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Growth of Very Thin Films of Mn_3Ge with a Perpendicular Magnetic Anisotropy

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Abstract

Structure and magnetic properties of tetragonal $D0_{22}$-Mn_3Ge thin films were studied with varying the film thickness down to 3 nm. The *c*-lattice constant of the films decreased with decreasing the thickness. Out-of-plane magnetization curves exhibited the large coercivity and high magnetic squareness with step-like magnetization reversal at coercivity even at 5 nm, indicating that the perpendicular magnetic anisotropy was still maintained in very thin films, thus $D0_{22}$-Mn_3Ge is a potential material for magnetic tunnel junctions electrodes for spin-transfer-torque magnetic random access memory.

1. Introduction

Magnetic films with a large perpendicular magnetic anisotropy (PMA) are being studied for developing Gbit class spin-transfer-torque magnetic random-access memory (STT-MRAM). The Gbit class STT-MRAM requires magnetic tunnel junctions (MTJs) as the memory cell, which should exhibit a low STT-switching current density (J_{c0}), and a high thermal stability factor (Δ), as well as a high tunnel magnetoresistance (TMR) ratio [1-3]. It has been considered that employment of a magnetic thin film electrode with a low Gilbert damping constant (α) (≤ 0.01), high perpendicular magnetic anisotropy constant (K_u) (≥ 10 Merg/cm^3), and high spin polarization (P) (~ 100%) is crucial to achieve the low J_{c0} (< 10^5 A/cm^2), high Δ (≥ 60), and large TMR ratio (≥ 200%). However, it is difficult to fulfill all of these requirements by conventional materials such as $[Co/Pt]_n$, $[CoFe/Pt]_n$ multilayers [4,5] and perpendicularly magnetized CoFeB [6]. Thus, exploring new magnetic material films with PMA are crucial for developing STT-MRAM.

Quite recently, we theoretically predicted that the $D0_{22}$-Mn_3Ge tetragonal Heusler alloy has a low α (9×10^{-4}), high K_u (> 22.9 Merg/cm^3), and half-metallic band dispersion (P = 100%) in the (001) crystallographic direction [7]. Independently, the ab-initio calculation showed a huge TMR effect in Mn_3Ge/MgO/Mn_3Ge MTJs [8]. Experimentally, it has been reported that $D0_{22}$-Mn_3Ge thin films were grown on MgO(001) [7], $SrTiO_3$(001) [9], and Cr-buffered MgO(001) substrates [10]. In particular, the $D0_{22}$-Mn_3Ge film grown on the Cr-buffered MgO(001) substrates exhibited the magnetic squareness close to unity, step-like magnetization reversal at coercivity, and K_u over 11 Merg/cm^3 [10].

In the-above-mentioned previous studies, thicknesses of the $Mn_{3+x}Ge$ films were very large, *eg.* tens to hundreds nm thick, which is too thick for the applications. Reduction of the thickness down to ≤ 5 nm with keeping high quality is required for future application of $Mn_{3+x}Ge$ into STT-MRAM. In this study, crystal structure and surface roughness as well as magnetic properties of $D0_{22}$-Mn_3Ge thin films prepared on Cr-buffered MgO(001) substrates with reduced thicknesses were investigated.

2. Experiments

We prepared stacked films with structure of MgO(001) subs./Cr(40 nm)/Mn_3Ge(t)/MgO(3 nm) with ultra-high vacuum magnetron sputtering apparatus. Here, t is the thickness of the Mn_3Ge layer. Prior to the deposition of the films, the MgO substrate was thermally flushed in the sputtering chamber at 700˚C. The Cr layer was deposited at room temperature and subsequently annealed at 700˚C to obtain flat surface. The Mn_3Ge layer was deposited at 400˚C varying t from 130 nm to 3 nm. Finally, MgO layer was deposited at room temperature to prevent the Mn_3Ge layer from being oxidized. Crystal structure, magnetic properties, and surface roughness of the stacked films were characterized using x-ray diffractometer, vibrating sample magnetometer, and atomic force microscope (AFM).

3. Results

Figure 1 shows x-ray diffraction patterns of the stacked films with various t. Only $D0_{22}$-Mn_3Ge(004) peak and $D0_{22}$-Mn_3Ge(002) peak were observed for Mn_3Ge, suggesting that the Mn_3Ge films have (001)-oriented $D0_{22}$ structure. The intensity of the peaks reduces with reducing t and almost disappears at t = 5 nm. Besides, position of the peaks slightly shift to higher angle side, indicating reduction of axial ratio c/a from 1.89 at t = 130 nm to 1.87 at t = 10 nm. This behavior suggests that crystal lattice is elongated into in-plane direction at small t, which is likely because of the lattice mismatch between Cr and $D0_{22}$-Mn_3Ge (6.9%).

Figures 2(a) and 2(b) show the out-of-plane hysteresis curves and demagnetization curves, respectively, of the stacked films with various t (≥ 5 nm) measured with applying field perpendicular to the film plane. Clear PMA, high magnetic squareness, and step-like magnetization reversal at coercivity are observed in Fig. 2(b), suggesting high quality of the $D0_{22}$-Mn_3Ge film. At t = 5 nm, other similar materials, such as tetragonal Mn-Ga, lose their magnetic squareness [11, 12], unlikely the $D0_{22}$-Mn_3Ge thin film in this study. This fact suggests that $D0_{22}$-Mn_3Ge is more advantageous than the other materials in the small thickness range. Figure 3 shows t dependence of the coercivity (H_c). The H_c abruptly decreases at t = 5 nm while increases with decreasing t from 60 nm and reaches 30 kOe at 10 nm. This is possibly because of reduction of K_u induced by the crystal lattice elongation in in-plane direction which was suggested by the x-ray diffraction. Such behavior was also reported in highly-strained tetragonal Mn-Ga thin films prepared on Cr-buffered MgO(001) substrates [12]. It was difficult to characterize K_u for the film with t = 5 nm from magnetization measurements because the signal is too small. The precise estimation of K_u will be a future subject.

We also studied t dependence of surface roughness. Both R_a roughness and height difference between the peak and the valley (P-V) are reduced with reducing t (not shown here). R_a reaches 0.3 nm at t = 5 nm and further thinning yields abrupt increase of the roughness because the film is discontinuous.

4. Conclusion

We achieved to fabricate the 5 nm-thick high quality $D0_{22}$-Mn_3Ge films on Cr-buffered MgO(001) substrates that exhibited clear perpendicular magnetization, high magnetic squareness, and step-like magnetization reversal. Growth of further thinner (t < 5 nm) film with smaller surface roughness (R_a < 0.3 nm) is future problem.

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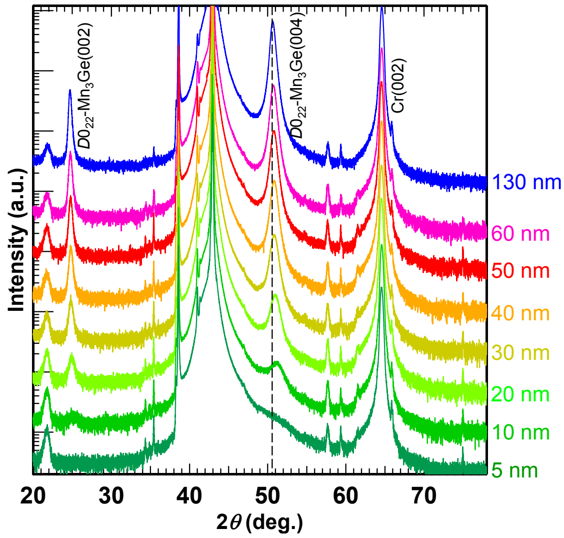

Fig. 1 X-ray diffraction patterns of the films with various thickness t. Dashed line represents the peak position of $D0_{22}$-Mn_3Ge(004) plane at t = 130 nm.

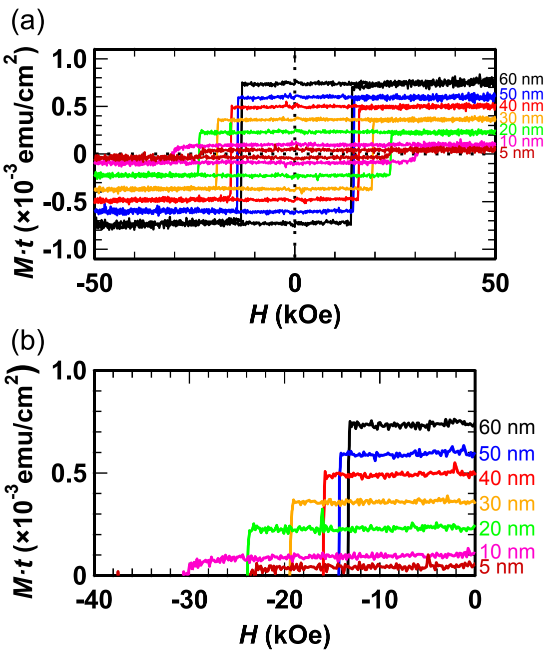

Fig. 2 (a) Full magnetization loops and (b) demagnetization curves of the films with various thickness t, measured with applying field perpendicular to the film plane. Their vertical axis are product of magnetization and thickness t.

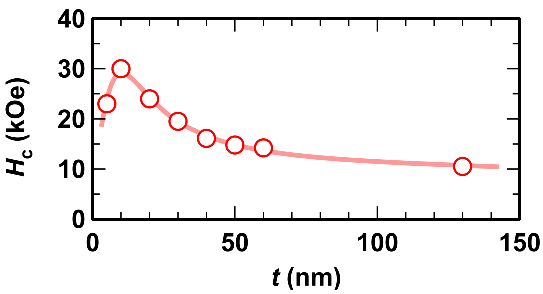

Fig. 3 The thickness t dependence of coercivity for the films.