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Temperature Dependence of Magnetic Damping in Heusler Alloy Thin Films

M. Oogane[1], S. Mizukami[2], Y. Kota[1], T. Kubota[2], H. Naganuma[1] A. Sakuma[1] and Y. Ando[1]

[1]Graduate School of Engineering, Tohoku University
6-6-05, Aramaki, Aoba-ku, Sendai, Miyagi 980-8579, Japan
Phone: +81-22-795-7949 E-mail: oogane@mlab.apph.tohoku.ac.jp
[2]WPI, Tohoku University
2-2-1, Katahira, Aoba-ku, Sendai, Miyagi 980-0812, Japan

1. Introduction

The control of magnetic damping in ferromagnetic materials is extremely important for achieving high-speed magnetization switching for some spintronics devices, such as magnetic random access memory (MRAM), and reduction of switching current density for spin-transfer-torque (STT) magnetization switching [1]. Half-metallic Heusler alloys are very attractive material, because they have highly spin-polarized conduction electrons [2] and low magnetic damping constant [3]. Such materials can reduce significantly STT switching current density, which is proportional to the damping constant and the reciprocal of spin injection efficiency.

The Gilbert damping constant $G = \alpha\gamma M_s$ for the Kambersky's torque correlation model [4] is expressed as

$$G = (\alpha\gamma M_S)\mu_B^2 D(E_F)(g-2)^2/\tau. \quad (1)$$

Here, α and γ are magnetic damping constant and magnetogyric ratio. M_s and μ_B are the saturation magnetization and Bohr magneton number, respectively. $D(E_F)$ is the total density of states (DOS) at the Fermi energy (E_F), g is the Lande's g factor, and τ is the electron scattering time. According to Eq. (1), the Gilbert damping constant can vary with DOS at E_F. The DOS for B2- or $L2_1$-ordered Co_2YZ full Heusler alloys can be systematically varied with the total valence electron number, which also changes with the compositions of Y and Z [5]. Thus, a Co_2YZ full Heusler alloy enables us to investigate the systematical correlation between magnetic damping and DOS at E_F. In addition, a Co_2YZ full Heusler alloy can exhibit low-damping because these alloys have a low-orbital magnetic moment.

The temperature dependence of magnetic damping is also important to clarify the origin of magnetic damping. According to the theoretical calculation [4], the temperature dependence of the magnetic damping can be determined by the contributions of inter- and intra- band transitions from the electronic system to the lattice near the Fermi level. Therefore, systematic investigation of temperature dependence is expected to clarify the relationship between the electronic band structure, microscopic transition process and macroscopic magnetic damping.

In this work, the magnetic damping constants and their temperature dependence for the epitaxitially grown $Co_2MnAl_xSi_{1-x}$ (CMAS) and $Co_2Fe_xMn_{1-x}Si$ (CFMS) Heusler alloy films were systematically investigated.

2. Experimental method

Films with MgO(001)-sub./Cr(40)/CMAS or CFMS(30)/Ta(2) (in nm) structures were prepared using magnetron sputtering system. We controlled the film composition by co-sputtering from Co-Mn-Si (Co: 43.7%, Mn: 27.95%, Si: 28.35%), Co-Mn-Al (Co: 43.7%, Mn: 27.95%, Al: 28.35%), and Co-Fe-Si (Co: 47.5%, Fe: 24.2%, Si: 28.3%) alloyed targets. We used ICP spectroscopy to analyze the film compositions. The CMAS and the CFMS films were annealed at 400°C and at 500°C respectively after deposition in order to increase the atomic site-ordering. The crystalline structure and magnetic properties were respectively characterized using x-ray diffraction (XRD) with Cu-K_α radiation and a superconducting quantum interference device (SQUID). The magnetic damping constant α and the magnetogyric ratio γ were measured by the FMR measurements at 4.2 – 300 K using an X-band microwave source (f = 9.4 GHz) and a TE_{011} cavity. The samples were fixed on a quartz rod and a goniometer was used to measure the out-of-plane angular (θ_H) dependence of the resonance field and the line width of the FMR spectra. The damping constant α was determined by analyzing the angular dependence of the resonance field and the line width in order to eliminate the extrinsic contribution, such as imhomogeneities of magnetic properties in the films, to the magnetic damping [6].

3. Experimental results and discussion

The XRD patterns indicate that the fabricated CMAS films have a (001)-orientation and a B2-ordered structure. The long-range order parameter of the B2 structure estimated from the peak intensities of (002) and (004) was 0.35 – 0.63. The epitaxitial growth was confirmed from the (220) peak observed in the pole–figure measurements for all CMAS films. The (111) peak from $L2_1$-ordering was not detected from the pole–figure measurements except for in the Co_2MnSi composition. The CFMS films also have a (001)-orientation. In addition, for all the CFMS films, the epitaxial growth and the $L2_1$-ordering were confirmed from the (111) pole-figure measurements. The long-range order parameter of the $L2_1$ structure estimated from the (111) peak intensity was 0.2 – 0.9. The saturation magnetization value measured by SQUID were about 20% lower than the values for the bulk samples, except for that for the Co_2MnAl film, indicating that the fabricated films included a certain amount of atomic site disorder. However, the sa-

turation magnetization increased when the valence electron number increased according to the Slater rule [7].

The obtained values of G dependence on the valence electron number are shown in Fig. 1 (Solid line). The α and γ values were obtained by analyzing the line width and the resonance field of FMR spectra. The G had the minimum value of 5.5×10^7 rad/s for the $Co_2Fe_{0.4}Mn_{0.6}Si$ film and increased rapidly for the $Co_2Mn_xFe_{1-x}Si$ with $x > 0.6$. The Gilbert damping constant is considered to be proportional to the square of the spin-orbit coupling parameter ξ and the total DOS at Fermi energy $D(E_F)$ as mentioned above. The electronic structure for the B2-ordered $Co_2MnAl_xSi_{1-x}$ and $L2_1$-ordered $Co_2Fe_xMn_{1-x}Si$ alloys were calculated, although the fabricated CMAS and CFMS films did not have complete B2- and $L2_1$-ordered structures. The dashed line in Fig. 1 is the total DOS at the Fermi level obtained by the first-principles approach. The electronic structure are calculated by using the tight-binding linear muffin-tin orbital (TB-LMTO) method in conjunction with the coherent potential approximation (CPA) to treat the partial disorder depending on the atomic concentration x. The exchange-correlation potential is determined based on the local spin density functional approximation (LSDA) without inclusion of additional Coulomb interaction U.

As seen in Fig. 1, the Gilbert damping constant measured by FMR technique seems to be roughly proportional to total DOS at E_F, so this result is consistent with above formulation. Small magnetic damping constant of $Co_2MnAl_xSi_{1-x}$ and $Co_2Fe_xMn_{1-x}Si$ ($x < 0.6$) may be attributed to their half-metallic property. In this region, the slight decrease of the magnetic damping constant with x is considered to be dominated by the DOS at E_F in majority spin states which is gradually decrease with increasing of the valence electrons number. In $Co_2Fe_xMn_{1-x}Si$ region, their half-metallic property is broken where E_F goes into the conduction band of minority spin states. It is possible to consider that the abrupt increasing of the magnetic damping constant of $Co_2Fe_xMn_{1-x}Si$ ($x > 0.6$) is explained by the contribution of the DOS in minority spin states.

Figure 2 shows temperature dependence of ΔH for $Co_2Fe_xMn_{1-x}Si$ Heusler alloy films, which is proportional to the magnetic damping if the films are homogeneous [6]. ΔH is normalized by that at 300K. As shown in Fig. 2, for the Mn-rich $Co_2Fe_xMn_{1-x}Si$ films, ΔH decreased with decreasing temperature (resistivity like). On the other hand, for the Fe-rich $Co_2Fe_xMn_{1-x}Si$ films, ΔH increased with decreasing temperature (conductivity like). In previous reports, the damping of Fe shows resistivity like behavior, while the damping of Ni shows conductivity like behavior both experimentally and theoretically [8, 9]. This difference of the temperature dependence can be explained by the different contribution of intra- and inter-band transitions of electrons to the damping. For the Ni sample, the contribution of inter-band transitions is dominant, because the localized states exist at X-point. We infer that the conductivity like behavior of the magnetic damping reflects the large DOS near the E_F for Co_2FeSi composition.

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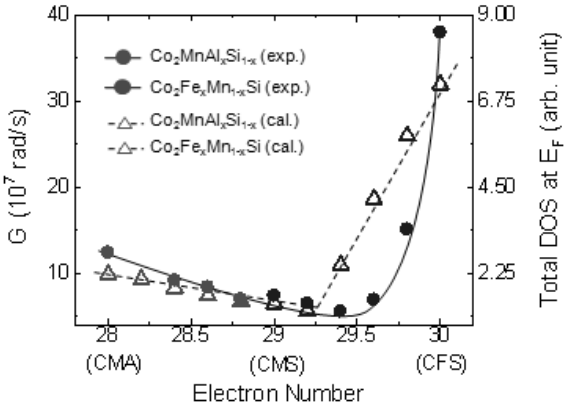

Figure 1 Valence electron number dependence of the Gilbert damping constant (solid line) and calculated density of states at Fermi energy (dashed line) for $Co_2MnAl_xSi_{1-x}$ and $Co_2Fe_xMn_{1-x}Si$ Heusler alloy films.

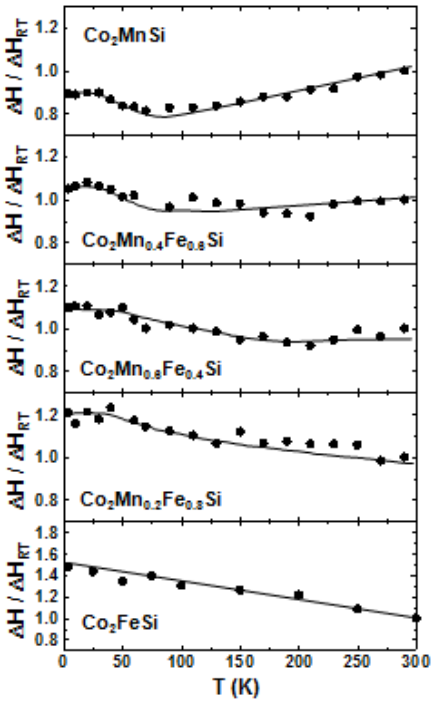

Fig. 2 Temperature dependence of ΔH for $Co_2Fe_xMn_{1-x}Si$ films.