Dependence of thickness of Fe buffer layer on magnetic properties for Mn$_{2.6}$Ga thin films

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D$_{022}$Mn$_{2.6}$Ga thin films were fabricated by an ultra-high vacuum electron beam vapor deposition system on a MgO (100) single crystalline substrate with different buffer layer thicknesses (0.7 - 5 nm). As the annealing temperature $T_a$ increased to 400°C, the squareness of the $M-H$ curves improved, and the saturation magnetization $M_s$ and magnetic anisotropy $K_u$ increased. At that time, from XRD patterns, D$_{022}$Mn$_{2.6}$Ga (002) superlattice and (004) fundamental peaks were clearly observed from all samples. Our results suggest the existence of a magnetic dead layer of about 3.5 nm in the MnGa layer. Because of this magnetic dead layer, a relatively high magnetic roughness $K_u$ of 9.3 Merg/cm$^3$ and low surface roughness $R_o$ of 0.93 nm were obtained from Mn$_{2.6}$Ga thin film on a 2-nm Fe buffer at $T_a = 400°C$. The results in this work suggest that Fe is a suitable buffer layer for perpendicular magnetized D$_{022}$MnGa thin film.

Key words: D$_{022}$MnGa thin film, saturation magnetization, magnetic anisotropy, electron beam vapor deposition system, surface roughness, buffer layer

1. Introduction

MnGa alloys show D$_{022}$ and L$_1_0$ structure in the composition range at approximately 69 · 76 (q phase) and, 64 · 67 (q$_1$ phase) and 58 · 61 (q$_2$ phase) at.% Mn in the binary phase diagram$^1$). Owing to outstanding magnetic properties such as a high magnetic anisotropy $K_u$ ~ 10 · 23.5 Merg/cm$^3$ $\gg$0, a low Gilbert damping constant $\alpha$ ~ 0.008 · 0.015$^{(5)}$, a relatively low saturation magnetization $M_s$ ~ 600 emu/cm$^3$ $\gg$0 and a high spin polarization $P$ ~ 58% (experimentally) $^{(6)}$, the MnGa thin films have been studied for applications of spintronic devices, including a magnetic random access memory operated by spin transfer torque (STT-MRAM). This device requires a guarantee of thermal stability and high speed writing and reading. That is to say, STT-MRAM needs perpendicularly magnetized magnetic tunnel junctions (p-MTJs) that have high $K_u$ and $P$. Nowadays, MTJ is demanded to achieve a high $K_u$ $\gg$ 10 Merg/cm$^3$, a high $P$ $\approx$ 70%, a low $\alpha$ $\leq$ 0.01 and a low $M_s$ $\approx$ 100 emu/cm$^3$ $\gg$0. From the point of view, a great potentiality for magnetic layers of MTJ is derived from MnGa thin films which shows high $K_u$, high $P$, low $\alpha$ and relatively small $M_s$. $^{(8,10)}$ However, there have been few reports about buffer layers for growth of MnGa thin films. Therefore, it is necessary to obtain the knowledge of buffer layers’ dependence on magnetic properties. The lattice mismatch between D$_{022}$Mn$_{2.6}$Ga and Fe is smaller than that of D$_{022}$Mn$_{2.6}$Ga and Cr. However, it is well known that Fe behaves an in-plane easy magnetization axis. On the other hand, a large perpendicular magnetic anisotropy (PMA) of 14 Merg/cm$^3$ from ultrathin Fe/MgO interface has been presented by J. W. Koo et al. $^{(14)}$. The, in-plane easy magnetization axis and the relatively high average roughness $R_o$ of 2.63 nm were observed from MnGa thin films on 5-nm Fe buffer at our previous work$^{(15)}$. Improvements of these properties are indispensable for application of MTJ films.

In this work, dependence of thickness of Fe buffer layers on magnetic properties for Mn$_{2.6}$Ga thin films have been investigated by using an ultra-high vacuum electron beam (UHV-EB) vapor deposition system.

2. Experimental procedure

All the samples prepared in this work were grown by an ultra-high vacuum electron beam vapor deposition system with base pressure less than 8.9 x 10$^{-7}$ Pa. MnGa target was fabricated from row materials of Mn (5N) and Ga (6N), through the arc melting method in argon atmosphere with base pressure less than 10$^{-3}$ Pa. The stacking structure is the MgO (100) single crystalline substrate / the Fe buffer layers (0.7 - 5 nm) / Mn$_{2.6}$Ga (20 nm) / the Cr capping layer (10 nm). The MgO (100) single crystal substrate was thermally flushed up to 700°C in the UHV chamber half an hour. The Fe buffer layers and the MnGa layer were deposited at room temperature and 300°C, respectively. Finally, the Cr capping layer was deposited at room temperature. Annealing process was carried out at 300 · 500°C 3 hours to improve the crystal quality. All growths are monitored in real time by using reflection high-energy electron diffraction (RHEED). The compositions of the films and the crystal structure of the samples were determined by an energy dispersive X-ray spectroscopy (EDX) and X-ray diffraction (XRD) with Cu-K$_\alpha$ radiation, respectively. The surface roughness of film was investigated by atomic force microscopy (AFM). The magnetic properties of thin films were measured by using superconducting quantum interference device (SQUID).
3. Results and discussion

Figure 1 shows RHEED patterns for different Fe buffer layer thicknesses and Mn$_{2.6}$Ga thin films. Fe buffer: (a) 5 nm, (b) 2 nm, (c) 1 nm and (d) 0.7 nm. Mn$_{2.6}$Ga thin film on Fe buffer: (e) 5 nm, (f) 2 nm, (g) 1 nm and (h) 0.7 nm.

Figure 2 shows XRD patterns for Mn$_{2.6}$Ga thin films on Fe buffer: (a) 5 nm, (b) 2 nm, (c) 1 nm and (d) 0.7 nm.

Figure 3 shows magnetization curves for Mn$_{2.6}$Ga thin film on Fe buffer: (a) 5 nm, (b) 2 nm, (c) 1 nm and (d) 0.7 nm. Black and red lines indicate the out-of-plane and in-plane magnetization curves.

The highest ordering parameter was observed on the low angle side, which showed the c-axis became long. Figure 3 shows that in the case of (a), the easy magnetization axis is the in-plane direction and (b)-(d) are out-of-plane directions. The result of (a) 5-nm Fe buffer, which shows the easy axis to the in-plane direction, was considered due to interface roughness for Fe layer (Neel “orange-peel” coupling though the magnetic dead layer) but island growth (Volmer-Weber). Therefore, as Fe becomes thinner, surface roughness of Fe becomes worse. The epitaxial growth of Mn$_{2.6}$Ga and surface reconstruction structure were observed from (e).

Figure 2 shows magnetization curves for Mn$_{2.6}$Ga on Fe buffer: (a) 5 nm, (b) 2 nm, (c) 1 nm and (d) 0.7 nm. Mn$_{2.6}$Ga thin film on 2-nm Fe buffer: (e) 5 nm, (f) 2 nm, (g) 1 nm and (h) 0.7 nm. Black and red lines indicate out-of-plane and in-plane magnetization curves.

Figure 4 shows the product of $M_i$ and $t$ as a function of $t$. Here, $t$ is a thickness of MnGa layers and $M_i$ is estimated by subtracting magnetization of Fe from total magnetization. The black circles and squares indicate the reference values of Mn$_{2.6}$Ga thin films on 5-nm Cr buffer presented by Y. Takahashi et al., and Mn$_{2.6}$Ga thin films on 2-nm Fe buffer in this work, respectively. A magnetic dead layer thickness $\sim$ 2 nm in the Cr buffer case and $\sim$ 3.5 nm in the Fe buffer case were shown in Fig. 4. Here, the magnetic dead layer means a layer of non-magnetic ones. It was shown that when Fe used for the buffer layer, the magnetic dead layer becomes larger than in the case of
Magnetization curves for Mn\textsubscript{2.6}Ga on 2-nm Fe buffer (a) without annealing and at (b) \( T_a = 300°C \), (c) 400°C and (d) 500°C. Black and red lines indicate the out-of-plane and in-plane magnetization curves.

Figure 5 shows XRD patterns for Mn\textsubscript{2.6}Ga on the 2-nm Fe buffer (a) without annealing and at (b) \( T_a = 300°C \), (c) 400°C and (d) 500°C. \( D_{022} \cdot \text{MnGa} \) (002) superlattice and (004) fundamental peaks were clearly observed from the all samples. As the \( T_a \) increased to (c) from (a), the (004) peak was shifted to a high angle side, which suggest that the c-axis turns to short. In addition, the ordering parameter (\( S_{022} \)) increased from 0.69 (a) to 0.78 (c). These results lead to a conclusion that annealing process was effective for the improvement of the crystal quality under \( T_a = 400°C \).

Figure 6 shows magnetization curves for Mn\textsubscript{2.6}Ga on the 2-nm Fe buffer (a) without annealing and at (b) \( T_a = 300°C \), (c) 400°C and (d) 500°C. As the \( T_a \) increased from (a) to (c), the squareness of the \( M-H \) curves improved, and value of both \( M_s \) and \( K_u \) increased. These values, however, decreased at (d). This result is in good agreement with the result of Fig. 5. The highest \( M_s \) of 273 emu/cm\(^3\) and \( K_u \) of 9.3 Merg/cm\(^3\) were obtained at (c).

Figure 7 shows AFM images for Mn\textsubscript{2.6}Ga on the 2-nm Fe buffer (a) without annealing and at (b) \( T_a = 300°C \), (c) 400°C and (d) 500°C. The relatively low surface roughness \( R_{a} \) of 0.93 nm was observed from (b) and (c). In the case of \( T_a = 500°C \), \( R_{a} \) became worse.

4. Summary

In this work, dependence of thickness of Fe buffer layers on magnetic properties for Mn\textsubscript{2.6}Ga thin films have been investigated by using an ultra-high vacuum electron beam (UHV-EB) vapor deposition system. The highest \( K_u \) was obtained from the 2-nm Fe buffer. When \( T_a \) is increased to 400°C, improvement of squareness of the \( M-H \) curve and increase of \( M_s \) and \( K_u \) were observed. From the XRD patterns, \( D_{022} \cdot \text{MnGa} \) the (002) superlattice and the (004) fundamental peaks were clearly observed from the all samples. Our result indicates that Fe buffer layers made about 3.5 nm of the magnetic dead layers in MnGa. Because of the existence of about 3.5 nm of magnetic dead layer, the relatively high \( K_u \) of 9.3 Merg/cm\(^3\) and the low surface roughness \( R_{a} \) of 0.93 nm might be obtained from Mn\textsubscript{2.6}Ga thin film.
on 2-nm Fe buffer at $T_a = 400^\circ$C. The results in this work suggest that Fe is a suitable buffer layer for application of high $K_u D_{022}$-MnGa.

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References

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