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The growth temperature and measurement temperature dependences of soft magnetic properties and effective damping parameter of (FeCo)-Al alloy thin films

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The soft magnetic properties and effective damping parameters of Fe$_{73}$Co$_{25}$Al$_2$ alloy thin films are discussed. The effective damping parameter $\alpha_{\text{eff}}$ measured by ferromagnetic resonance for the 10 nm-thick sample is nearly constant ($\approx 0.004 \pm 0.0008$) for a growth temperature $T_s$ from ambient to 200 $^\circ$C, and then tends to decrease for higher temperatures and $\alpha_{\text{eff}}$ is $0.002 \pm 0.0004$ at $T_s = 300$ $^\circ$C. For the 80 nm-thick sample, the $\alpha_{\text{eff}}$ seems to increase with $T_s$ from $\alpha_{\text{eff}} = 0.001 \pm 0.0002$ at $T_s =$ ambient to $\alpha_{\text{eff}} = 0.002 \pm 0.0004$. The $\alpha_{\text{eff}}$ is found nearly constant ($\alpha_{\text{eff}} = 0.004 \pm 0.0008$) over a temperature range from 10 to 300 K for the 10 nm films with the different $T_s$ (ambient, 100 and 200 $^\circ$C). Together with an increasing non-linearity of the frequency dependence of the linewidth at low $T_s$, extrinsic contributions such as two-magnon scattering dominate the observed temperature dependence of effective damping and linewidth. © 2018 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/). https://doi.org/10.1063/1.5007744

I. INTRODUCTION

For future high frequency device applications of soft magnetic thin films, further improvement in saturation magnetization ($M_s$), permeability ($\mu$), coercivity ($H_c$), eddy current loss and damping parameter ($\alpha_{\text{eff}}$) is indispensable.1 Among many candidates of materials to choose, FeCo-based alloy thin films are attractive because they exhibit high $M_s$ and low $\alpha_{\text{eff}}$.2–5 A recent work on Fe$_{73}$Co$_{25}$Al$_2$ thin films reported the thickness dependence of effective damping parameter $\alpha_{\text{eff}}$ and showed the values of $\alpha_{\text{eff}} = 0.0004$ at about 85nm, indicating an attractive candidate as soft magnetic materials for future high frequency device applications.5 However, since the coercivity for those films was still high for any practical use, lowering coercivity is desirable. The present paper describes a systematic study of the growth- and measurement-temperature dependences of soft magnetic properties and damping parameter of Fe$_{73}$Co$_{25}$Al$_2$ thin films.

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II. EXPERIMENTAL

Multilayers of [Fe (0.45 nm)/Fe$_{66}$Co$_{34}$ (1.3 nm)/Al (0.038 nm)] x N were sputter-deposited onto MgO (100) by DC magnetron sputtering in Ar atmosphere of 4 mTorr, where N = 5 and 37, corresponding to the total thickness of 10 and 80 nm, respectively. The substrate-deposition temperatures (T$_s$) were varied from ambient to 350 °C. In order to induce a uniaxial magnetic anisotropy, an in-plane field of 50 Oe was applied during deposition. A 5 nm thick Ru layer was over-coated at ambient temperature for protection. The base pressure prior to deposition was better than 2 x 10$^{-7}$ Torr. The deposition rates for Fe, Fe$_{66}$Co$_{34}$ and Al were 0.15, 0.17 and 0.038 nm/s, respectively.

The film thicknesses were estimated by X-ray reflectivity. Structural analyses were performed by X-ray diffraction (XRD) with Cu K$_{α}$ radiation, high resolution transmission electron microscopy (TEM) and energy-dispersive X-ray spectroscopy (EDX). The composition of these samples was estimated as Fe$_{73}$Co$_{25}$Al$_{2}$ by EDX.$^5$ Measurements of magnetic properties were carried out by a vibrating sample magnetometer (VSM) in fields up to 10 kOe. Two different types of measurements for magnetization dynamics were carried out by ferromagnetic resonance (FMR); namely over a frequency range from (i) 12 to 66 GHz at room temperature and (ii) 10 to 40 GHz for a temperature range from 10 to 300 K.

III. RESULTS AND DISCUSSION

A. Growth temperature dependence

Figure 1 shows the XRD patterns for 80 nm-thick Fe$_{73}$Co$_{25}$Al$_{2}$ alloy thin films deposited onto MgO (100) substrate. Structural analyses were performed by X-ray diffraction (XRD) with Cu K$_{α}$ radiation, high resolution transmission electron microscopy (TEM) and energy-dispersive X-ray spectroscopy (EDX). The composition of these samples was estimated as Fe$_{73}$Co$_{25}$Al$_{2}$ by EDX.$^5$ Measurements of magnetic properties were carried out by a vibrating sample magnetometer (VSM) in fields up to 10 kOe. Two different types of measurements for magnetization dynamics were carried out by ferromagnetic resonance (FMR); namely over a frequency range from (i) 12 to 66 GHz at room temperature and (ii) 10 to 40 GHz for a temperature range from 10 to 300 K.

![FIG. 1. XRD patterns for Fe$_{73}$Co$_{25}$Al$_{2}$ alloy thin films deposited onto MgO (100) substrate. Low angle XRD patterns for the films deposited at 100 °C are shown in the inserted figure where blue line shows the pattern of (200)$_{FeCoAl}$ and red line shows of (200)$_{MgO}$.](image-url)
(200)_{bcc} separated at every 90 degree. In addition, it was also found that these peaks were shifted by 45 degree with respect to the peaks of (200)_{MgO}, indicating that the film is a single crystalline film with $<100>_{FeCoAl}/<110>_{MgO}$.

Figure 2 shows the TEM cross sectional image, together with the diffraction patterns for 50 nm-thick Fe$_{73}$Co$_{25}$Al$_{2}$ alloy thin films deposited at ambient temperature onto MgO (100) substrate. The TEM image shows the columnar structure grown along the film normal with the average width of about 20-30 nm. The diffraction patterns indicate that the film is polycrystalline film and its growth direction is $<110>_{FeCoAl}$, which is different of the films deposited above 100 °C.

Figure 3(a) are the M-H curves for the 10 nm-thick samples deposited at various $T_s$. These curves were measured along the direction of $<100>_{FeCoAl}$ and $<110>_{FeCoAl}$ by VSM. The shape of the curve measured along the direction of $<100>_{FeCoAl}$ is significantly changed from the sample with the $T_s$ of 100 °C to 200 °C, where the remanence $M_r$ becomes much higher with higher $T_s$. The values of $M_s$, $H_c$ and $M_r/M_s$ for the samples with the thicknesses of 10 and 80 nm deposited at various $T_s$ are summarized in Figure 3(b). It is seen that $M_r$ remains unchanged (1,600 emu/cm$^3$) with $T_s$. On the other hand, $H_c$ measured along the direction of $<100>_{FeCoAl}$ changes with $T_s$, becoming minimum at around 100 and 200 °C for the 10 and 80 nm-thick samples, respectively. The observed decrease of $H_c$ is probably caused by reducing a residual stress in the films which induces magnetic anisotropy through magneto-elastic effect. The $M_r/M_s$ measured along the $<110>_{FeCoAl}$...
decreases with $T_s$, becoming minimum at $T_s = 200 \, ^\circ\text{C}$. The $M_r/M_s$ along the $<100>_{\text{FeCoAl}}$ on the other hand, increases with $T_s$ and it becomes higher than that along the $<110>_{\text{FeCoAl}}$ above $T_s$ of 150 $^\circ$C.

Figure 4(a) shows the FMR linewidth $\Delta H$ as a function of resonance frequency $f_{\text{res}}$ for Fe$_{73}$Co$_{25}$Al$_2$ alloy thin films deposited at various $T_s$. The linewidth $\Delta H$ tends to decrease with $T_s$, and the linearity of these relationships is improved for higher $T_s$ over a wide range of frequency for the 10 nm-thick sample. However, for the 80 nm-thick film, the nonlinear frequency dependence of $\Delta H$ is found for $T_s = \text{ambient}$ and 100 $^\circ$C. As $T_s$ goes higher, the crystallinity becomes improved, as found by XRD and TEM. Therefore, one would expect the contributions of crystalline anisotropy field to the linewidth broadening which varies from grain to grain.

For the 10 nm thick sample fabricated at $T_s = \text{ambient temperature}$, the nonlinear linewidth evolution can be attributed as the characteristic of two-magnon scattering due to the boundary of Ru/FeCoAl, as shown by Lenz et al.\textsuperscript{7} The $\alpha_{\text{eff}}$ was estimated based on the linear relationship, as shown by a dotted line, fitted to the following equation.

$$\Delta H = \Delta H_0 + \frac{4\pi}{\sqrt{3}} \gamma \alpha_{\text{eff}} f_{\text{res}}.$$  

The result of $\alpha_{\text{eff}}$ as a function of $T_s$ is shown in Figure 4(b). It is found that the $\alpha_{\text{eff}}$ for the 10 nm-thick sample is nearly constant ($\approx 0.004 \pm 0.0008$) for $T_s$ from ambient to 200 $^\circ$C, and then tends to decrease for higher temperatures and $\alpha_{\text{eff}}$ is 0.002 $\pm$ 0.0004 at $T_s = 300 \, ^\circ$C. For the 80 nm-thick sample, although there is much scatter in the data points, the $\alpha_{\text{eff}}$ seems to increase with $T_s$ from $\alpha_{\text{eff}} = 0.001 \pm 0.0002$ at $T_s = \text{ambient}$ to $\alpha_{\text{eff}} = 0.002 \pm 0.0004$. It should be pointed out that the sample fabricated at $T_s = 150 \, ^\circ$C has $\alpha_{\text{eff}} = 0.0007 \pm 0.0002$, in agreement within an error with the value reported.\textsuperscript{5} As pointed out by Li et al.,\textsuperscript{8} there can be a contribution from eddy current even in relatively thin films. An estimation of damping parameter contribution of eddy current loss in a 80 nm-thick cobalt film is about 0.001, and therefore in the present study its contribution to the measured effective damping parameter may not be negligible for the 80 nm-thick samples. However, due to the quadratic dependence on the film thickness this contribution is negligible for the 10 nm-thick film. Angle dependent measurements of the $H_{\text{res}}$ and $\Delta H$ were also performed, showing a four fold symmetry for the resonance field, which is consistent with the in-plane XRD measurements, with the easy axis along the $<100>_{\text{FeCoAl}}$. 

FIG. 4. (a) FMR linewidth $\Delta H$ as a function of resonance frequency $f_{\text{res}}$ and (b) growth temperature $T_s$ dependence of effective damping parameter $\alpha_{\text{eff}}$ for Fe$_{73}$Co$_{25}$Al$_2$ alloy thin films deposited onto MgO (100) substrate. The reported result in Ref. 5 is shown as the red square.
FIG. 5. Measurement temperature dependence of effective damping parameter $\alpha_{\text{eff}}$ for Fe$_{73}$Co$_{25}$Al$_2$ alloy thin films deposited onto MgO (100) substrate at ambient, 100 and 200 °C with 10 nm thickness. Also shown are the results of Permalloy thin films and of YIG thin films.

B. Measurement-temperature dependence

Figure 5 shows the temperature dependence of $\alpha_{\text{eff}}$ for the 10 nm-thick films with different growth temperatures $T_s$, together with the data of permalloy and YIG thin films reported. For all the samples under consideration, the $\alpha_{\text{eff}}$ are nearly constant ($\alpha_{\text{eff}} = 0.004 \pm 0.0008$) over a temperature range from 10 to 300 K for the three different $T_s$ (ambient, 100 and 200 °C). On the other hand, the permalloy and the YIG thin films exhibit the decrease with decreasing temperature, although the permalloy film shows a slight increase for a range from 100 to 50 K. The present result of $\alpha_{\text{eff}}$ vs. $T$ is at variance with those results. It is noted that in the present study an increasing non-linearity of the frequency dependence of the linewidth at low growth temperatures was observed, therefore it is likely that extrinsic contributions such as two-magnon scattering dominate the observed temperature dependence of effective damping and linewidth. Although further studies are necessary, the present result of the $\alpha_{\text{eff}}$ which is insensitive to temperature suggests that a thin (around 10 nm-thick) Fe$_{73}$Co$_{25}$Al$_2$ alloy thin film may be useful for high frequency device applications.

IV. SUMMARY

The growth- and measurement-temperature dependences of soft magnetic properties and effective damping parameters of Fe$_{73}$Co$_{25}$Al$_2$ alloy thin films are discussed. The saturation magnetization $M_s$ is about 1,600 emu/cm$^3$, independent of thickness and the substrate deposition temperature $T_s$. Coercivity $H_c$ is found to decrease with $T_s$ up to around 100-200 °C, which is probably caused by reducing the stress in the film.

The effective damping parameter $\alpha_{\text{eff}}$ measured by ferromagnetic resonance (FMR) over a frequency range from 12 to 66 GHz at room temperature and over a temperature range from 10 to 300 K. For the 10 nm-thick sample the effective damping parameter is nearly constant ($\approx 0.004 \pm 0.0008$) for $T_s$ from ambient to 200 °C, and then tends to decrease for higher temperatures and $\alpha_{\text{eff}}$ is $0.002 \pm 0.0004$ at $T_s = 300$ °C. For the 80 nm-thick sample, the $\alpha_{\text{eff}}$ seems to increase with $T_s$ from $\alpha_{\text{eff}} = 0.001 \pm 0.0002$ at $T_s = $ ambient to $\alpha_{\text{eff}} = 0.002 \pm 0.0004$. As pointed out by Li et al., there can be a contribution from eddy currents even in relatively thin films. However, due to its quadratic thickness dependence eddy currents do not contribute significantly to the linewidth of the 10 nm film.
The temperature dependence of $\alpha_{\text{eff}}$ obtained for a frequency range from 10 to 40 GHz for the 10 nm films with the different growth temperatures $T_s$ (ambient, 100 and 200 °C) shows that the $\alpha_{\text{eff}}$ is nearly constant ($\alpha_{\text{eff}} = 0.004 \pm 0.0008$) over a temperature range from 10 to 300 K. Together with an increasing non-linearity of the frequency dependence of the linewidth at low growth temperatures, extrinsic contributions such as two-magnon scattering are likely responsible for the observed absence of a temperature dependence of the effective damping and linewidth.

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