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Magnetic and structural properties of Co_2FeAl thin films grown on Si substrate

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ABSTRACT

The correlation between magnetic and structural properties of Co_2FeAl (CFA) thin films of different thicknesses ($10\text{ nm} < d < 100\text{ nm}$) grown at room temperature on MgO-buffered Si/SiO_2 substrates and annealed at 600 °C has been studied. x-ray diffraction (XRD) measurements revealed an (011) out-of-plane textured growth of the films. The deduced lattice parameter increases with the film thickness. Moreover, pole figures showed no in-plane preferential growth orientation. The magneto-optical Kerr effect hysteresis loops showed the presence of a weak in-plane uniaxial anisotropy with a random easy axis direction. The coercive field, measured with the applied field along the easy axis direction, and the uniaxial anisotropy field increase linearly with the inverse of the CFA thickness. The microstrip line ferromagnetic resonance measurements for in-plane and perpendicular applied magnetic fields revealed that the effective magnetization and the uniaxial in-plane anisotropy field follow a linear variation versus the inverse CFA thickness. This allows deriving a perpendicular surface anisotropy coefficient of -1.86 erg/cm^2.

1. Introduction

Heusler X_2YZ alloys [1,2] (X being a transition metal element, Y being another transition metal element and Z being a group III, IV, or V element) are an interesting class of materials due to their potential use as magnetic electrodes in giant and tunnel magnetoresistance devices used in magnetic memories (MRAM) [3], in low field magnetic sensors [4] and in microwave components for spintronic applications [5]. The most prominent representatives of the this kind of spintronic materials are Co-based full Heusler alloys due to their predicted half metallic character (magnetic materials that exhibit a 100% spin polarization rate at the Fermi level) even at room temperature and due to their high Curie temperature [6]. These make them ideal sources of high spin polarized currents to realize very large magnetoresistance values. Co_2FeAl (CFA) is one of the Co-based Heusler alloys having a very high Curie temperature (1000 K) and, theoretically predicted, a half-metallic character of their spin-split band structure. It can provide a giant tunneling magnetoresistance (360% at room temperature) [7] when used as an electrode in magnetic tunnel junctions, which makes CFA promising for practical applications. However, the crystalline structure and the chemical order of such materials strongly influence their magnetic and structural properties. Moreover, the substrate material, as well as the crystalline orientation of the substrate and the film thickness, have an impact on the magnetic anisotropy of magnetic thin films, such as CFA, because of the band hybridization and the spin–orbit interaction at the interface. Therefore, the correlation between their magnetic and structural properties and their dependence on film thicknesses, for precise control of the magnetic properties required by the integration of CFA as a magnetic electrode in spintronic devices, should be investigated. For this purpose, microstrip ferromagnetic resonance (MS-FMR), magneto-optical Kerr effect (MOKE) magnetometry and X-ray diffraction (XRD) techniques are used.

2. Sample preparation

CFA thin films of different thicknesses ($10\text{ nm} < d < 100\text{ nm}$) were grown on $Si(001)/SiO_2$ substrates using a magnetron sputtering system with a base pressure lower than 3×10^{-9} Torr. Prior to the deposition of the CFA films, a 4 nm thick MgO buffer layer was grown at room temperature (RT) by *rf* sputtering from a MgO

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polycrystalline target under an Argon pressure of 15 mTorr. Next, CFA thin films of different thicknesses were deposited at room temperature by dc sputtering under an Argon pressure of 1 mTorr, at a rate of 0.1 nm/s. Finally, the CFA films were capped with MgO (4 nm)/Ta(4 nm) bilayer.

Depending on sites occupied by the X, Y and Z atoms in the Heusler cell, different phases can be adopted by the Heusler alloys giving rise to chemical or atomic disorder. Heusler alloys with the totally ordered phase $L2_1$ transform into the B2 structure (when the Y and Z atoms randomly share their sites: Y–Z disorder). Moreover, they form an A2 structure when X, Y and Z randomly share all the sites. This chemical disorder strongly influences many of their physical properties. Indeed, it is reported by Picozzi that some types of disorder might lead to additional states at the Fermi level, thus reducing the spin polarization [8]. Furthermore, some Heusler alloys are amorphous in the as prepared state. Therefore, an annealing process is required to initiate the crystallization and to induce the atomic ordering for best Heusler alloys properties. After the growth of the stack, the structures were thus *ex-situ* annealed at 600 °C during 15 min in vacuum.

The structural properties of the samples have been characterized by XRD using a four-circle diffractometer. Their magnetic static and dynamic properties have been studied by magneto-optical Kerr effect magnetometer (MOKE) and microstrip ferromagnetic resonance (MS-FMR) [9], respectively.

3. Structural properties

The X-rays θ–2θ diffraction patterns for CFA thin films of different thicknesses revealed one peak which is attributed to the (022) diffraction line of CFA (Fig. 1a).

The lattice parameter (a), shown in Fig. 1b, increases with the increasing CFA thickness, similarly to samples grown on MgO substrates, where a direct correlation exists with the enhancement of the chemical order [10]. However, the lattice parameters remain smaller than the reported one in the bulk compound with the $L2_1$ structure (0.574 nm). Due to the overlap of the potential (002) CFA peak with the substrate reflections it is difficult to accurately evaluate de degree of chemical order in our films. Pole figures around the (022) type CFA peaks (Fig. 1c) indicate that the CFA films show a strong (011) fiber-texture with no in-plane preferential growth direction.

4. Magnetic properties

To analyze the experimental results, the total magnetic energy given by Eq. (1) is considered.

$$E = -M_sH[\sin\theta_M \sin\theta_H \cos(\varphi_M-\varphi_H)+\cos\theta_M\cos\theta_H] \\ -(2\pi M_s^2-K_\perp)\sin^2\theta_M - \frac{1}{2}(1+\cos 2(\varphi_M-\varphi_u))K_u \quad (1)$$

In the above expression φ_M (resp. φ_H) represents the in-plane (referring to the substrate edges) angle defining the direction of the magnetization M_s (resp. the external applied field H), while θ_M (resp. θ_H) is the out-of-plane angle between the magnetization (resp. the external field H) and the normal to the sample plane. φ_u defines the angles of the planar uniaxial anisotropy easy axis with respect to this substrate edge. K_u and $K_\perp$ are in-plane and out-of-plane uniaxial anisotropy constants, respectively.

For an in-plane applied magnetic field, the studied model provides the following expression (2) for the frequencies of the experimentally observable magnetic modes:

$$F_n^2 = \left(\frac{\gamma}{2\pi}\right)^2 \left[\begin{array}{l} H\cos(\varphi_H-\varphi_M)+H_u\cos 2(\varphi_M-\varphi_u) \\ +\frac{2A_{ex}}{M_s}\left(\frac{n\pi}{d}\right)^2 \end{array}\right] \\ \times \left[\begin{array}{l} H\cos(\varphi_H-\varphi_M)+4\pi M_{eff}+ \\ \frac{H_u}{2_s}(1+\cos 2(\varphi_M-\varphi_u))+\frac{2A_{ex}}{M_s}\left(\frac{n\pi}{d}\right)^2 \end{array}\right] \quad (2)$$

Where $(\gamma/2\pi)=g\times 1.397\times 10^6$ Hz/Oe is the gyromagnetic factor.

We introduce the effective magnetization $M_{eff}=H_{eff}/4\pi$ obtained by:

$$4\pi M_{eff} = H_{eff} = 4\pi M_s - 2K_\perp / M_s = 4\pi M_s - H_\perp \quad (3)$$

As experimentally observed, the effective perpendicular anisotropy term $K_\perp$ (and, consequently, the effective perpendicular anisotropy field $H_\perp$) is thickness dependent. $K_\perp$ describes an effective perpendicular anisotropy term which writes as:

$$K_\perp = K_{\perp v} + 2K_{\perp s}/d \quad (4)$$

where $K_{\perp s}$ refers to the perpendicular anisotropy term of the interfacial energy density. Finally we define $H_u=2K_u/M_s$ as the in-plane uniaxial anisotropy field. The uniform precession mode corresponds to $n=0$. The other modes to be considered (perpendicular standing modes: PSSW) are connected to integer values of n: their frequencies depend upon the exchange stiffness constant A_{ex} and upon the film thickness d.

In the case of an out-of-plane perpendicular applied magnetic field, the precession frequency is given by:

$$F_\perp = \left(\frac{\gamma}{2\pi}\right)\left[H - 4\pi M_{eff} + \frac{2A_{ex}}{M_s}\left(\frac{n\pi}{d}\right)^2\right] \quad (5)$$

4.1. Static properties

The average magnetization at saturation measured by vibrating sample magnetometer at room temperature for all samples has been found to be $M_s = 1000 \pm 50$ emu/cm^3. The typical MOKE hysteresis loops, measured versus external magnetic field directions with respect to one of the substrate edges for all the samples, are represented in Fig. 2a for the 50 nm thick film. The shape of

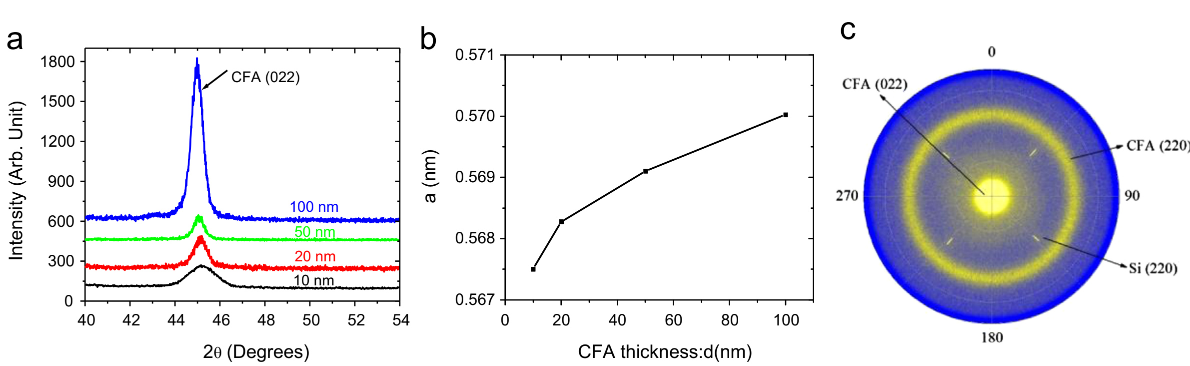

Fig. 1. Thickness dependence of (a) θ–2θ patterns (b) lattice parameter; and (c) pole figure around a (022) peak of 50 nm thick CFA film.