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Magnetic damping constant of Co_2FeSi Heusler alloy thin film

Mikihiko Oogane,[a)] Resul Yilgin, Masatsugu Shinano, Satoshi Yakata, Yuya Sakuraba, Yasuo Ando, and Terunobu Miyazaki
Department of Applied Physics, Graduate School of Engineering, Tohoku University, Aoba-yama 05, Sendai 980-8579, Japan

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Co_2FeSi films were prepared using magnetron sputtering technique on Cr buffer layers and MgO(001) substrates at various annealing temperatures. We investigated the crystal structures, magnetic properties (M_s and H_c), surface roughness, and magnetic damping constants (α) of the prepared Co_2FeSi films. Out-of-plane angular dependences of the resonance field and the linewidth of the ferromagnetic resonance spectra were measured and fitted using the Landau-Lifshitz-Gilbert equation to determine the damping constant. The as-deposited Co_2FeSi film exhibited an amorphous and disordered structure; the α value was 0.008. In contrast, the Co_2FeSi films annealed over 300 °C showed epitaxial growth and had a (001)-oriented and $L2_1$ ordered structure. Both disordered and $L2_1$ ordered Co_2FeSi films showed similar α values. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2709751]

I. INTRODUCTION

Half-metallic ferromagnets (HMFs), which have full spin polarization, have attracted great interest because of their potential use in spin electronic devices such as magnetic random-access memory (MRAM). Some groups of full-Heusler alloys ($Co_2MnAlSi$, Co_2FeSi, Co_2MnSn, etc.) have been calculated theoretically to have a half-metallic band structure.[1–3] Recently, the large tunnel magnetoresistance (TMR) effect has been observed by several groups in magnetic tunnel junctions (MTJs) with full-Heusler alloy electrodes.[4–6] These results experimentally prove the half-metallicity of the Heusler alloys. Development of ferromagnetic materials with both high spin polarization and small magnetic damping constant (α) is extremely important for application in advanced spin electronic devices such as spin RAM, in which the control of magnetization is carried out using current-injected magnetization switching (CIMS) technique.[7,8] The switching current density for CIMS is proportional to the α value and the current density can be reduced by increasing the spin polarization.[8] Heusler alloys are considered to be ideal candidates to achieve high spin polarization at RT, but investigations of magnetic damping in Heusler alloys have remained limited.

In this study, we investigated crystal structures, magnetic properties, surface roughness, and magnetic damping constants of Co_2FeSi Heusler alloy films prepared using magnetron sputtering. Ferromagnetic resonance (FMR) technique was used to determine the damping constants of the prepared films. Out-of-plane angular dependences of the resonance field (H_R) and the linewidth (ΔH_{pp}) of the FMR spectra were measured and analyzed using the Landau-Lifshitz-Gilbert (LLG) equation, considering the effect of magnetic inhomogeneities in the films, as reported previously.[9]

a)Electronic mail: oogane@mlab.apph.tohoku.ac.jp

II. EXPERIMENTAL PROCEDURE

MgO(001) substrate/Cr(30 nm)/Co_2FeSi(30 nm) films were prepared using magnetron sputtering. A sputtering target used for Co_2FeSi layer had a stoichiometric CoFeSi (Co:Fe:Si=50:25:25) composition. The Cr buffer layer was deposited at ambient temperature followed by annealing at 700 °C. The (001)-oriented growth and very flat surface of the Cr buffer layer were confirmed, respectively, using x-ray diffraction (XRD) and atomic force microscopy (AFM). The Co_2FeSi films were grown on the Cr buffer layer at ambient temperature. The films were subsequently annealed at various temperatures (T_a). Results of XRD and AFM analyses, respectively, confirmed the crystal structure and surface roughness of the Co_2FeSi films. We measured magnetization curves using a vibrating sample magnetometer (VSM). The FMR measurements were carried out using an *X*-band (9.7 GHz) microwave source and a TE_{102} model cavity. The sample was fixed on a quartz rod and a goniometer was used to measure out-of-plane angular dependences of the resonance field and the linewidth of the FMR spectra.

III. RESULTS AND DISCUSSION

Figure 1(a) shows XRD patterns of Co_2FeSi films annealed at various T_a. The as-deposited film showed an amorphous and disordered structure because only (200)Cr peak was observed in the as-deposited film, except for peaks from MgO substrate. The (200) and (400)Co_2FeSi peaks were observed in films with T_a=300 and 400 °C, indicating a perfect (001)-preferred orientation. In addition, ideal epitaxial growth in the films with T_a=300 and 400 °C were confirmed from the ϕ scan for (111) and (220) peaks shown in Fig. 1(b). The XRD peaks with all odd (*hkl*) indices for full-Heusler alloy are known to originate in the superlattice reflection in the $L2_1$ structure with complete atomic order among Co, Fe, and Si sites. The (111) peak of $L2_1$ was observed clearly in the ϕ-scan profile for films with T_a=300

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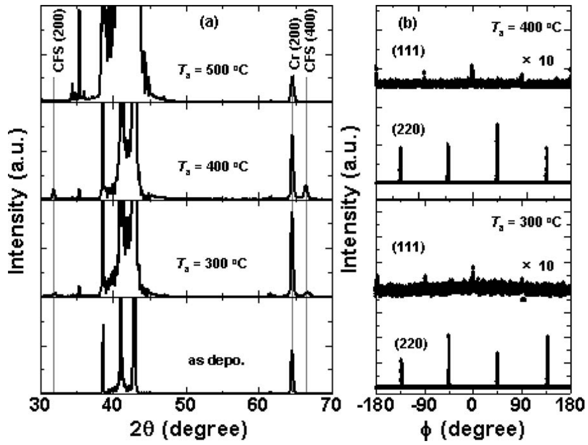

FIG. 1. (a) XRD (θ-2θ scan) patterns for Co_2FeSi films with various annealing temperatures (T_a). (b) and (c), respectively, show ϕ-scan profiles of films with T_a=400 and 300 °C.

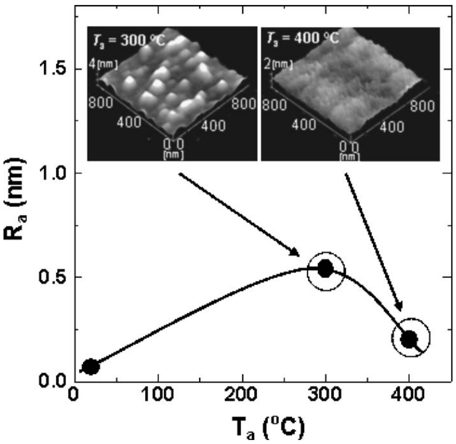

FIG. 3. Annealing temperature (T_a) dependence of surface average roughness for Co_2FeSi films. The insets show AFM images of the film with T_a =300 and 400 °C.

and 400 °C. Figure 1(a) shows that the peaks from Co_2FeSi had disappeared in the film with T_a=500 °C. We infer that the disappearance of the peaks from Co_2FeSi resulted from diffusion of the Cr buffer layer into the Co_2FeSi layer.

Figure 2(a) shows magnetization curves of the Co_2FeSi films with various T_a. Magnetization of the films increased steeply and saturated at low magnetic fields. This behavior agreed well with that of the bulk case, except for the film with T_a=400 °C. The film with T_a=500 °C showed no ferromagnetic property (the magnetization was almost zero). Figure 2(b) shows that the saturation magnetization exhibited a maximum at around T_a=300 °C. However, that maximum magnetization value is 20% smaller than that of the bulk case,[10] indicating that the film includes a certain amount of atomic site disorder. The decreased magnetization and increased coercive field for the film with T_a=400 °C are attributable to a certain amount of Cr diffusion into the Co_2FeSi layer.

We examined the effect of annealing temperature on surface roughness of the Co_2FeSi films. Figure 3 shows the average roughness (R_a) as a function of T_a. The insets are AFM images obtained on the surface of the Co_2FeSi films with T_a=300 °C (left) and T_a=400 °C (right). The scan area was 1000×1000 nm^2. The AFM image of the film with T_a =300 °C showed grain growth of the film, where R_a was about 0.5 nm. In contrast, the AFM image of the film with T_a=400 °C showed a very smooth and flat surface. We infer from the AFM result that the atomic interlayer mixing at the Cr/Co_2FeSi interface improved the surface morphology of the Co_2FeSi film.

Figures 4(a) and 4(b) show typical results of out-of-plane angular (θ_H) dependences of the resonance field (H_R) and the linewidth (ΔH_{pp}) of the FMR spectra for the Co_2FeSi film with T_a=300 °C, as indicated by open circles. The coordinate system for measurement of FMR spectra is shown in the inset of Fig. 4(c). The experimentally measured ΔH_{pp} is assumed to be expressed as $\Delta H_{pp}=\Delta H_{pp}^{\alpha}+\Delta H_{pp}^{4\pi M_{\rm eff}}+\Delta H_{pp}^{\theta_H}$. The linewidths attributable to intrinsic damping (ΔH_{pp}^{α}) and distributions of magnitude ($\Delta H_{pp}^{4\pi M_{\rm eff}}$) and direction ($\Delta H_{pp}^{\theta_H}$) of the effective demagnetization field in the films are expressed, respectively, as

$$\Delta H_{pp}^{\alpha} = \alpha(H_1 + H_2)\left|\frac{d(\omega/\gamma)}{dH_{\rm res}}\right|^{-1}, \qquad (1)$$

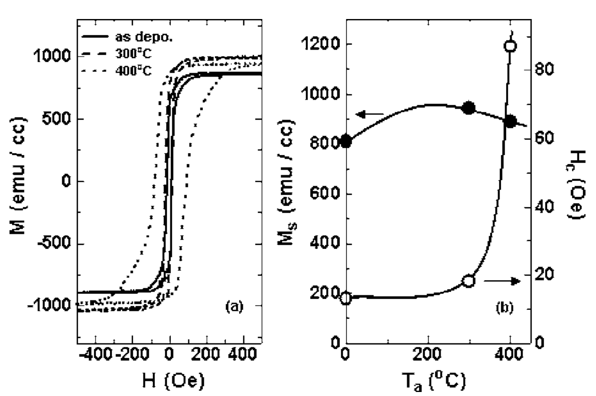

FIG. 2. (a) Magnetization curves for Co_2FeSi films annealed at various temperatures (T_a). (b) Saturation magnetization M_s and coercive field H_c as a function of T_a.

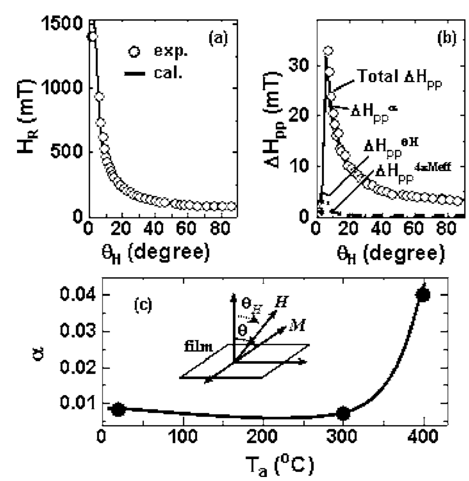

FIG. 4. Out-of-plane angular dependences of (a) resonance field and (b) linewidth of FMR spectrum for the Co_2FeSi film annealed at 300 °C. Open circles indicate the experimental results. Bold lines indicate the calculated H_R and total ΔH_{pp}. Thin, broken, and dotted lines, respectively, indicate ΔH due to intrinsic damping, distribution of the effective demagnetization, and fluctuation of θ_H. (c) Annealing temperature dependence of magnetic damping constant for Co_2FeSi films.

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$$\Delta H_{pp}^{4\pi M_{eff}} = \left| \frac{dH_{res}}{d(4\pi M_{eff})} \right| \Delta 4\pi M_{eff}, \tag{2}$$

$$\Delta H_{pp}^{\Delta\theta_H} = \left| \frac{dH_{res}}{d\theta_H} \right| \Delta\theta_H. \tag{3}$$

In those equations, ω is the microwave frequency and H_{res} is the resonance field that is given by the following relations, considering the Zeeman energy, the demagnetization energy, and the perpendicular magnetic anisotropy energy:

$$\omega/\gamma = \sqrt{H_1 H_2}, \tag{4}$$

$$H_1 = H_{res}\cos(\theta_H - \theta) - 4\pi M_{eff}\cos 2\theta, \tag{5}$$

$$H_2 = H_{res}\cos(\theta_H - \theta) - 4\pi M_{eff}\cos^2\theta. \tag{6}$$

We fitted our experimental results of angular dependences of H_R and ΔH_{pp} using Eqs. (1)–(6). Typical results of fitting for the Co_2FeSi film with T_a=300 °C are shown in Figs. 4(a) and 4(b), where the bold lines show the calculated angular dependences of H_R and total ΔH_{pp}. The thin, broken, and dotted lines in Fig. 4(b), respectively, indicate the results of calculations of ΔH_{pp}^{α}, $\Delta H_{pp}^{4\pi M_{eff}}$, and $\Delta H_{pp}^{\theta_H}$. The calculated results of H_R and ΔH_{pp} agree well with the experimental data. All α Gilbert damping constants obtained from fitting include error within 10%. Figure 4(c) shows the annealing temperature dependence of the α damping constants for the Co_2FeSi film. The as-deposited Co_2FeSi film showed the α value of 0.008, which is a similar α value to that for $Ni_{80}Fe_{20}$, as reported previously.[9] The α value of the film with T_a=300 °C was similar to that of the as-deposited film, although the crystal structure of the film with T_a=300 °C differed drastically from that of the as-deposited film. Annealing temperature dependence of the α value of Co_2FeSi Heusler alloy film differs from that of a Co_2MnAl Heusler alloy film reported previously.[11] Regarding the Co_2MnAl film, the α value decreased with increasing degree of atomic order by annealing process. Theoretical investigations are necessary to elucidate the electronic band structures of Co_2FeSi and Co_2MnAl with both an ordered and a disordered structure to clarify the origin of the different annealing temperature dependences between Co_2FeSi and Co_2MnAl films. The film with T_a=400 °C exhibited the large α value of 0.04. This large α value is also attributable to atomic mixing at the Cr/Co_2FeSi interface.

IV. SUMMARY

We investigated the crystal structure, magnetic properties, surface roughness, and magnetic damping constant of Co_2FeSi films with various annealing temperatures. The crystal structure of the as-deposited Co_2FeSi films was amorphous. On the other hand, the Co_2FeSi film with T_a =300 °C had (001)-oriented and $L2_1$ ordered structure. Both as-deposited and T_a=300 °C films exhibited a similar magnetic damping constant value: ~0.008. In the Co_2FeSi film with T_a=400 °C, the magnetization decreased and the coercive field and magnetic damping constant increased. Further investigations are necessary to clarify the relationship between these behaviors observed in the T_a=400 °C film and the interlayer mixing at the Cr/Co_2FeSi interface.

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