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Journal of Magnetism and Magnetic Materials 310 (2007) e696–e698

Journal of magnetism and magnetic materials

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Analysis of magnetic anisotropy for $Co_2Cr_{0.6}Fe_{0.4}Al$ thin films epitaxially grown on GaAs

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available on line 20 November 2006

Abstract

The structural and magnetic properties of $Co_2Cr_{0.6}Fe_{0.4}Al$ (CCFA) thin films epitaxially grown on GaAs substrates by sputtering were investigated. The CCFA film directly grown on GaAs showed a cube-on-cube crystallographic relation, while it was rotated by 45° in the (001) plane when a thin MgO layer was inserted between the CCFA and GaAs. Both samples showed strong magnetic anisotropy, in which a uniaxial anisotropy with an easy axis of $[110]_{GaAs}$ or $[1\text{-}10]_{GaAs}$ dominated with a slight cubic anisotropy having easy axes of $\langle 110\rangle_{CCFA}$ superimposed. The uniaxial anisotropy constants were approximately 1.6 times as large as the cubic anisotropy constants for both samples.

PACS: 75.30.Gw; 75.50.Cc; 75.70.-i

Keywords: Heusler alloy; CCFA; magnetic anisotropy; GaAs

Co-based full-Heusler alloy thin films are promising ferromagnetic electrode materials for spintronic devices because of their intrinsically high spin polarization at room temperature (RT). Relatively high tunnel magneto-resistance (TMR) ratios were recently observed in magnetic tunnel junctions (MTJs) using Co_2MnSi (67% at RT and 570% at 2 K)[1] or Co_2(Cr, Fe)Al (CCFA) (90% at RT and 240% at 4.2 K)[2]. In experiments on spin injection from Heusler materials into semiconductors, however, relatively low spin injection efficiency was achieved [3], [4]. The possible reasons for the low efficiency are the formation of a magnetically-dead layer and/or the loss of half-metallicity at Heusler-material/semiconductor interfaces. Insertion of a thin MgO layer between the Heusler material and the semiconductor is expected to be a useful approach for achieving a high spin injection efficiency. In this paper, we report on the structural and magnetic properties of CCFA thin films epitaxially grown on GaAs substrates by magnetron sputtering with and without a MgO interlayer, and analyze their magnetic anisotropy.

Layer structures consisting of a 400-nm-thick undoped GaAs and a 50-nm-thick n-GaAs were grown by molecular beam epitaxy (MBE) at 580°C on GaAs(001) substrate. Then the sample was capped with an arsenic protective layer and transported in air to an ultrahigh vacuum chamber equipped with magnetron sputtering cathodes and an electron beam (EB) evaporator. Prior to the growth of the CCFA film, the arsenic cap was removed by heating the sample to 400°C. We prepared two kinds of CCFA thin films on GaAs. In the first kind (sample A), a 50-nm-thick CCFA film was directly grown on GaAs by RF-magnetron sputtering at 400°C. In the second kind (sample B), a 50-nm-thick CCFA film was prepared by sputtering on a 1.5-nm-thick MgO layer grown by EB evaporation on GaAs.

Figures 1(a) and 1(b) show x-ray pole figures of CCFA 022 diffractions for both samples. Here, we set the GaAs[110] direction to the origin of ϕ. We confirmed epitaxial growth of both samples. The crystallographic relationship with respect to the GaAs was CCFA(001)[110]||GaAs(001)[110], *i.e.*, a cube-on-cube relationship for the sample A (without the MgO layer), while it was CCFA(001)[110]||GaAs(001)[100] (45° rotated) for the sample B (with the MgO layer).

Figures 2(a) and 2(b) show the magnetic hysteresis curves measured at RT. The magnetic field was applied along the GaAs [110] and [1-10]axes. The shape of the hysteresis curves observed in the sample A, which was almost similar to those observed in MBE-grown CCFA[5] or other Heusler materials[6], [7] on GaAs, was different from that

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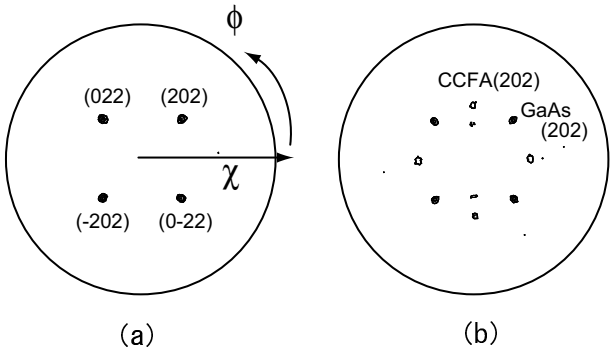

Fig. 1. X-ray pole figures of 022 diffractions for (a) sample A, and (b) sample B.

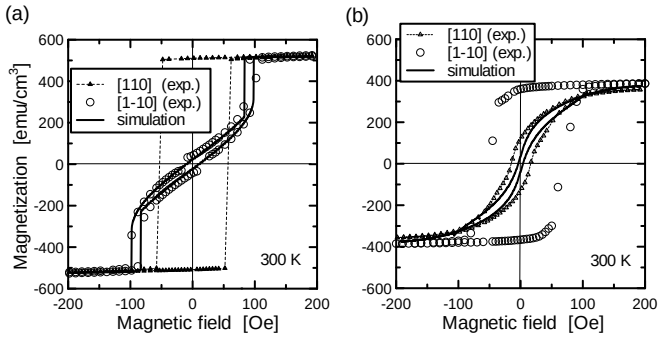

Fig. 2. Magnetic hysteresis curves for (a) sample A and (b) sample B. Circles and triangles indicate the experimental data and solid lines indicate simulation. The magnetic field was applied along $[110]_{\mathrm{GaAs}}$ and $[1\text{-}10]_{\mathrm{GaAs}}$ axes.

observed in the sample B.

To understand the magnetic anisotropy, we simulated the hysteresis curves using the Stoner-Wohlfarth formulation for coherent rotation reversal. The free energy density with combined cubic anisotropy and uniaxial anisotropy can be modeled as

$$E=\frac{K_1}{4}\sin^2 2(\varphi-\alpha)+K_u\sin^2(\varphi-\beta)-MH\cos(\varphi-\theta) \quad (1)$$

where K_1 and K_u are cubic and uniaxial anisotropy constants, α and β are the easy axis directions for cubic and uniaxial anisotropy with respect to the $[110]_{\mathrm{GaAs}}$ direction, M is the magnetization, H is the magnetic field, and φ and θ are the directions of M and H.

The anisotropy constants and easy axis directions were deduced by fitting the experimental data for the hard axis directions ($[1\text{-}10]_{\mathrm{GaAs}}$ for the sample A and $[110]_{\mathrm{GaAs}}$ for the sample B), since the coherent rotation reversal is dominant only when the magnetic field is applied along the hard axis direction, while domain-wall motion inevitably occurs for other directions.

The simulated results (solid lines) are also shown in Fig. 2. The close agreement between the experimental results and the simulation indicates that the assumed magneto-anisotropy model is valid. Table 1 summarizes the deduced easy axis directions and anisotropy constants for both samples. The value of α in the sample A differed by 45° compared to that in the sample B, while the value of β differed by 90°. These results suggest that the direction of cubic anisotropy is related to the crystal orientation of the CCFA film, while that of the uniaxial anisotropy is related to the crystal orientation of the GaAs.

	sample A	sample B
α [deg.]	0° ($\langle 110\rangle_{\mathrm{GaAs}}$),	45° ($\langle 100\rangle_{\mathrm{GaAs}}$)
β [deg.]	0° ($[110]_{\mathrm{GaAs}}$),	90° ($[1\text{-}10]_{\mathrm{GaAs}}$)
K_1 [erg/cm^3]	2.2×10^4	1.1×10^4
K_u [erg/cm^3]	3.7×10^4	1.8×10^4

Table 1
Easy axis directions and anisotropy constants for CCFA on GaAs without and with MgO.

The origin of the cubic anisotropy is explained by the crystal symmetry of the CCFA. The origin of the uniaxial anisotropy, on the other hand, remains an open question, although many theoretical models, such as a reconstruction of the semiconductor substrates, formation of an interface alloy, or anisotropic interfacial bonds, have been proposed [7]. We found that the GaAs influenced the uniaxial anisotropy of the CCFA even in the presence of the thin MgO interlayer. The uniaxial anisotropy constants were approximately 1.6-1.7 times as large as the cubic anisotropy constants for both samples, indicating that the uniaxial anisotropy was dominant compared to the cubic anisotropy.

In summary, we have successfully grown epitaxial CCFA films on GaAs substrate with and without a MgO interlayer. The CCFA film directly grown on GaAs showed a cube-on-cube crystallographic relation, while it was rotated by 45° in (001) plane when a thin MgO layer was inserted. Both samples showed strong magnetic anisotropy originated from the GaAs substrate symmetry.

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