnetostriction ($\lambda_s = 2\times10^{-6}$) near the region of critical damping. Measurements of the angular dependence of the ferromagnetic resonance linewidth in Tb-doped $Ni_{0.8}Fe_{0.2}$ films show little change similar to the behavior observed in undoped $Ni_{0.8}Fe_{0.2}$ films, although the linewidths are considerably larger. This is in contrast to systems such as $Ni_{0.8}Fe_{0.2}$ on NiO, which have a large angular dependence indicating that the relaxation process proceeds through the generation of spin waves. The enhanced damping in the Tb-doped films appears, therefore, to be mediated through direct phonon generation. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1452708]

I. INTRODUCTION

Rare-earth doping has been shown to be an effective method to increase the high-frequency magnetic damping in ferromagnetic oxides[1–3] and transition-metal thin films.[4–6] In the case of microwave applications, increased damping, due to the presence of rare-earth impurities, is undesirable since low-loss materials are usually required. For real-time applications, such as magnetic recording write heads, read sensors, and magnetic random-access memory (MRAM), it may be desirable to increase the magnetic damping to reduce both unwanted oscillations occurring during high-speed sense operations and chaotic behavior occurring during memory-element switching. Several models have been introduced to explain the increased magnetic damping due to the addition of rare-earth impurities.[1,3,7,8] These models usually assume that the rare-earth impurities act as an intermediate system that couples the magnetization to a thermal bath formed by the phonons. These models, however, do not describe in detail how the impurities couple to the lattice and do not address the possibility that the impurities can couple strongly to spin-wave excitations that subsequently relax by phonon emission. The details of how the long-wavelength magnetization excitations relax are important in determining the high-frequency performance of small magnetic devices.[9] If the magnetization relaxes through the generation of spin waves, the device response will decrease and become noisy. Further, for successive MRAM write operations, the switching threshold will vary considerably if a bit is reversed before the magnetic system has fully relaxed after an initial reversal.

In this article we examine how the magnetostriction of rare-earth-doped $Ni_{0.8}Fe_{0.2}$ films correlates with the high-frequency damping. It is expected that, if the rare-earth impurities couple efficiently to the lattice, the observed magnetostriction should increase with doping in a manner similar to that of the high-frequency damping. Tb (a non-*S*-state ion) and Gd (an *S*-state ion) dopants were used since these dopants were expected to give strong and weak spin-lattice coupling, respectively. If the increase in magnetostriction is too severe then rare-earth doping will not be a practical means of damping control. We found that high-frequency damping can be increased dramatically while maintaining magnetostriction within an acceptable range. Further, it was found that there was not a strict correlation between the increase in damping and magnetostriction.

The angular dependence of the ferromagnetic resonance (FMR) linewidth was measured to give an indication whether the doping-induced damping is due to the generation of phonons or spin waves. The FMR linewidth in the Tb-doped films showed a weak angular dependence similar to

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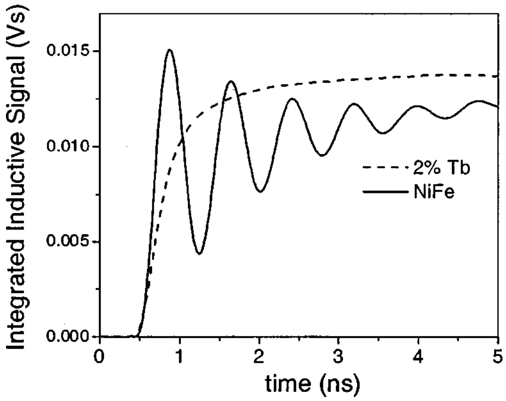

FIG. 1. Time dependence of the integrated inductive voltage of undoped and 2% Tb-doped 50 nm thick $Ni_{0.8}Fe_{0.2}$ films in response to a 60 ps rise-time step pulse. The integrated inductive signal is proportional to the average transverse magnetization. The undoped films show underdamped behavior with a damping constant of $\alpha=0.0082$. The 2% doped film shows a critically damped response with $\alpha=0.124$.

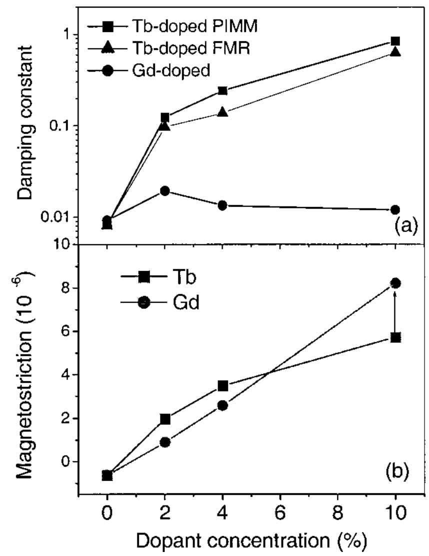

FIG. 2. (a) Damping constants of Tb-doped and Gd-doped 50 nm thick $Ni_{0.8}Fe_{0.2}$ films. (b) Saturated magnetostriction λ_s of Tb-doped and Gd-doped 50 nm thick $Ni_{0.8}Fe_{0.2}$ films. For the 10% Tb-doped film the anisotropy was larger than the applied field (3.2 kA/m, 40 Oe) and the arrow indicates the correction required to obtain λ_s.

that observed in undoped $Ni_{0.8}Fe_{0.2}$ films and quite different from the large angular dependence observed in systems that have strong spin-wave damping.

II. EXPERIMENT

Thin films of $(Ni_{0.8}Fe_{0.2})_{1-x}R_x$, where R=Tb or Gd and $0<x\leqslant 0.1$, were cosputtered onto oxidized silicon substrates. All films were 50 nm thick and deposited in a 10 kA/m magnetic field to induce a uniaxial anisotropy. The magnetostriction was measured with a beam-deflection system using 3.2 kA/m (40 Oe) rotating fields. The high-frequency response was measured with both a pulsed inductive microwave magnetometer (PIMM)[10] and traditional FMR techniques. The PIMM system measures the induced voltage produced by a time-varying thin-film magnetization generated in response to a 60 ps rise-time magnetic field pulse. The PIMM data were fit with the Landau–Liftshitz (LL) equation with a damping term given by $(-\alpha\gamma\mu_0/M_s)\mathbf{M}\times(\mathbf{M}\times\mathbf{H})$, where α is the damping constant, γ is the gyromagnetic ratio, M_s is the saturated magnetization, $\mathbf{M}$ is the film magnetization, and $\mathbf{H}$ is the total effective field. FMR measurements were done in a TE_{102} resonant cavity with an unloaded resonance frequency of $f_0=9.78$ GHz. The FMR linewidth was characterized as a function of the magnetization angle as the magnetic field angle was varied out of the plane of the film. The frequency linewidth, $\Delta\omega$, was obtained from the measured field linewidth, ΔH, using $\Delta\omega=(d\omega_{res}/dH)\Delta H$, where $d\omega_{res}/dH$ is the derivative of the resonant frequency with respect to the applied field.[11] The in-plane FMR damping constant was obtained from the measured in-plane field linewidth using $\Delta H=(2/\gamma\mu_0\sqrt{3})\alpha 2\pi f_0$.

Figure 1 shows the magnetization response of undoped and 2% Tb-doped, 50 nm thick $Ni_{0.8}Fe_{0.2}$ films being driven with a 60 ps rise-time 0.2 kA/m magnetic field pulse. A 1.0 kA/m bias field was applied along the easy axis. As seen, the undoped $Ni_{0.8}Fe_{0.2}$ is underdamped, with magnetization oscillations persisting up to 4 ns after the application of the drive pulse. The 2% doped film shows a more strongly damped magnetization rotation that attains its quiescent state in ~1 ns. The final rotation angle is ~8° for both data sets shown. The LL damping parameter α, obtained by fitting the real-time PIMM data, was 0.0082 for the undoped $Ni_{0.8}Fe_{0.2}$ and 0.124 for the 2% doped $Ni_{0.8}Fe_{0.2}$. The 2% Tb doped film is close to the critical-damping condition where the observed oscillations disappear.

Rare-earth-doped transition-metal films have been shown to retain most of their soft magnetic properties if the doping levels are low (<4%).[4–6] Further, low doping levels do not destroy desirable device properties such as giant magnetoresistance. Spin valves were fabricated using a standard 5 nm $Ni_{0.8}Fe_{0.2}$/1 nm $Co_{0.9}Fe_{0.1}$ free layer and a 5 nm $Ni_{0.8}Fe_{0.2}$ 2% Tb/1 nm $Co_{0.9}Fe_{0.1}$ free layer. The addition of Tb slightly increased the sheet resistance (23.8 to 25.2 Ω for antiparallel alignment) and decreased the magnetoresistance (8.0% to 5.4%). The impact of rare-earth doping could be further reduced by doping only the free-layer region farthest from the spacer interface.

III. MAGNETOSTRICTION AND FMR MEASUREMENTS

The saturated magnetostriction λ_s for Tb- and Gd-doped $Ni_{0.8}Fe_{0.2}$ films is shown in Fig. 2(b). For the 10% Tb-doped film, the applied field (3.2 kA/m, 40 Oe) was less than the anisotropy field (4.8 kA/m, 60 Oe) and the arrow in Fig. 2(b) indicates the approximate correction required to obtain the saturated magnetostriction from the measured magnetostriction. The magnetostriction of the undoped films is negative and shows a positive increase as the Tb and Gd doping increase. The behavior of the Tb- and Gd-doped series are very similar. There is a zero magnetostriction point near 1% doping, and at 2% doping the magnetostriction is $(1\text{ to }2)\times 10^{-6}$. This value is sufficiently low to allow this material to be used in GMR sensors or MRAM elements. The measured high-frequency damping, as determined from LL fits of

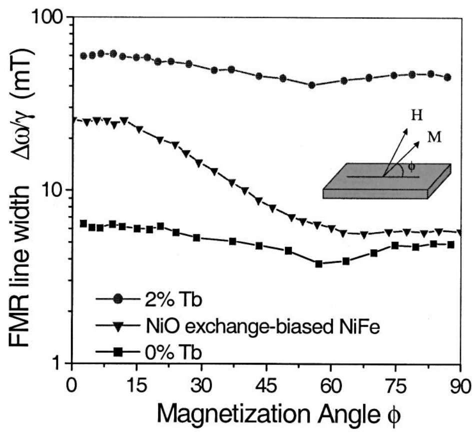

FIG. 3. The FMR frequency linewidth as a function of magnetization angle for 50 nm thick $Ni_{0.8}Fe_{0.2}$ and 2% Tb-doped $Ni_{0.8}Fe_{0.2}$ films. Also shown is the frequency linewidth for a 10 nm thick $Ni_{0.8}Fe_{0.2}$ film on NiO from Ref. 11. The Tb-doped film shows a similar angular dependence to that of the $Ni_{0.8}Fe_{0.2}$ film despite an overall factor of 10 increase in the damping. The $Ni_{0.8}Fe_{0.2}$ on NiO shows a qualitatively different angular dependence indicative of relaxation by spin-wave generation.

the PIMM data and in-plane FMR linewidth, is shown in Fig. 2(a) for both the Gd and Tb doped series. In contrast to the magnetostriction data, the high-frequency damping, for the Tb and Gd doped series, are very different. The Tb-doped series shows a rapid increase in damping whereas the Gd-doped series shows little variation. This result is consistent with earlier work on both ferromagnetic oxides[3] and transition-metal films.[4,5] Tb dopants, due to their nonzero orbital angular momentum, have anisotropic electron densities which cause lattice distortions when orbital moments rotate in response to transition-metal magnetization rotation.

The FMR frequency linewidths for an undoped and a 2% Tb-doped film, as a function of magnetization angle, are shown in Fig. 3 (the FMR linewidths have been normalized by the gyromagnetic ratio $\gamma = 1.76\times10^{11}\ \mathrm{T}^{-1}\ \mathrm{s}^{-1}$). Both the undoped and doped $Ni_{0.8}Fe_{0.2}$ films show similar angular dependence despite an overall increase in linewidth by a factor of 10. Both series show weak angular dependencies with a 30% decrease in the linewidth as the magnetization rotates out of the film plane. This decrease in linewidth is consistent with the decrease expected due to the change in ellipticity of the precession as the magnetization rotates out of plane assuming a constant α.[12] Both series show a weak minimum at a magnetization angle of $\phi = 55°$. The angular dependence of the FMR linewidth of a $Ni_{0.8}Fe_{0.2}$ film on NiO, from Ref. 11, is shown for comparison. In contrast to the $Ni_{0.8}Fe_{0.2}$ and 2% Tb-doped $Ni_{0.8}Fe_{0.2}$ films, the $Ni_{0.8}Fe_{0.2}$ film on NiO shows a strong angular dependence of the FMR linewidth, with a decrease in linewidth by a factor of 4.3 as the magnetization rotates out of the film plane. The strong angular dependence of the FMR linewidth for $Ni_{0.8}Fe_{0.2}$ on NiO has been interpreted as evidence for damping due to two-magnon processes.[11] The uniform magnetization relaxes by generating spin waves (magnons) created by the magnetic disorder in the exchange biasing at the $Ni_{0.8}Fe_{0.2}$–NiO interface. The strength of this relaxation is proportional to the number of degenerate spin-wave modes, which decreases rapidly as the magnetization rotates out of plane.

IV. DISCUSSION AND CONCLUSIONS

The angle-independent FMR linewidth lends support to the long-held conjecture that rare-earth impurities couple directly to the lattice. To confirm this conjecture, however, more work is needed to directly measure the spin-wave population excited during long-wavelength magnetization rotations. Even if the majority of energy flow is directly to the lattice, spin-wave generation may be present in sufficient quantities to affect device performance.

Our data indicate that, while magnetostriction and high-frequency damping are related, there is no prescribed dependence of damping on magnetostriction. In particular, critical damping can be engineered with low magnetostriction, and large magnetostriction can occur with low damping. While the presence of magnetostriction necessarily mandates a flow of energy into long-wavelength phonons,[13] this process is not the main mechanism of energy loss in the rare-earth-doped transition metals. Rather, the energy loss is most likely due to the generation of short-wavelength phonons and is determined by the details of the local ferrimagnetic order.[14] If the Tb ions have a strong random anisotropy (which competes with the antiferromagnetic Ni–Tb, Fe–Tb exchange interactions) then strong short-wavelength lattice distortions can be produced with little or no long-wavelength lattice distortions (magnetostriction).

Together, the demonstration of critically damped behavior with low magnetostriction and the suggestion that the majority of magnetic energy goes directly into phonons rather than spin waves, indicate that rare-earth doping may be a viable technique for the control of magnetic damping in spintronics applications.

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