Intrinsic Gilbert Damping Constant in Co_2MnAl Heusler Alloy Films

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Intrinsic α-damping constants of Co_2MnAl Heusler alloy films prepared by magnetron sputtering were investigated. After deposition of Co_2MnAl films, the films were annealed at 200–400°C to control the crystal structure and the atomic order between Co, Mn, and Al sites. Ferromagnetic resonance (FMR) technique was used to obtain α values of Co_2MnAl films in this study. Out-of-plane angular dependences of the resonance field (H_R) and linewidth (ΔH_{pp}) of FMR spectra were measured and fitted using the Landau–Lifshitz–Gilbert (LLG) equation. The authors were able to fit all experimental results well because of the lack of inhomogeneities in prepared Co_2MnAl films. The α-damping constants obtained from the fitting results decreased with increasing annealing temperature and showed a minimum value of 0.007 at 300°C. It was found that a degree of B2 structure order can sensitively affect α-damping constants of Co_2MnAl films.

Index Terms—**Ferromagnetic resonance (FMR), Heusler alloy, linewidth, resonance field, α-Gilbert damping constant.**

I. Introduction

HEUSLER alloys have been studied intensively since the time when Heusler reported in 1903 that ferromagnetic alloys were producible from nonferromagnetic constituents copper–manganese bronze and group B elements [1]. Predictions of high spin polarization in some of Heusler alloys [2] indicate a large potential for application in spin-electronics devices, especially for producing magnetic random access memory (MRAM) [3]. However, the α-Gilbert damping constant of Heusler alloy films has not been investigated, even though the α-damping constant is extremely important for achieving high-speed magnetization switching.

Ferromagnetic resonance (FMR) technique is commonly used in the study of thin ferromagnetic films to determine magnetic properties such as g-factor, magnetization, magnetic anisotropy constant, spin relaxation time, and intrinsic α-Gilbert damping constant. Those magnetic properties can be estimated from the resonance peak position of FMR spectra. Thus, α-Gilbert damping parameter is related to the linewidth of FMR spectra [4].

α-Gilbert damping constants of Co_2MnAl Heusler alloy films in this work, prepared by magnetron sputtering and annealed at various temperatures, were investigated. α-Damping constants of the films were evaluated by analyzing the experimental results of out-of-plane angular dependence of H_R and ΔH_{pp} of FMR spectra.

II. Experiment

The 50-nm-thick Co_2MnAl films were grown on SiO_2 substrate by magnetron sputtering technique under 0.1 Pa Ar pressure. The base pressure was less than 5×10^{-7} Pa in the sputtering system. The prepared Co_2MnAl films were annealed at 200–400°C in a high-vacuum furnace. X-ray diffraction (XRD) method with Cu $K\alpha$ radiation confirmed the film structure. Saturation magnetization of the films was measured using superconducting quantum interference device (SQUID). 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 linewidth of FMR spectra.

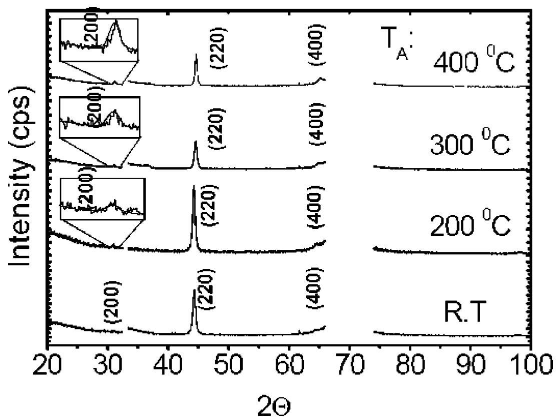

Fig. 1. XRD pattern of Co_2MnAl films at room temperature and annealing temperature (T_A) at 200–400°C.

III. Result and Discussion

Fig. 1 shows out-of-plane XRD patterns of Co_2MnAl films as prepared and annealed at 200–400°C. All prepared films showed (220) and small (400) peaks, but only for the as-prepared film: A (200) peak was not observed. The as-prepared film had an A2 structure with a disorder among Co, Mn, and Al sites. The (200) peaks of the B2 structure, revealing partial disorder between Mn and Al sites, were observed in diffraction patterns of the films annealed at over 200°C. The ratio of intensity of (200) and (220) peaks increased concomitant with increasing annealing temperature. The result indicated that a degree of B2 order in the film increased by annealing. Peaks originated from

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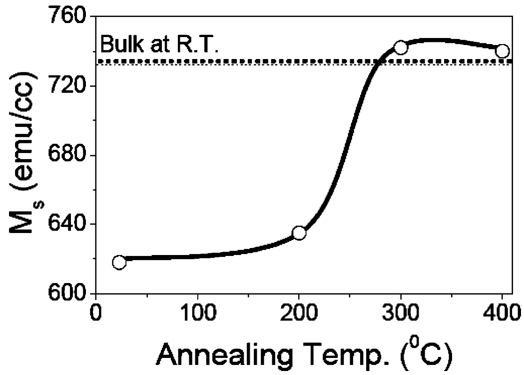

Fig. 2. Annealing temperature dependence of saturation magnetization (M_S) for Co_2MnAl.

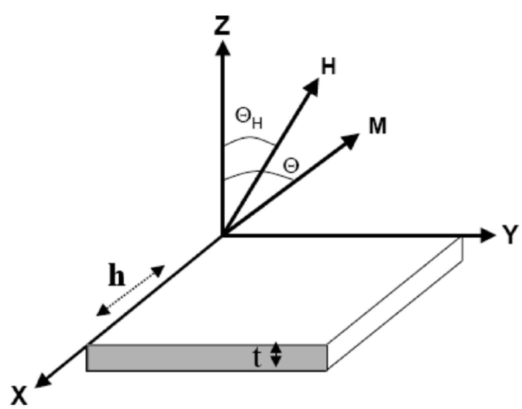

Fig. 3. Coordinate system used for measurement and analysis of the out-of-plane angular dependence of FMR.

$L2_1$ structure, revealing complete atomic order among all Co, Mn, and Al sites, were not observed.

Fig. 2 shows annealing temperature dependence of saturation magnetization (M_S) measured at room temperature. The M_S value increased with increasing annealing temperature and reached a value of bulk Co_2MnAl with B2 structure around 300°C. Miura *et al.* suggested that the disorder between Co and Mn sites can decrease saturation magnetization [5]. The result for M_S is consistent with X-ray results in Fig. 1. They indicated that almost all fractions of the films annealed at 300 and 400°C were B2 structure.

We performed measurements and numerical analyses of the out-of-plane angular dependence of FMR to evaluate the α-Gilbert damping constant for Co_2MnAl films with various annealing temperatures. The coordinate system for analysis and measurement is as shown in Fig. 3. In Fig. 3, $\mathbf{M}$, $\mathbf{H}$, and $\mathbf{h}$, respectively, indicate the vectors of magnetization, the external direct current (dc) magnetic field, and the external microwave field. $\mathbf{H}$ lies in the yz plane—its direction is defined as $\theta_{\mathbf{H}}$. The direction of $\mathbf{h}$ is parallel to the x-direction. All measured FMR spectra consisted mainly of broad and strong resonance absorption. Fig. 4(a) and (b) shows the typical result of $\theta_{\mathbf{H}}$ dependences of the resonance field (H_R) and resonance peak-to-peak linewidth (ΔH_{pp}), respectively.

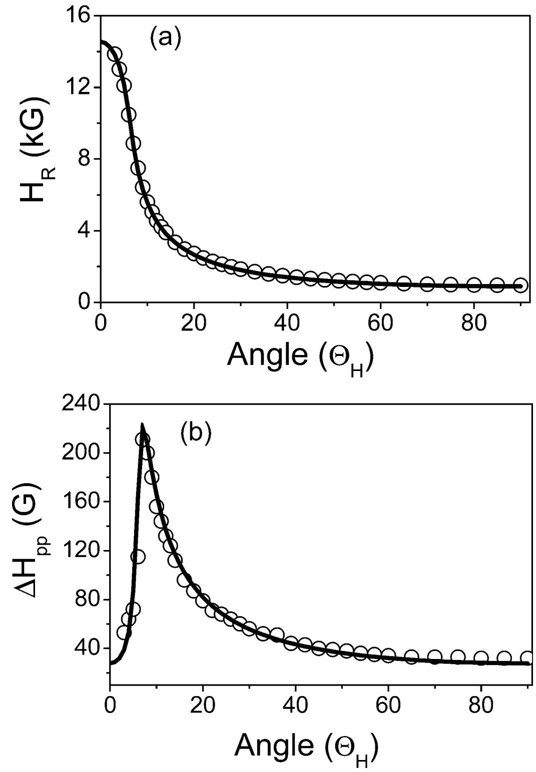

Fig. 4. (a) and (b) Typical angular dependence of resonance field (H_R) and linewidth (H_{pp}) of FMR spectra for the Co_2MnAl film annealed at 300°C. Open circles and solid lines, respectively, represent experimental and fitting results.

Dynamics of magnetization can be described using the Landau–Lifshitz–Gilbert (LLG) equation [6], [7]

$$\frac{d\mathbf{M}}{dt} = -\gamma(\mathbf{M}\times\mathbf{H}) + \frac{\alpha}{|\mathbf{M}|}\left(\mathbf{M}\times\frac{d\mathbf{M}}{dt}\right). \quad (1.1)$$

Here, $\mathbf{M}$ and $\mathbf{H}$, respectively, indicate the vectors of magnetization and the sum of the effective magnetic field acting on $\mathbf{M}$ and the external microwave field. The symbol γ and α, respectively, represent the gyro-magnetic ratio, defined as $\gamma = g\mu_B/h$, and the Gilbert damping constant. In (1.1), the first term represents magnetic precession and the second term represents damping of the motion. The resonance field (H_R) is obtainable from dispersion equation given by

$$\begin{aligned}\left(\frac{\omega}{\gamma}\right)^2 &= H_1 \times H_2\\ H_1 &= H_R\cos(\theta_H-\theta) - 4\pi M_{\text{eff}}\cos^2\theta\\ H_2 &= H_R\cos(\theta_H-\theta) - 4\pi M_{\text{eff}}\cos 2\theta. \quad (1.2)\end{aligned}$$

The theoretical ΔH_{pp} linewidth for FMR spectra is expressed as [4], [8]

$$\Delta H_{pp}^{\alpha} = \frac{1}{\sqrt{3}}\frac{\alpha}{M_S}\left(E_{\theta\theta} + \frac{E_{\phi\phi}}{\sin^2\theta}\right)\left|\frac{d\left(\frac{\omega}{\gamma}\right)}{dH_R}\right|^{-1}. \quad (1.3)$$

Therein, E is total energy and ω is microwave frequency.

Solid lines in Fig. 4(a) and (b), respectively, represent the fitting results using (1.2) and (1.3). The calculated data fit both

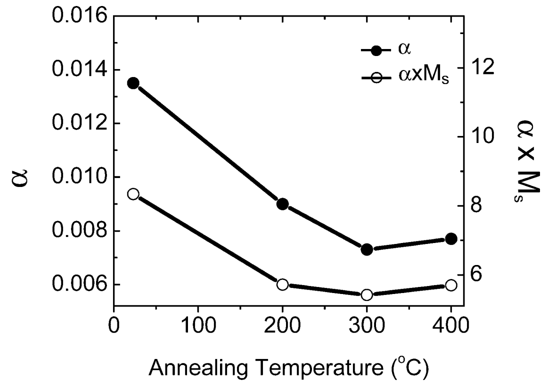

Fig. 5. Annealing temperature dependence of α value and $\alpha \times M_S$.

experimental data of H_R and ΔH_{pp}. We assumed the distribution of the effective field and the film's surface roughness, which could broaden the spectra, in the fitting of ΔH_{pp} as reported before [4]. However, we could fit the experimental data of ΔH_{pp} for all of the Co_2MnAl films with different annealing temperatures without inhomogeneous parameters. The fitting result indicates that all prepared Co_2MnAl films have very few inhomogeneities and the α-Gilbert damping constant were obtainable with high accuracy. Fig. 5 shows the annealing temperature dependence of the evaluated α-damping constant and $\alpha \times M_S$ of Co_2MnAl films. By increasing the annealing temperature, the damping constant decreased and showed a minimum value of 0.007 at 300°C of annealing temperature. The α-Gilbert damping constant is expected to be proportional to $1/M_S$ [9], [10]. However, Fig. 5 shows that $\alpha \times M_S$ also showed similar annealing temperature dependence of α. Therefore, in our case, M_S did not greatly affect the α value. We consider that α-damping constant of Co_2MnAl film was reduced by annealing, increasing a degree of B2 order. In ordered alloys, atomic disorder should affect damping of magnetization sensitively. The minimum α-damping constant observed for Co_2MnAl film was smaller than that of typical $Ni_{80}Fe_{20}$ thin film, 0.008, but M_S of Co_2MnAl is smaller than that of $Ni_{80}Fe_{20}$ [8]. We infer that the observed small α-damping constant of Co_2MnAl resulted from small spin–orbit interaction [10]. We will discuss the relation between the α-damping constant and spin–orbit interaction in detail elsewhere.

IV. Conclusion

The α-Gilbert damping parameter of Co_2MnAl films with different annealing temperatures was investigated. The obtained X-ray results confirmed that the film grown on a room temperature substrate had an A2 structure, whereas the degree of B2 order increased with increasing annealing temperature. The M_S of Co_2MnAl films also increased with increasing annealing temperature. The α-damping constant of prepared Co_2MnAl films was evaluated, analyzing out-of-plane angular dependence of H_R and ΔH_{pp} of FMR spectra. The authors were able to fit the experimental results very well by using the Landau–Lifshitz–Gilbert (LLG) equation; no inhomogeneous parameters were used for fitting. It was found that the α-damping constant decreased with increasing annealing temperature and showed a minimum value of 0.007 at around 300°C of annealing temperature. The degree of B2 order in the Co_2MnAl film is inferred to sensitively affect the α-damping constant.

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