

Epitaxial Growth and Magnetic Properties of MnAl Films using CrRu Buffer Layer

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Abstract

The τ -phase MnAl films were epitaxially grown on MgO(100) substrate with CrRu buffer layer by dc sputtering. The magnetic and structural properties were studied systematically by varying the growth temperature. The films grown at 300°C possess higher magnetic anisotropy constant of about 2×10^6 erg/cc. The saturation magnetization obtained in that sample was about 470 emu/cc. The CrRu buffer layer and growth temperature plays an important role in the epitaxial growth of τ -phase MnAl thin films. It is observed that there is a strong correlation between structural and magnetic properties of the MnAl film which can be tuned by the growth temperature.

Keywords: Epitaxial Growth, Buffer Layer, Tau Phase, Magnetic Anisotropy Constant.

INTRODUCTION

Ferromagnetic material of L1₀ class has drawn considerable interest over the decades due to its potential applications not only in high density data recording media and permanent magnet, but also in spintronic devices such as spin-RAM, high power oscillator, spin light-emitting diodes, spin field-effect transistors etc. [1-

4]. Millimeter waves are recently detected in perpendicular magneto tunnel junction (MTJ) using L1₀ materials [5].

Low damping constant is also reported in perpendicularly magnetized L1₀ class material [6-7]. Therefore, the utility of perpendicular MTJ of L1₀ class material is promising in spin RAM and STT-RAM

devices in the future. In order to fabricate such a device with higher recording density, it is important to have a combination of magnetic properties of high K_u , low M_S and low damping constant (α). Besides, due to the limited availability and high costs of mining and processing of rare-earth elements, rare-earth-free magnetic materials are also needed [8].

Considering these factors, τ -phase MnAl is one of the potential L10 materials and therefore, it has drawn a lot of attention in recent years compared to other L10 materials. However, the τ -phase MnAl is metastable in bulk and easily broken into other phases, which is not ferromagnetic [9]. Several attempts have been made to get epitaxial thin film. In most cases, the saturation magnetization and magnetic anisotropy obtained a low value [9-11]. There are some reports of the epitaxial τ -phase of MnAl in thin-film form in semiconductor substrate [12-13]. However, MBE is required to fabricate the films. The other reports of τ -phase of MnAl films on MgO(100) substrate requires post annealing[14-15]. The τ -phase MnAl films are very sensitive to the growth temperature, substrate and buffer layer. Therefore, alternative buffer layer and

easier fabrication technique is essential. In this paper, we have showed the crystal structure and magnetic properties of MnAl thin films on various buffer layer and substrate. The dependence of growth temperature on the magnetic and structural properties was studied.

EXPERIMENT

The MnAl alloy thin films in this study were fabricated using dc sputtering in a high vacuum of base pressure 2×10^{-7} torr on MgO(100) and STO(100) substrates with Pd and CrRu buffer layer with a thickness of 40 nm. The sputtering target material was a single alloy composed of Mn-46% and Al-54%. The deposition rate was 2.21 nm/min and film thickness was about 40 nm. The MnAl films were deposited at the various growth temperatures (TS) ranging from 150 to 500°C. Finally, MnAl films were capped of 4 nm Ta to avoid any oxidation. It is noted that the substrates were cleaned by acetone, ethyl alcohol and deionized water. The substrate was flushed at 500°C to clean the surface before deposition. Magnetic measurements were done using VSM. The structure of the films was studied by a Bruker X-ray Diffractometer. The surface morphology was studied by atomic force microscopy (AFM).

RESULTS AND DISCUSSION:

In order to ensure requisite magnetic properties, it is necessary to obtain good quality MnAl films. The choice of the substrate or buffer layer with good lattice matching is an important factor for good quality films. The probable choice of the materials for MnAl films with lattice misfit is shown in the table-1 below.

Table 1

Material	Lattice Misfit
MgO	7%
Cr (at 45° angle)	4%
GaAs	2%
Pd	0.8%
STO	0.3%
CrRu (at 45° angle)	0.07%

Among the materials, there are some reports of epitaxial growth of MnAl thin films using Cr and GaAs. Therefore, we have tried four other materials. As a substrate, we choose MgO(100) and STO(100) and on the other hand, as a buffer layer, we choose Pd and CrRu to grow MnAl film. Thus, we made four kinds of samples (a) MgO(100)/MnAl, (b) STO(100)/MnAl, (c) MgO(100)/CrRu/Pd/MnAl and (d) MgO(100)/CrRu/MnAl films. The deposition temperature in all cases was kept at 300°C.

Fig. 1 shows the XRD $\theta/2\theta$ scan results of the samples. The (001) and (002) peak of MnAl is observed in the sample grown on MgO(100) with CrRu buffer layer. This indicates the epitaxial growth of MnAl film grown MgO(100) substrate with CrRu buffer layer. On the other hand, there are no peaks of MnAl films in other samples indicating amorphous nature. Therefore, one can say that the CrRu buffer layer plays an important role for the epitaxial growth of MnAl thin films. The M-H loop measurement in in-plane (blue curve) and perpendicular (red curve) direction were carried out in those samples and shown in **fig. 2**. It is observed that only the MnAl films grown onto MgO(100) with CrRu buffer layer show ferromagnetic properties, while others show paramagnetic behavior.

It is also understood from the loop that the MnAl thin films grown onto MgO(100) with CrRu buffer layer have perpendicular magnetization. In order to study the role of deposition temperature, the MnAl thin films were grown at various temperatures on MgO(100) substrate with CrRu buffer layer. The XRD pattern of $\theta/2\theta$ scan of the MnAl films was carried out as shown in **fig. 3**. In all these samples, the (200) CrRu buffer layer peak is clearly observed. The lattice constant based on the (200) peak is

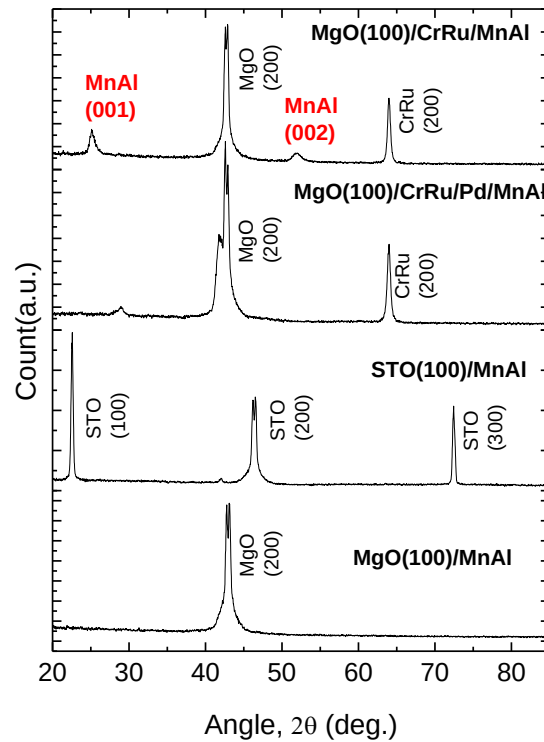


Fig. 1 The $\theta/2\theta$ scan of MnAl thin films grown at various substrates and buffer layers

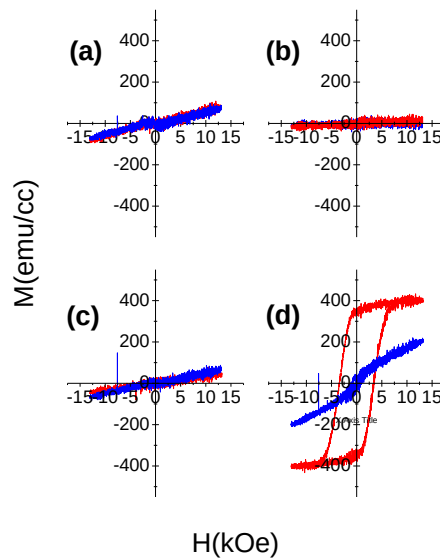


Fig.2 The M-H loop of MnAl thin films grown at various substrates and buffer layers

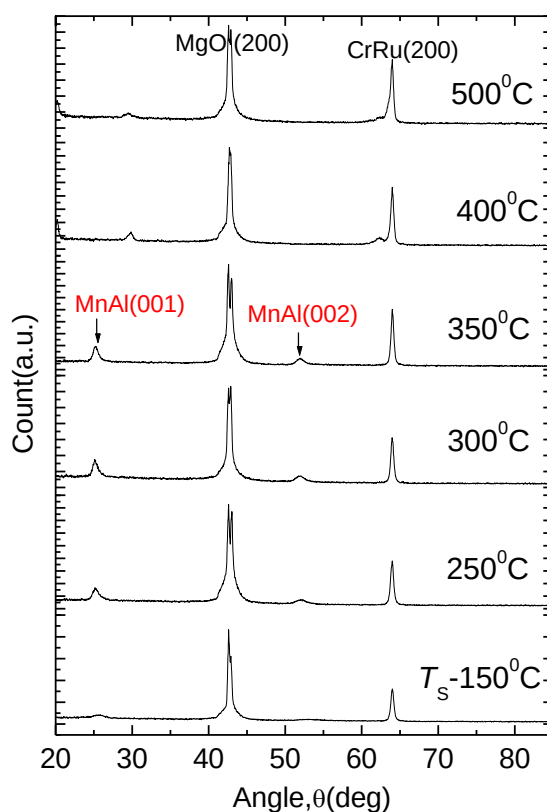


Fig. 3 The $\theta/2\theta$ scan of MnAl thin films grown at various growth temperatures

obtained as $2.77\text{\AA}$. With a 45° angle, the lattice constant, a of CrRu obtained as $3.91\text{\AA}$ approximately, which is very close to the bulk lattice constant value of MnAl [15-16]. The lattice misfit in this case is about 0.7%. At the T_s range from 150 to 350°C , two peaks of MnAl films are observed at about 25.3 and 54.4 .

These peaks correspond to (001) and (002) of τ -phase MnAl. Above $T_s > 350^\circ\text{C}$, there is no peak of MnAl that corresponds to τ -phase of MnAl. Even, the ε -phase is not

observed. There is a small peak observed at around 29° which might be due to the transformation of MnAl into some other phases. However, it is not clearly understood at this moment. The out of plane lattice constant (c) is calculated and depicted in **fig.4. (a)**. It is observed that the c value increases with T_s until 350°C . It is also observed that the (001) peak width decreases with T_s as shown in **fig. 4(b)**.

The (001) and (002) peak observed at 150 - 350°C are fitted using Gaussian fitting and

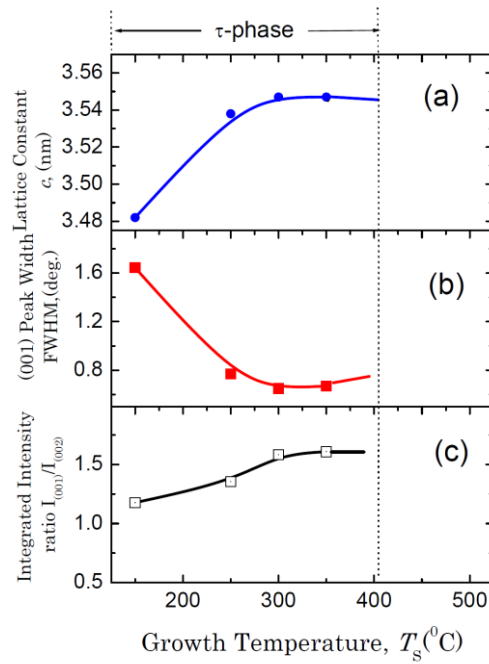


Fig. 4 (a) The lattice constant, (b) the (001) peak width (c) integrated intensity ratio, $I(001)/I(002)$ of the MnAl films as a function of the growth temperature (T_s)

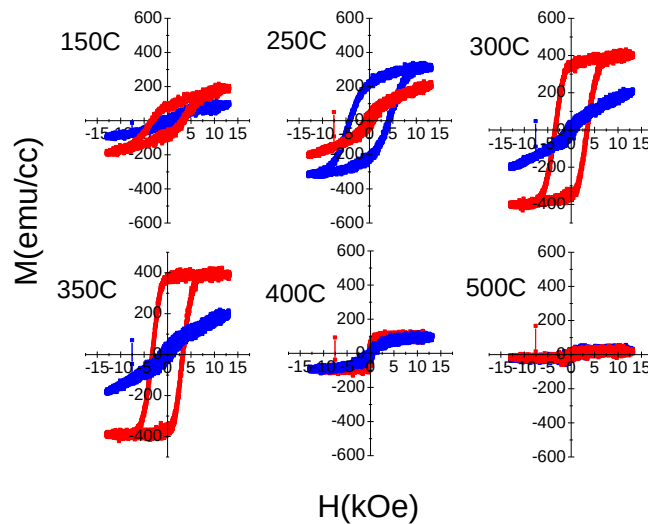


Fig.5 In-plane (blue curve) and perpendicular (red curve) M-H loop of MnAl films as a function of the substrate temperature (T_s)

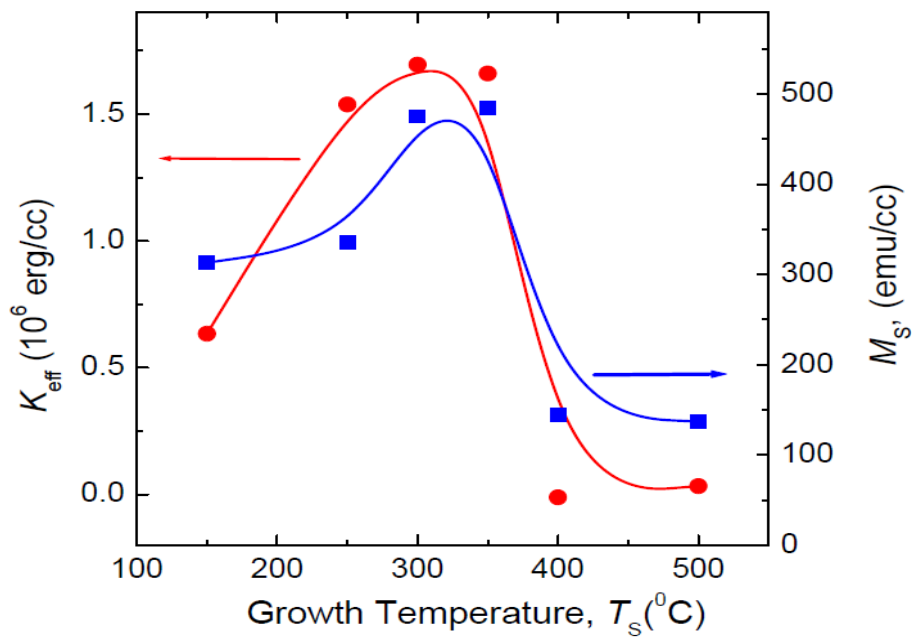


Fig.6 The saturation magnetization (M_s) and effective magnetic anisotropy constant (K_{eff}) with the variation of T_s

The integrated intensity was calculated. As the ordering depends on the integrated intensity ratio of (001) and (002), the ratio are also calculated and plotted in **fig.4(c)**. It is observed that the integrated intensity ratio is enhanced with the T_s . Therefore, one can tell from all these XRD results that the τ -phase of MnAl is obtained at the growth temperature of 250-350°C. From the integrated intensity ratio, it can be said that the ordering increases with T_s and maximum observed is at 350°C.

The room temperature in-plane and perpendicular M-H loop of MnAl films grown at the various growth temperatures

(T_s) is shown in **fig. 5**. It is evident from these loops that there is a strong dependence of the magnetization of MnAl films on the growth temperature. The magnetization is going to saturate earlier in perpendicular case compared to in-plane in the T_s range of 150 to 350°C. The magnetization of MnAl is perpendicular to the film plane at this temperature range. However, there is no big difference of the in-plane and perpendicular loop above 350°C. The effective magnetic anisotropy (K_{eff}) is calculated from the area enclosed between the perpendicular and in-plane M-H loop [11].

The saturation magnetization (M_s) and the effective magnetic anisotropy (K_{eff}) are plotted as a function of substrate temperature in **fig. 6**. At lower T_s , the M_s and K_{eff} are relatively small. It is maximum at 300°C and then goes on decreasing. One can estimate the uniaxial magnetic anisotropy from the K_{eff} and M_s by this equation: $K_U = K_{eff} + 2\pi M_s^2$. The maximum value of K_U is obtained at 300°C of about 2×10^6 erg/cc which is comparable to the other reports. According to the theoretical calculation, it is predicted that the slight tetragonal distortion may cause a change in anisotropy energy of magnetic properties [14]. It is observed that there is a slight increase in the c value according to XRD results as shown in **fig. 4(a)**. This may cause tetragonal distortion and therefore, higher c valued samples

exhibit higher magnetization and higher magnetic anisotropy constant. These samples have higher ordering and exhibit higher anisotropy. Therefore, there exists a close relationship between the magnetic and structural properties of MnAl films.

The surface morphology is a very important factor for the materials to be applicable in any practical devices. The surface morphology was studied by AFM for all the samples with the scan area of $2\mu\text{m} \times 2\mu\text{m}$ and shown in **fig. 7**. The average surface roughness (R_a) was estimated and depicted in **fig.8**. It is seen from the figure that the R_a is increasing with the growth temperature (T_s). At 150°C, the R_a is about 0.3nm while at 500°C, it is about 2.5 nm.

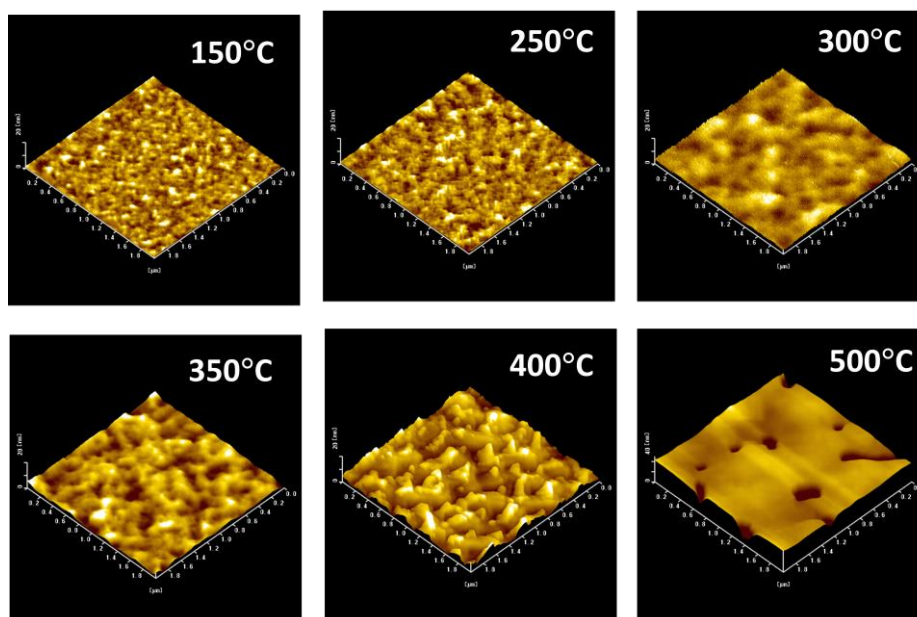


Fig.7 The surface morphology of MnAl films as a function T_s

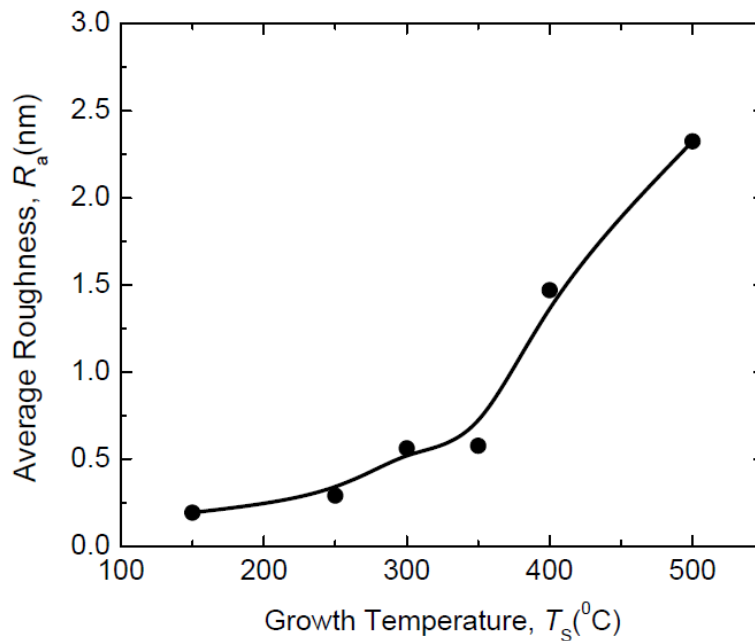


Fig. 8 The variation of average surface roughness with the variation of growth temperature

CONCLUSION

The magnetic and structural properties of MnAl films grown on MgO(100) and STO(100) substrates with Pd and CrRu buffer layer using dc sputtering were studied. The crystal structure and magnetic properties of MnAl films are very sensitive with the substrate and buffer layer. From our study, it is observed that the composition of MnAl, CrRu buffer layer and growth temperature, all are crucial in the epitaxial growth of τ -phase of MnAl films. The films having a higher value of lattice constant c , lower dispersion and higher intensity of (001) peak possess higher magnetization and higher magnetic

anisotropy constant. The highest observed value of M_s was around 470 emu/cc and magnetic anisotropy (K_U) of about 2×10^6 erg/cc. A close relationship is observed between the structural and magnetic properties of the films. The magnetic and structural properties could be tailored effectively by controlling the growth temperature.

ACKNOWLEDGEMENTS

The author greatly acknowledges the support of Japan Society of Promotion of Science (JSPS) for this research. This work was supported by the Funding Program for World-Leading Innovative

R&D on Science and Technology (FIRST program) of Japan Society for Promotion of Science (JSPS), Research and Development for Next-Generation Information Technology of MEXT and grand-in-aid for scientific research S (No.24226001).

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