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Research articles

Magnetic and electrical transport properties of Fe-doped $Mn_{1.25}Ga$ films deposited on different substrates

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ABSTRACT

$L1_0$-MnGa alloys have attracted intensive attention due to their great potential in the field of magnetic recording, permanent magnets and spintronic devices. Here we present the magnetic and electrical transport properties of Fe-doped $L1_0$-$Mn_{1.25}Ga$ alloy films deposited on different substrates by magnetron sputtering. It is found that Fe-doped $L1_0$-$Mn_{1.25}Ga$ films deposited on both $SrTiO_3$ and MgO substrates have high (0 0 1) orientation while the film deposited on MgO substrate has better magnetic property with larger magnetic anisotropy constant, coercivity, and a magnetic energy product of 3.0 MGOe, which is mainly due to strain arisen from the larger lattice mismatch. Moreover, the deposition temperature plays an important role in electrical transport properties of the films. The film deposited on $SrTiO_3$ substrate at 250 °C shows an ordinary Hall effect while anomalous Hall effect when the deposition temperature is 300, 400 and 500 °C.

1. Introduction

Mn-Ga Heusler alloys have attracted much attention in magnetic recording, permanent magnet and spintronics application [1–3]. Among Mn-Ga alloys, $L1_0$-MnGa and $D0_{22}$-MnGa are the most interesting magnetically ordered phases. $L1_0$-Mn_xGa alloy exhibits ferromagnetic property for $0.76 \le x \le 1.8$. Ferrimagnetic $D0_{22}$-Mn_xGa alloy appears for $2 \le x \le 3$ [4]. According to the First-principle calculations, $L1_0$-MnGa and $D0_{22}$-MnGa alloys have high perpendicular magnetic anisotropy (PMA) of 26 and 20 Merg/cc [5,6], appropriate saturation magnetization (M_s) of 845 and 305 emu/cc [1,6,7], large magnetic energy product ($(BH)_{max}$) of 23.65 and 4.06 MGOe [8], respectively. There have been some experimental reports on confirming excellent magnetic properties of Mn-Ga alloy used as magnetic recording and permanent magnet materials [9]. Furthermore, $L1_0$-MnGa and $D0_{22}$-MnGa alloys were theoretically predicated to have high spin polarization (P) of 71% and 88% at the Fermi level [10], low Gilbert damping constant (α) of 0.0003 and 0.001 [6], respectively, which shows potential in spintronic devices. Indeed, recent experiment demonstrated a large linear tunneling magnetoresistance ratio up to 27.4% and huge dynamic range up to 5600 Oe in the $L1_0$-MnGa based magnetic tunnel junction [11].

However, there are few reports on magnetic and electrical transport properties of Mn_xGa alloy film tuned by the stress/strain. In this work, we investigated systematically the magnetic and electrical properties of the Fe-doped Mn_xGa films grown on (1 0 0)-oriented single crystal Si, $SrTiO_3$, and MgO substrates. The lattice mismatch between the film and the substrate will induce the stress/strain. Doping of a small amount of 3*d* ferromagnetic metal Fe helps to improve the magnetic property and magnetoresistance ratio [12], which tailors anomalous Hall effect (AHE) of the Mn_xGa film. We find that Fe-doped $L1_0$-$Mn_{1.25}Ga$ films deposited on both $SrTiO_3$ and MgO substrates have high (0 0 1) orientation. Meanwhile, the deposition temperature influences obviously electrical transport properties of the films. The film on $SrTiO_3$ substrate at 250 °C shows an ordinary Hall effect while anomalous Hall effect at 300, 400 and 500 °C.

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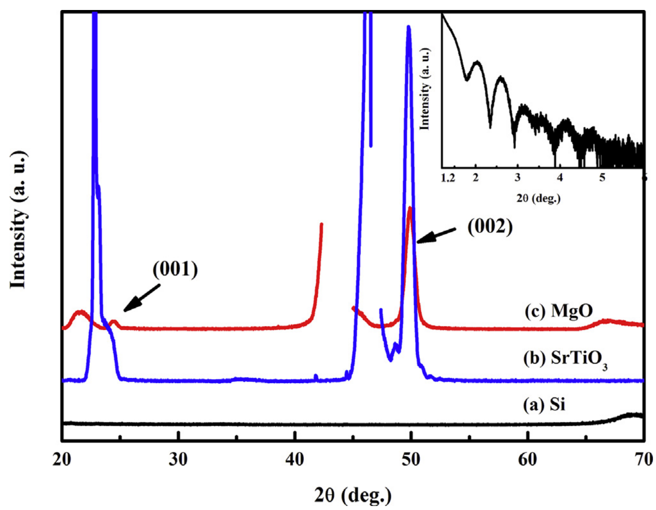

Fig. 1. XRD patterns of Fe-doped $Mn_{1.25}Ga$ films deposited on (a) Si, (b) $SrTiO_3$ and (c) MgO substrates at 400 °C. The inset is XRR curve of the film deposited on MgO substrate.

2. Experiments

Fe-doped $Mn_{1.25}Ga$ films with nominal thickness of 12 nm were prepared on (1 0 0) oriented single crystal Si, $SrTiO_3$, and MgO substrates by magnetron sputtering at different temperatures on an ATC 1800-F magnetron sputtering system. The base pressure of the deposition chamber was about 1.2×10^{-7} Torr and Ar gas was kept at a pressure of 3.0 mTorr during sputtering process. The targets with the stoichiometry composition of $Mn_{50}Ga_{50}$ and $Fe_{50}Mn_{50}$ with better than 99.95% purity were used co-sputtering under various deposition temperature. Before deposition, the substrate was heated to the deposition temperature for 10 min to prevent moisture and contamination. After deposition, the sample was also *in-situ* annealed at deposition temperature for 30 min.

The composition of the film was estimated to be about $Mn_{1.25}GaFe_{0.14}$ by Thermo Fisher ESCALAB250XI X-ray photoelectron spectroscopy (XPS) and the thicknesses were determined by X-ray reflectivity measurements (XRR). The crystal structures of the films were characterized by X-ray diffraction (XRD) on Rigaku D/max-2500 diffractometer with Cu K_α radiation using a current of 200 mA and voltage of 40 kV. The data points between $2\theta = 42.3°–45°$ (MgO substrate) or $46.6°–47.4°$ ($SrTiO_3$ substrate) were deleted due to high diffraction peaks intensities of single crystal substrates in the process of measurement. The magnetic properties of the films were measured at room temperature using Lake Shore 7407 vibrating sample magnetometer (VSM) with maximum applied field of 20 kOe. The Hall effect was measured at 300 K on Lake Shore 775 HMS Matrix Hall effect measurement system (HEMS) using Van der Pauw method with magnetic field applied perpendicular to the film plane.

3. Results and discussion

XRD patterns of Fe-doped $Mn_{1.25}Ga$ films deposited on different substrates at 400 °C are shown in Fig. 1. The film deposited on Si substrate is amorphous (Fig. 1(a)), which may be due to strong reaction between metal layer and active silicon, similar experimental result has been reported by Feng et al [13]. For the film deposited on $SrTiO_3$ substrate, the (0 0 2) diffraction peak of $L1_0$-MnGa is observed clearly in Fig. 1(b), and the (0 0 1) peak overlaps with the diffraction peak of the substrate, indicating that the film has (0 0 1) orientation. For the film deposited on MgO substrate, the (0 0 1) and (0 0 2) diffraction peaks around at $2\theta = 24.3°$ and 49.8° of the $L1_0$-MnGa phases can be seen in Fig. 1(c), which indicates that Fe-doped $L1_0$-$Mn_{1.25}Ga$ film grows epitaxially on (1 0 0) oriented MgO substrate and shows a (0 0 1) texture. Lattice constants c for Fe-doped $L1_0$-$Mn_{1.25}Ga$ films deposited on $SrTiO_3$ and MgO substrates are 3.659 and 3.651 Å, respectively, which are smaller than the bulk value of 3.69 Å [14], suggesting that the tensile strains exist in the films. All unlabeled peaks in the XRD patterns are from substrates. The inset in Fig. 1 is XRR curve of the film deposited on MgO substrate at 400 °C. The distinct Kiessing fringe indicates the film has good flatness [15]. The film thickness calculated is about 15.2 nm.

Fig. 2 shows the out-of-plane and in-plane magnetic hysteresis loops with the initial magnetization curves of Fe-doped $Mn_{1.25}Ga$ films deposited on different substrates at room temperature. The corresponding magnetic parameters are listed in Table 1. The film deposited on Si substrate displays soft magnetic behavior with a very small coercivity H_c and low saturation magnetization M_s due to amorphous structure. The films deposited on $SrTiO_3$ and MgO substrates exhibit high magnetic anisotropy, suggesting the formation of tetragonal structure consistent with the XRD data (Fig. 1). The out-of-plane and in-plane coercivities of the film deposited on MgO substrate are 4.13 and 0.36 kOe, respectively, while the coercivities of the film deposited on $SrTiO_3$ substrate decrease in both directions, 1.24 and 0.16 kOe, respectively. This observation may originate in the stress induced anisotropy. The calculated lattice mismatch between the substrates and $L1_0$-MnGa films are 6.29% and 13.40% for $SrTiO_3$ and MgO substrates, respectively. The larger lattice mismatch induces large stress, further resulting in the larger strain induced magnetic anisotropy and larger coercivity [16]. In general, magnetic anisotropy includes magnetocrystalline anisotropy and stress anisotropy. The stress anisotropy constant K_{stress} is proportional to the stress σ as given by K_{stress}, $K_{stress} = 3\lambda\sigma/2$ [17–19], where λ is the magnetostriction constant and σ is the stress. The effective anisotropy constant K_u^{eff} can be expressed as $H_A M_s/2$, where, H_A is the anisotropy field which could be obtained by extrapolating the perpendicular and parallel hysteresis loops, M_s is the saturation magnetization [20]. For the film deposited on MgO substrate, the K_u^{eff} is estimated to be 0.56×10^7 erg/cc, larger than that of the film deposited on $SrTiO_3$ substrate. The values of $(BH)_{max}$ can reach to 3.0 MGOe, which is larger than that previously reported results [1]. These results suggest that magnetic property can be tuned by utilizing the lattice mismatch induced strain.

Next, we investigated the electrical properties of Fe-doped $Mn_{1.25}Ga$ films on different substrate by measuring the Hall resistivity as a function of applied magnetic field. In ferromagnetic materials, the total Hall resistivity ρ_H is described by $\rho_H = R_o H + R_s 4\pi M_s$, where the R_o is ordinary Hall coefficient associated with the Lorentz force acting on the moving charge in the magnetic field, and R_s is anomalous Hall effect (AHE) coefficient associated with the irregularity of the left and right carrier scattering during their spin–orbit interactions in magnetic materials [21]. In the case of sample on Si substrate, because of the low magnetization as shown in Fig. 2(a), no AHE appears [22]. Fig. 3(a) and (b) show the ρ_H-H curves of the Fe-doped $L1_0$-$Mn_{1.25}Ga$ film deposited on $SrTiO_3$ and MgO substrates, respectively. The ρ_H of the films deposited on $SrTiO_3$ and MgO substrate are 1.62 and 1.95 μΩ.cm, respectively, which are larger than that of ferromagnetic $L1_0$-FePt thin film (0.88 μΩ.cm) [23]. In the $L1_0$-$Mn_{1.25}Ga$ film, R_0 is much smaller than R_s, thus the Hall resistivity can be simplified by $\rho_H = R_s 4\pi M_s$, the