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Research articles

Magnetic and structural properties of $L1_0$ Mn-Ga epitaxially grown islands

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ABSTRACT

Magnetic and structural properties of $L1_0$ $Mn_{53}Ga_{47}$ islands epitaxially grown onto MgO(1 0 0) substrates are discussed. The samples were fabricated by sputter-deposition at a substrate temperature T_s during deposition. The samples deposited at T_s above 500 °C were found to form the island structure of Volmer-Weber type. The average size of the islands fabricated at T_s = 600 °C is around 200 nm in width and 60 nm in height. The XRD and TEM analyses indicate that those islands are of the $L1_0$ phase with the ⟨0 0 1⟩ axis perpendicular to the substrate surface. The lattice constants ***a*** and ***c*** are 3.91 ± 0.01 Å and 3.65 ± 0.02 Å, respectively, which are larger by 0.8%, and smaller by 1.5% respectively, as compared to the bulk values of the same composition. The order parameter of these islands is found to increase from 0.7 to 0.8 for T_s = 450–500 °C, and then remains nearly constant (≈0.8) for higher T_s. The M-H hysteresis loops exhibit a high squareness for all the samples for T_s = 450–600 °C. The saturation magnetization M_s is about 220 and 350 emu/cm^3 for T_s = 450 and 600 °C, respectively. The out-of-plane coercivity H_c is 5 and 13 kOe for T_s = 450 and 600 °C, respectively. The temperature dependence of M_s for the sample made at T_s = 600 °C was measured and fitted to an empirical relation in order to estimate T_c. The estimated T_c around 600 K is in reasonable agreement with the reported value of bulk $L1_0$ $Mn_{53}Ga_{47}$. The uniaxial perpendicular magnetic anisotropy constant K_u estimated by the out-of-plane torque curves is around 1.1×10^7 and 8.3×10^6 erg/cm^3 at 5 and 300 K, respectively. The initial magnetization curves of these islands exhibit a typical pinning mode for the coercivity mechanism. A phenomenological discussion of the coercivity is presented on the basis of Kronmuller's formula. It is found that the coefficient α and effective demagnetizing factor N_{eff} in the formula by Kronmuller are approximately 0.38 and 12. For the magnetic anisotropy mechanism, the power law relation between $K_u(T)$ and $M_s(T)$ is examined. It is found that the exponent n for $K_u(T) \propto M_s(T)^n$ varies from 2.3 to 3.5 for T from 350 to 5 K. However, the n in a whole temperature range from 5 to 350 K is 2.6. The n = 2.6 suggests a deviation from the single-ion mechanism, and is consistent with the theoretical predictions of Ga contribution.

1. Introduction

Recently the manganese gallium (Mn-Ga) alloys have attracted much attention because of their versatile and attractive magnetic properties for various applications including rare-earth free permanent magnet, sensors and spintronics devices. The bulk phase diagram for this binary alloy system is complicated and has not been well established even now. In the case of thin films, the situation is even more complicated since the stability of the structure is much dependent on fabrication method and type of substrates. Furthermore, the origin of the magnetic properties such as coercivity and magnetic anisotropy constants of a thin film which is often not of a single phase but of multiphases is difficult to discuss, unless the sample is epitaxially grown.

Among many phases of the Mn-Ga binary alloys, the $L1_0$ phase (P4/mmm) has been reported to be stable over a composition range from about 54 to 64 at% in a temperature range from ambient to about 600 °C [1–4]. The $L1_0$ MnGa thin films were reported to exhibit high perpendicular uniaxial magnetic anisotropy constant K_u in the order of 10^7 erg/cm^3, accordingly high coercivity (> 10 kOe) at room temperature. It is of interest to note that Mn and Ga do not have a large spin orbit coupling coefficient, but they do exhibit high magnetic anisotropy constant. In order to understand the origin of such large magnetic

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anisotropy, Kota and Sakuma [5] employed the tight-binding linear muffin tin orbital (TB-LMTO) method to calculate the electronic structure in the atomic sphere approximation. They concluded that the large magneto-crystalline anisotropy results from the selection rule of spin orbit interaction (SOI) even though SOI for the individual atoms is weak. Also, Al-Aqtash and Sabirianov discussed on the basis of self-consistent electronic structure calculations using the density functional theory about the effect of strain on magnetic anisotropy constant of $L1_0$ MnGa alloys, and concluded that the magnetic anisotropy energy is sensitive to a change in lattice constant ***c*** [6].

In order to clarify experimentally about the magnetic anisotropy mechanism, the temperature dependence of K_u was discussed in terms of a power law with M_s. This way, one would differentiate the single-ion model from the two-ion model. For example, in the $L1_0$ FePt case n = 2 was found for the power law of $K(T) \approx c\ M_s(T)^n$ [7,8]. This result suggested that the two-ion model was responsible for the magnetic anisotropy mechanism. However, there has been little report found in literature regarding $L1_0$ MnGa alloy thin films, and its mechanism is still open for discussion.

Coercivity H_c, is one of the extrinsic quantities sensitive to film morphology. The observed H_c is much smaller than the intrinsic magnetic anisotropy field, H_k. The reduction from H_k is often discussed in conjunction with the demagnetizing effect and the coupling between grains. Kronmuller [9] discussed extensively the role of pinning sites and the demagnetizing effect associated with the defect and impurities in this reduction. Suzuki et al. [10] discussed the coercivity mechanism in Co/Pt multilayers based on the Kronmuller's formula. Kronmuller et al also discussed it for NdFeB magnets [9]. It is of great interest to study the coercivity mechanism of $L1_0$ MnGa thin films with the high perpendicular magnetic anisotropy, and to correlate it with the film morphology.

The present paper describes both the coercivity mechanism and also the magnetic anisotropy mechanism of $L1_0$ MnGa epitaxially grown single crystalline thin films.

2. Experimental

Multilayer thin films of $Mn_{50}Ga_{50}$ and Mn with various thicknesses were deposited onto MgO(1 0 0) single crystal substrates by using DC magnetron sputtering at substrate-deposition temperature T_s = 450–600 °C. The base pressure was better than 10^{-8} Torr. The fabricated thin films were then capped by a 5 nm thick Ru layer at ambient temperature after the system cooled down. The $Mn_{50}Ga_{50}$ alloy targets and Mn targets (purity 99.999%) were used. The deposition rates of MnGa and Mn were 0.03 and 0.01 nm/s, respectively, calibrated by X-ray reflectivity.

Based on preliminary experiments [11], it was found that the optimum layer-thicknesses for MnGa and Mn were 2 nm and 0.5 nm, respectively, and the total repetition was 25.

Measurements of magnetic properties were performed by using an alternating gradient magnetometer (AGM) in fields H up to 18 kOe at room temperature, and a vibrating sample magnetometer (VSM) and a torque magnetometer in H up to 90 kOe over a temperature range from 5 to 400 K. The structural properties were characterized by X-ray diffraction (XRD) with Cu Kα radiation and scanning/transmission electron microscopy (S/TEM) together with energy dispersive spectroscopy (EDS). The cross-sectional sample was prepared by focused ion beam (FIB). The lattice constants ***a*** and ***c*** were estimated by X-ray diffraction at ψ angle 0 and 43.5°, from $L1_0$ (0 0 2) and (2 0 2) peaks, where the ψ is the angle between the film normal and the bisector of the incident and diffracted beam. The angle 43.5° is the angle between $L1_0$ MnGa (2 0 2) and (0 0 2) planes.

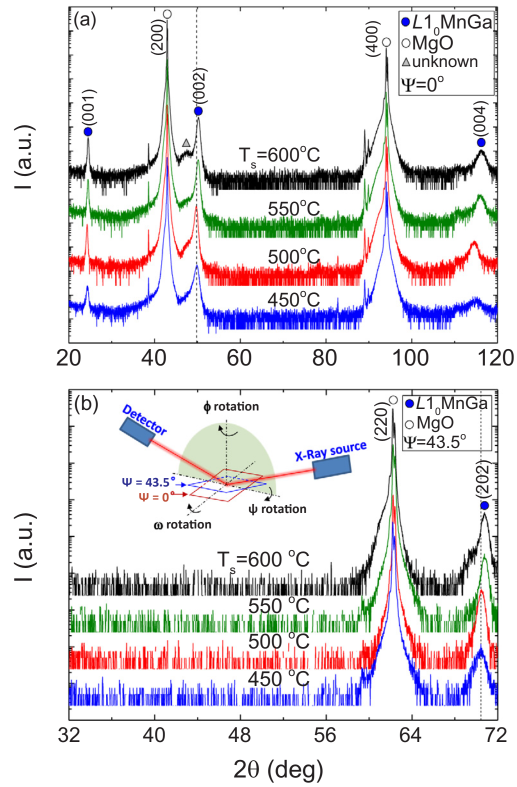

Fig. 1. The 2θ-ω scan XRD patterns measured at (a) ψ = 0 and (b) 43.5° for the samples deposited at the various T_s. The dotted lines show a guideline for observation of peak shift. The inset figure in (b) shows the illustration of the measurement.

3. Results and discussions

3.1. Structure

Fig. 1 shows the 2θ-ω scan XRD patterns measured at (a) ψ = 0 and (b) 43.5° for the samples with various T_s. The dotted lines for (2 0 0) and (2 0 2) are merely the guide for eyes for the peak shift with T_s. As shown in Fig. 1(a) for ψ = 0°, the diffraction peaks from the {0 0 1}, {0 0 2} and {0 0 4} planes of the $L1_0$ phase are observed. It is thus concluded that the samples are epitaxially grown with the ⟨0 0 1⟩ axis along film normal. The unknown peaks at around 47.6° are observed, whose intensity increases with T_s. One possibility is the unknown peak belongs to the $(4\,2\,\bar{1})$ peak of Mn_5O_8 with monoclinic c2/m structure, since the sample at T_s = 600 °C was oxidized with 15 at% O. On the other hand, the 2θ-ω scan at ψ = 43.5° shows $L1_0$ (2 0 2) peaks. The peak intensities exhibit low fluctuation with various T_s except the sample with T_s = 450 °C shows lower intensity. The inset figure in Fig. 1(b) shows the illustration of the measurement at ψ = 0 and 43.5°, as well as the in plane rotation angle ϕ.

Fig. 2 shows the ϕ scan XRD patterns for $L1_0$ {2 0 2} peaks at ψ = 43.5° and MgO {2 2 0} peaks at ψ = 45° for a range of 360°, where the angle ϕ is the rotation angle whose axis is the thin film normal, as shown in Fig. 1(b). As can be seen, the $L1_0$ {2 0 2} peaks show a four-fold symmetry, demonstrating a tetragonal structure. On the other hand, the MgO {2 2 0} peaks show similar four-fold symmetry. No offset was observed for the $L1_0$ {2 0 2} and MgO {2 2 0} peaks. Therefore, it can be determined that the $L1_0$ MnGa is grown on the MgO lattice epitaxially and well ordered.

The order parameter S was estimated from the superlattice (0 0 1) and fundamental (0 0 2) peak intensities. Considering that the theoretical integrated intensity I of x-ray diffraction peaks can be written as