Physics Letters A 381 (2017) 1202–1206

Contents lists available at ScienceDirect

Physics Letters A

www.elsevier.com/locate/pla

Thickness dependence of magnetic anisotropy and intrinsic anomalous Hall effect in epitaxial Co_2MnAl film

K.K. Meng [a,*], J. Miao [a], X.G. Xu [a], J.H. Zhao [b], Y. Jiang [a]

[a] *School of Materials Science and Engineering, University of Science and Technology Beijing, Beijing 100083, China*
[b] *State Key Laboratory of Superlattices and Microstructures, Institute of Semiconductors, Chinese Academy of Sciences, Beijing 100083, China*

ARTICLE INFO

Article history:
Received 16 December 2016
Received in revised form 13 January 2017
Accepted 2 February 2017
Available online 7 February 2017
Communicated by M. Wu

Keywords:
Spintronics
Heusler alloy
Molecular-beam epitaxy
Magnetic properties

ABSTRACT

We have investigated the thickness dependence of magnetic anisotropy and intrinsic anomalous Hall effect (AHE) in single-crystalline full-Heusler alloy Co_2MnAl (CMA) grown by molecular-beam epitaxy on GaAs(001). The magnetic anisotropy is the interplay of uniaxial and the fourfold anisotropy, and the corresponding anisotropy constants have been deduced. Considering the thickness of CMA is small, we ascribe it to the influence from interface stress. The AHE in CMA is found to be well described by a proper scaling. The intrinsic anomalous conductivity is found to be smaller than the calculated one and is thickness dependent, which is ascribed to the influence of chemical ordering by affecting the band structure and Fermi surface.

1. Introduction

Co-based full-Heusler alloys in a chemical form of Co_2YZ have attracted much attention in recent years due to high Curie temperature and high spin polarization, which are promised properties for the technological development of spintronics [1,2]. These ferromagnets possess a gap at Fermi level in the minority band but exhibit metallic behavior in the majority band, therefore the spin-polarization at the Fermi level is considered to be 100% [3–5]. Recently, some of these alloys including Co_2MnSi, Co_2FeAl and $Co_2Fe_xMn_{1-x}Si$ have been incorporated into magnetic tunnel junctions or current-perpendicular-to-plane giant magnetoresistance as ferromagnetic electrodes, achieving relatively high magnetoresistance [6–9]. Therefore the integration of Cobalt-based Heusler alloys as a ferromagnetic electrode in spintronic devices requires detailed investigation of their magnetic properties such as magnetic anisotropy and spin-dependent transport properties such as anomalous Hall effect (AHE).

In connection with spintronics, the AHE is presently receiving new attention. Electrons moving through a ferromagnet will acquire a transverse velocity with opposite directions for different spin orientations due to spin orbit coupling (SOC), since the charge currents have usually a net polarization, this spin-dependent transverse velocity will result in a net transverse anomalous Hall voltage [10,11]. A major challenge in this field is to clarify the microscopic origin of the AHE, which has been a controversial subject for more than half a century. Karplus and Luttinger have proposed that the intrinsic AHE arises from the transverse velocity of Bloch electrons induced by SOC together with interband mixing [12–17]. On the other hand, the extrinsic mechanisms including skew scattering and side jump come from the asymmetrical scattering of conduction electrons due to SOC [18–20]. To explore and distinguish the possible mechanisms of AHE, a unified scaling describing the AHE resistivity ρ_{AH} in terms of the longitudinal resistivity ρ_{xx} has always been investigated. In contrast to the conventional picture that ρ_{AH} scales with the total resistivity irrespective of its sources, recent experimental studies have revealed that both ρ_{AH} and the scaling relation are qualitatively different for various types of electron scattering.

In the previous work on investigating the AHE in Heusler alloys, a common practice is tuning the longitudinal resistivity of ferromagnetic material by varying the content or annealing at different temperatures to study the scaling between ρ_{AH} and ρ_{xx} [21–23]. This approach suffers from the deficiency that the different content not only provides additional scattering centers that modulate the extrinsic AHE contribution, but also could modify the electronic structure and make the interpretation of intrinsic AHE difficult. Utilizing the finite size effect on electric resistivity in the thickness regime where the band structure is preserved with little modification, this deficiency can be overcome. Working on epitaxial GaAs/Fe films, Tian et al. have limited the scattering of electrons to two sources, one by interface roughness and another by phonons, with independent control on their strengths through

* Corresponding author.
E-mail address: kkmeng@ustb.edu.cn (K.K. Meng).

http://dx.doi.org/10.1016/j.physleta.2017.02.004
0375-9601/

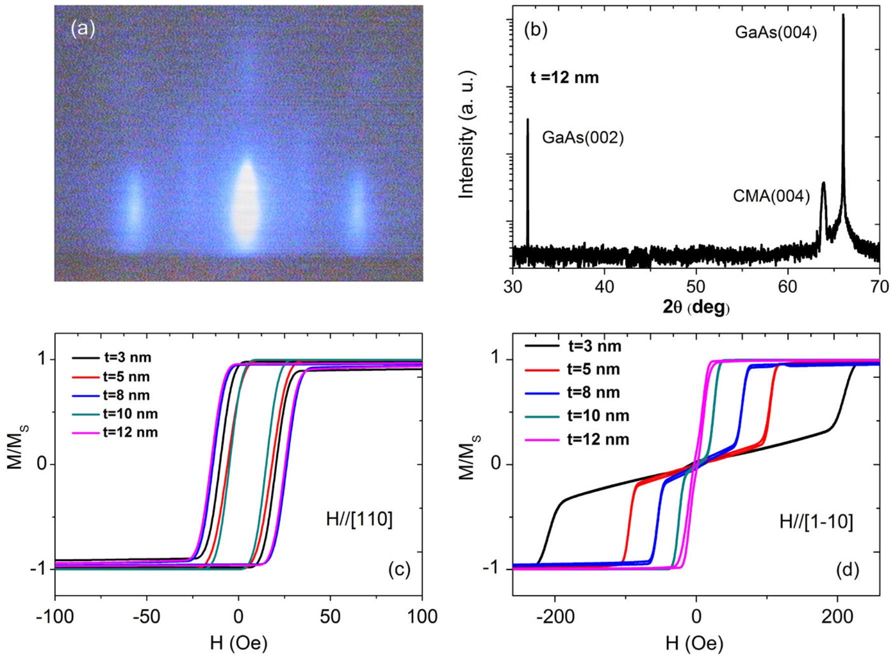

Fig. 1. (a) The RHEED pattern of CMA film. (b) DCXRD pattern of 12-nm-thick CMA film. (c) Normalized in-plane hysteresis loops of CMA films with varying thickness, and the field is applied along [110] direction. (d) Normalized in-plane hysteresis loops of CMA films with the field applied along [1–10] direction.

the film thickness and sample temperature [24]. A comprehensive scaling between the anomalous Hall resistivity and longitudinal resistivity has been finally established, giving

$$\rho_{AH} = \alpha\rho_{xx0} + \beta\rho_{xx0}^2 + b\rho_{xx}^2 \quad (1)$$

where ρ_{xx0} is the residual resistivity induced by impurity scattering, ρ_{xx} denotes the longitudinal resistivity, α is the parameter of the skew scattering, β denotes the side jump, and b the intrinsic anomalous Hall conductivity. Using this scaling, Wu et al. have investigated the AHE in the ultrathin film regime for Fe (001) (1–3 nm) films epitaxial on MgO(001) [25]. They have identified that the coefficient of skew scattering has a reduction from metallic to localized regime, while the contribution of side jump has inconspicuous change except for a small drop below 10 K. Furthermore, the intrinsic anomalous Hall conductivity decreases with the reduction of thickness below 2 nm. It seems that the mechanisms of AHE and the influence from localization can be clearly explored with varying the thickness of the films. The effect of the interface is similar to that of doping the bulk material with layers of impurities, and the density of these impurities can be easily controlled by means of the film thickness [26]. Therefore, the advantage of a thin film approach in AHE study is that by tuning the film thickness, the impurity density can be continuously manipulated. The investigation and clarification of these intriguing issues are of fundamental importance for better understanding the underlying physics of AHE.

In this paper, we have investigated thickness dependence of magnetic anisotropy and AHE in single-crystalline full-Heusler alloy Co_2MnAl (CMA) grown by molecular-beam epitaxy on GaAs(001). The magnetic anisotropy is ascribed to the competition between the uniaxial and fourfold anisotropy, and the corresponding anisotropy constants have been deduced. Considering the thickness of CMA is small, we ascribe the uniaxial anisotropy to the influence from interface stress. The origin of the fourfold interface anisotropy seems to be the modification of the electronic structure at the interface. The AHE in CMA is found to be well described by the scaling given by Tian et al. The intrinsic anomalous conductivity is also found to be thickness dependent, which is ascribed to the influence of chemical ordering by affecting the Fermi surface. On the other hand, the variance of α and β with temperature have a small impact on the total anomalous Hall conductivity, and the localization correction is weak.

2. Experimental details

Co_2MnAl films with the thickness of $t = 3, 5, 8, 10, 12$ nm were deposited on the more spatially isotropic $c(4 \times 4)$ reconstructed GaAs(001) surface by molecular-beam epitaxy at 260 °C. In order to emphasize the effect from interface and localization, the thickness of CMA in this paper is in the range of 3∼12 nm. Streaky RHEED patterns emerged during deposition as shown in Fig. 1(a), indicating epitaxial growth. In order to protect the surfaces from oxidation, films were capped with 2 nm of aluminum. The samples were first characterized using double crystal x-ray diffraction (DCXRD) to check the crystal structure. DCXRD patterns of the 12-nm-thick CMA film is taken as an example and shown in Fig. 1(b). Besides the (004) and (002) diffractions of GaAs substrate, we can only observe the (004) diffraction peak of CMA, indicating the A2 structure as discussed in our previous work [27]. Assuming the lattice constant to be that of GaAs is 0.5654 nm, the effective cubic lattice constant of CMA is about 0.58 nm. The magnetic properties were investigated by a superconducting quantum interference magnetometer. The films were then patterned into Hall bars with a nominal length l of 2.5 mm and a width w of 0.2 mm using photolithography and ion-beam etching, and the transport properties were carried out in a physical property measurement system (Quantum Design PPMS-9T system).

3. Results and discussion

Hysteresis loops of CMA films measured at 300 K under the external magnetic field along the [110] and [1–10] directions are shown in Fig. 1(c) and (d) respectively, and the magnetization is normalized to the saturation magnetization M_S. In-plane uniaxial magnetic anisotropy with easy axis parallel to the [110] direction is found. All the films have small coercive field, which is not evidently changed with varying thickness. In the [1–10] direction, discontinuities appear at the so-called split field H_S which is a