Effect of light rare earth element Nd doping on magnetization dynamics in Co–Nb films

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$(Co_{0.85}Nb_{0.15})_{100-x}Nd_x$ (x=0, 1.1, 3.4, and 6.4) soft magnetic thin films have been prepared on Si substrates by oblique sputtering ~16°. The dynamic properties of the films were systematically investigated in a wide frequency range from 0.1 to 7 GHz. Strong enhancement of the damping parameter which is one key materials parameter that controls the dynamic response and the full width at half maximum of the imaginary permeability spectra were observed when Nd element was doped. The fitted value of the damping parameter for $(Co_{0.85}Nb_{0.15})_{93.6}Nd_{6.4}$ film is around 0.1, which is almost one order larger than that 0.015 of $(Co_{0.85}Nb_{0.15})_{100}$ film. © *2010 American Institute of Physics*. [doi:10.1063/1.3383044]

I. INTRODUCTION

The dynamic response of magnetic materials is of fundamental interest and is essential for various applications in modern magnetic storage technology.[1] The applications of soft magnetic film materials are usually based on the analysis of the dynamic magnetic properties or the process of magnetization subjected to an effective magnetic anisotropy field $\mathbf{H}_{\mathrm{eff}}$ as given by the Landau–Lifshitz–Gilbert (LLG) equation[2]

$$\frac{d}{dt}\mathbf{M} = -\gamma\mathbf{M}\times\mathbf{H}_{\mathrm{eff}} + \frac{\alpha}{4\pi M_S}\left(\mathbf{M}\times\frac{d}{dt}\mathbf{M}\right), \qquad (1)$$

where γ is the gyromagnetic ratio, $\mathbf{M}$ is the instantaneous magnetization vector, and $4\pi M_s$ is the saturation magnetization of the film. The first term in Eq. (1) describes the gyroscopic precession of $\mathbf{M}$ with a characteristic precession or resonance frequency f_r proportional to $\mathbf{H}_{\mathrm{eff}}$.[3] The second term in Eq. (1) describes its dissipation. The dissipation, or magnetic damping, is described by the dimensionless constant α. Therefore, the key materials parameters which describe the dynamic response of soft magnetic thin films are the resonance frequency and the damping parameter.

For application it is desirable that the damping parameter and the resonance frequency of magnetic materials can be tuned independently. While the resonance frequency can be controlled relatively easily base on the bianisotropic picture[4] by, e.g., controlling the in-plane uniaxial magnetic anisotropy,[5,6] the ways to change the damping parameter are doping ferromagnetic (FM) thin films with transition metal elements,[7,8] depositing multilayer,[9,10] or diluting the FM material.[11–13] Previously most studies on this topic were focused on NiFe-based films and heavy rare earth element doping.[7–9,14–16]

Amorphous Co–Ti,[17] Co–Nb,[6] and Co–Zr (Ref. 18) thin films have attracted much attention since they have attractive soft magnetic properties, which are required in many high frequency applications.[19] In this work, we investigate the properties of Co–Nb thin films with doping low light rare earth element Nd. The soft magnetic properties of the samples are retained by doping Nd, and a tuning of the damping parameter α is achieved.

II. EXPERIMENT

$(Co_{0.85}Nb_{0.15})_{100-x}Nd_x$ (x=0, 1.1, 3.4, and 6.4, respectively) soft magnetic thin films with thickness ~160 nm were prepared by radio frequency sputtering on Si(111) substrates attached to a water cooling system. A Co plate of 70 mm in diameter and 3 mm in thickness was used as the target on which Nb and Nd chips were placed. The composition of the deposited films was adjusted by controlling the number of the Nd chips, at the same time, the number and the location of the Nb chips remained unchanged. Films were deposited at an oblique angle of 16° to enhance the anisotropy field.[6,20] The oblique angle is defined as the angle between the normal direction of target and the line from the target center to the substrate center, as shown in Fig. 1 of Ref. 6. The background pressure was less than 2×10^{-5} Pa, and the working Ar pressure was 0.15 Pa with an Ar flow rate of 20 SCCM (SCCM denotes cubic centimeter per minute at STP), and the radio frequency power density was 1.7 W/cm^2. The compositions were measured by energy dispersive x-ray spectroscopy. The static magnetic measurements were performed using a vibrating sample magnetometer (Lakeshore model 7304). The microwave permeability measurements of the films were carried out with a PNA E8363B vector network analyzer using the microstrip method from 100 MHz to 7 GHz.[21] All the above measurements were carried out at room temperature.

III. RESULTS AND DISCUSSION

Figure 1 shows the in-plane magnetic hysteresis loops of the $(Co_{0.85}Nb_{0.15})_{100-x}Nd_x$ thin films. The static magnetic

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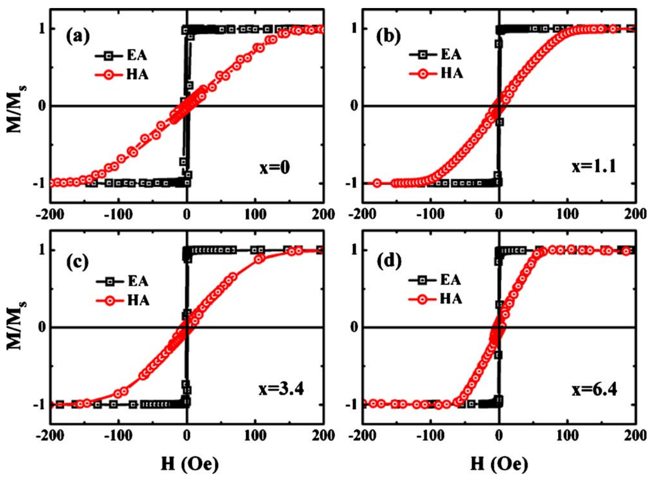

FIG. 1. (Color online) EA and HA magnetization loops of $(Co_{0.85}Nb_{0.15})_{100-x}Nd_x$ films with varying Nd concentration.

properties approximate ideal easy axis (EA) and hard axis (HA) loop shapes, as evidenced by high coercive squareness along the EA and near-zero remanence along the HA. Difference in the hysteresis loops measured along EA and HA exhibits an in-plane uniaxial magnetic anisotropy. The coercivity of all samples with Nd doping keeps low values, which looks insensitive to the Nd concentration. The dependence of coercivity and static magnetic anisotropy field on Nd composition for $(Co_{0.85}Nb_{0.15})_{100-x}Nd_x$ films is shown in Fig. 2. The coercivity along EA H_{ce} is slightly reduced from ~ 4 Oe for CoNb film to less than ~ 1 Oe within the Nd-doped films. From the *M-H* loops, the static magnetic anisotropy field $H_{k\text{-sta}}$ varying from 70 to 140 Oe is roughly estimated, which shows no coherent dependence on Nd concentration.

The permeability spectra of the films are shown in Fig. 3, where μ' and μ'' represent the real and imaginary parts of complex permeability, respectively. Compared to the static measurements of *M-H* loops shown in Fig. 1, the permeability spectra have more obvious dependence on the Nd concentration, indicated by shifting of resonance frequency and broadening of the peak width of the imaginary complex permeability

In order to determine the values of $4\pi M_s$ and dynamic anisotropy $H_{k\text{-dyn}}$, we measured the resonance frequency f_r,

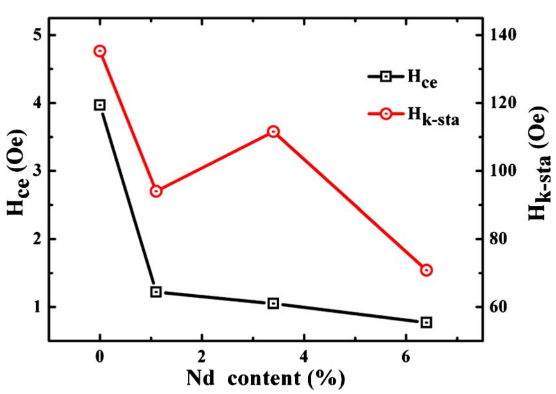

FIG. 2. (Color online) Dependence of EA coercivity H_{ce} and static magnetic anisotropy field $H_{k\text{-sta}}$ on the Nd concentration.

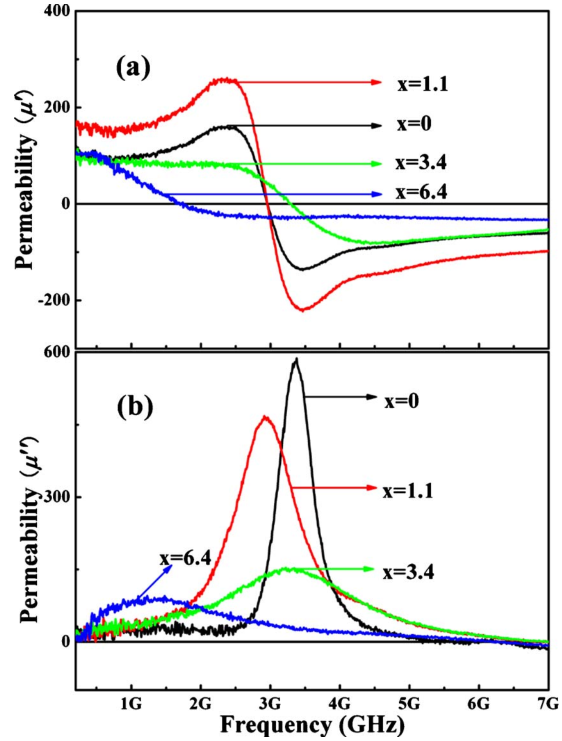

FIG. 3. (Color online) Frequency dependence of the real μ' (a) and imaginary μ'' (b) parts of complex permeability of $(Co_{0.85}Nb_{0.15})_{100-x}Nd_x$ films, respectively.

at which the μ'' show maximum, as a function of an applied magnetic field H_{appl} along in-plane EA. As shown in Fig. 4, the square value of f_r shows a linear relationship with H_{appl}, which indicates that the resonance mechanism of $(Co_{0.85}Nb_{0.15})_{100-x}Nd_x$ films is natural resonance. The permeability spectrum of a thin film corresponding to the uniform gyromagnetic resonance can be calculated from the LLG equation. In the limit $H_{k\text{-dyn}} \ll 4\pi M_s$, the resonance frequency can be simplified as[8]

$$f_r^2 = \gamma^2 4\pi M_S (H_{k\text{-dyn}} + H_{appl}), \qquad (2)$$

where $\gamma = 2.8$ GHz/kOe. Plotting f_r^2 as a function of H_{appl} then allows calculation of $4\pi M_s$ from the slope and of $H_{k\text{-dyn}}$ from the intersection with the abscissa. The saturated

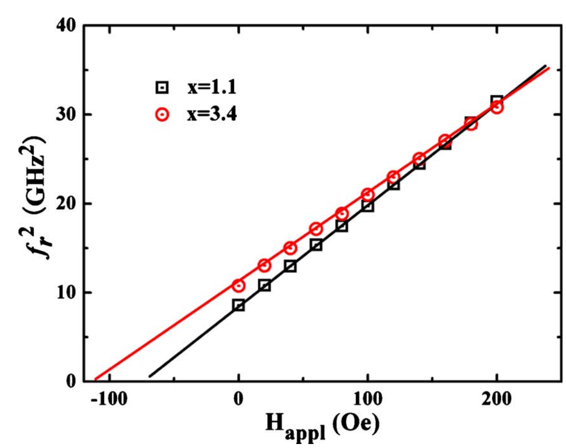

FIG. 4. (Color online) Dependence of the square of resonance frequency f_r^2 on the applied field H_{appl} of $(Co_{0.85}Nb_{0.15})_{100-x}Nd_x$ films.

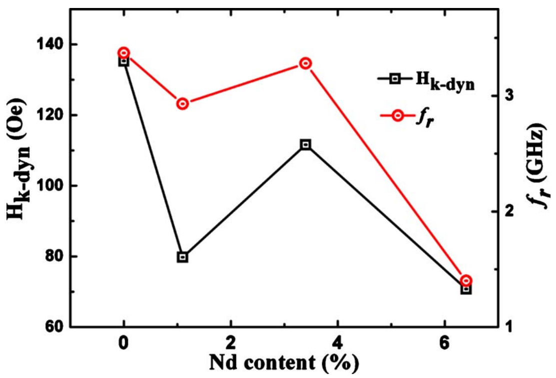

FIG. 5. (Color online) Dependence of EA dynamic anisotropy $H_{k\text{-dyn}}$ and resonance frequency f_r on the Nd concentration.

magnetizations $4\pi M_s = 14.6$ kOe and 12.7 kOe for $(Co_{0.85}Nb_{0.15})_{98.9}Nd_{1.1}$ and $(Co_{0.85}Nb_{0.15})_{96.6}Nd_{3.4}$ films can be obtained, respectively.

Figure 5 shows the values of $H_{k\text{-dyn}}$ and f_r at zero external field as a function of Nd concentration. The varying tendency of f_r is similar to $H_{k\text{-dyn}}$, but not entirely consistent since $f_r^2 \propto H_{k\text{-dyn}} 4\pi M_s$ at $H_{\text{appl}}=0$, and $4\pi M_s$ of Co–Nb film has been varied with the increase in Nd concentration. It can also be found that the dynamic anisotropy field obtained from the dynamic measurement is consistent with that from static measurement. The slight discrepancy between both values was also observed in other material systems.[22]

Based on the LLG equation, the permeability spectrum of an in-plane magnetized thin film can be expressed as[23,24]

$$\mu = 1 + \frac{f_m(f_0 + f_m + i\alpha f)}{f_r^2 - f^2 + if\Delta f_r}, \qquad (3)$$

where $f_m = \gamma 4\pi M_s / 2\pi$, $f_0 = \gamma H_{k\text{-dyn}} / 2\pi$, $f_r^2 = f_0^2 + f_m f_0$, and $\Delta f_r = \alpha(2f_0 + f_m)$. All the experimental results of permeability spectra in Fig. 3 can be fitted with Eq. (3). $4\pi M_s$ and $H_{k\text{-dyn}}$ take the values from Fig. 4. The fitted results of α is shown in Fig. 6. A linear relationship between α and Nd concentration is found. From the slope of the linear increase we determine the contribution to the total effective damping parameter of Nd concentration by the formula, $\alpha = \alpha_{\text{CoNb}} + C_{\text{Nd}} \alpha_{\text{Nd}}$,[14] where C_{Nd} is the Nd atomic concentration in percent. The value for α_{Nd} is 0.014, and $\alpha_{\text{CoNb}} \approx 0.013$ for

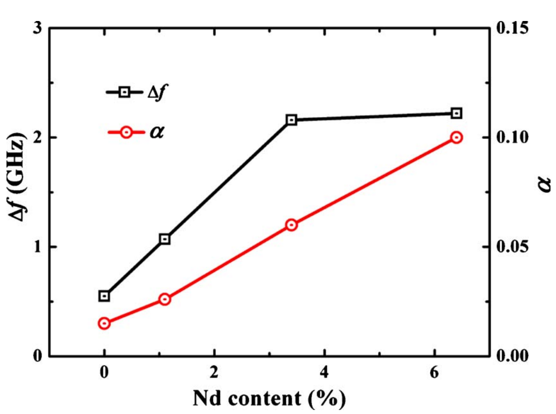

FIG. 6. (Color online) Dependence of the FWHM Δf and damping parameter α on the Nd concentration.

CoNb film, which are considerably larger than the bulk value $\alpha_{\text{Co}} \approx 0.005$ in Co.[25,26] In Fig. 3, the most obvious dependences of the spectra on the Nd concentration are that the resonance peak of the imaginary part grows gradually broader, and meanwhile the maximum peak value μ'' decreases.

By means of the imaginary part of the frequency-dependent permeability, the full width at half maximum (FWHM) Δf can be obtained with the results shown in Fig. 6. The pure Co–Nb film has a linewidth of about 0.55 GHz and the value increases in Nd-doped film and reaches 2.22 GHz for the Nd concentration of 6.4. Based on the relationship between Δf and α expressed as[27] $\Delta f \propto (4\pi M_s + H_{k\text{-sta}})\alpha$ for $\alpha \ll 1$, Δf should increase linearly with α when $4\pi M_s$ and $H_{k\text{-sta}}$ keep constant. But in this case, $4\pi M_s$ and $H_{k\text{-sta}}$ of the Co–Nb–Nd films are variables due to the introduction of Nd element. These give rise to the different dependence Δf and α on Nd concentration.

IV. CONCLUSION

In summary, we have developed an effective method to tune the magnetization dynamics in soft materials retaining the important soft magnetic properties. Although it is difficult to get an accurate dependence of the static anisotropy on Nd concentration, the resonance frequency is consistent with that of static anisotropy. This work also showed that the dynamic damping effect in the CoNb-based soft magnetic films could be greatly strengthened by doping light rare earth element Nd. The FWHM of imaginary permeability is broadened correspondingly.

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