MnGa (001) Textured Film Fabricated on Thermally Oxidized Si Substrate for Application to Ion Beam Bit Patterned Media

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(001) oriented MnGa films were grown on thermally oxidized Si substrates and ion beam patterned films using the MnGa grown on Si substrates were fabricated. The buffer layer of Cr (20 nm) / MgO (5 nm) / CrB (5 nm) / NiTa (25 nm) was used and highly (001) oriented and flat Cr buffer layer was obtained by high temperature annealing of 800°C. The large saturation magnetization M_s of 0.58 T, which is 74 % of that of the epitaxial MnGa grown on MgO(001) substrate, was confirmed by growing the MnGa on the Cr buffer layer. As well as the large M_s, the MnGa on Si substrate exhibited a large perpendicular anisotropy. By using the (001) oriented MnGa on Si substrate, ion beam patterned structures whose pitch sizes down to 100 nm, corresponding to the areal density of 65 Gb/in^2, were obtained. These results indicate that low-cost and high-density BPM were fabricated by the ion irradiation on MnGa grown on Si substrate. Further improvement of the crystal orientation of the buffer layer will be necessary to realize the MnGa BPM with the areal density of 1 Tb/in^2 and more.

***Index Terms*—MnGa, Ion Irradiation, Bit Patterned Media**

I. Introduction

Bit patterned media (BPM) is a promising candidate for future hard disk drive (HDD) technology, since BPM provide large thermal stability and low switching field compared to conventional granular media. BPM is considered to achieve an areal density of 20 Tb/in^2 by combining with heat-assisted or microwave-assisted magnetic recording. In a general BPM fabrication process, magnetic dots are separated physically by ion milling, and then trenches between the bits are filled with nonmagnetic materials [1]. Surface flattening to reduce surface roughness to a nanometer scale is necessary for the stable flying of a read/write head in an HDD system. On the other hand, there is an alternative technique utilizing ion irradiation for the BPM fabrication [2]. The magnetism of a media is locally modified by the ion irradiation, whereas the ion irradiation does not physically etch the surface of the magnetic materials. Therefore, the flattening process can be excluded, making the fabrication processes simple and the fabrication cost low.

At an early stage of the ion irradiation BPM, Co/Pt [2]-[5] and Co/Pd [6], [7] films were used, since their perpendicular magnetic anisotropies were modified by the ion irradiation, i.e., the ion irradiation altered the easy axis of the magnetic anisotropy of Co/Pt and Co/Pd from perpendicular to in-plane. However, the Co/Pt and Co/Pd BPM fabricated by the ion irradiation have a serious problem for the practical application, since the adjacent bits were exchange coupled through the in-plane magnetized (irradiated) regions, which limits the ultimate density of the BPM. Previously, we reported that the ion irradiation into $L1_0$-ordered MnGa films changes the magnetism of the MnGa from ferromagnetic to paramagnetic associated with the phase change from $L1_0$-ordred to A1-disordred phase [8], [9]. We also reported that dot-patterned MnGa films fabricated by local ion-beam irradiation have sufficiently flat surfaces and negligibly small bit edge damage [9], [10]. However, these results were obtained using the MnGa grown on MgO(001) single crystal substrates which are not practical for the application. In this study, we report (001) textured $L1_0$-MnGa films on thermally oxidized Si substrates for the practical application of the MnGa BPM fabricated by the ion irradiation.

Similar studies have been extensively done for the growth of (001) textured $L1_0$-FePt films on low-cost substrates such as glass substrates, and (001) oriented $L1_0$-ordered FePt films were grown by inserting functional buffer layers [11]-[13]. In this paper, we inserted several buffer layers and tuned the growth temperature and annealing temperature to obtain highly (001) textured $L1_0$-MnGa films on thermally oxidized Si substrates.

II. Experimental Methods

The sample stack was Cr (5 nm) / MnGa (15 nm) / Cr (20 nm) / MgO (5 nm) / CrB (5 nm) / NiTa (25 nm) / SiO_2 / Si substrate. All the layers except for the MgO layer were deposited by RF magnetron sputtering, and the MgO layer was deposited by e-beam evaporation. NiTa and CrB are known to be effective to obtain (001) oriented MgO buffer layer for the improvement of the magnetic properties of $L1_0$ FePt films [14]. Before the deposition of the MgO layer, the sample was transferred to the evaporation chamber without breaking the

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vacuum. After the deposition of the MgO layer, the sample was transferred back to the sputtering chamber, then the Cr buffer layer was sputtered on the MgO layer at R.T., followed by the annealing at T_a^{Cr} = 600 or 800 ˚C for 60 min. The MnGa layer was grown at temperatures T_s^{MnGa} of R.T., 200 and 300 ˚C, and then annealed at 400 ˚C for 60 min. The Cr layer was deposited as a protective layer at a temperature lower than 150˚C. As a reference sample, an epitaxial MnGa film was grown on the MgO(001) single crystal substrate. The surface of the MgO substrate was cleaned by 1 keV Ar^+ ion bombardment followed by the heating at 600 ˚C for 10 min. The sample stack was Cr (5 nm) / MnGa (15 nm) / Cr (20 nm) / MgO(001) substrate. The growth temperatures are 400 ˚C and 300 ˚C for the Cr buffer and MnGa layers, respectively. The post-annealing was carried out at 600 ˚C and 400 ˚C for 60 min after the deposition of the Cr buffer and MnGa layers, respectively. Finally, the Cr layer was deposited as a protective layer.

For patterning, ZEP520A was used as a resist and electron beam lithography with the acceleration energy of 100 kV was performed to form patterned resist masks with a thickness of ~ 100 nm. Uniform ion irradiation was carried out through the masks by an ion implantation system. 30 keV Kr^+ ions were irradiated at an ion dose of 1 × 10^{14} ions/cm^2, which is sufficient to kill the ferromagnetism of 15 nm thick MnGa films on MgO substrates [8], [9]. The residual resist masks were removed by O_2 plasma ashing in a reactive ion etching chamber.

Magnetization curves were measured by an alternating gradient field magnetometer with a maximum field of 2 T. Crystal structures were analyzed by X-ray diffraction (XRD) using Cu Kα radiation. Surface morphologies and magnetic domain structures were characterized by atomic force microscopy (AFM) and magnetic force microscopy (MFM), respectively.

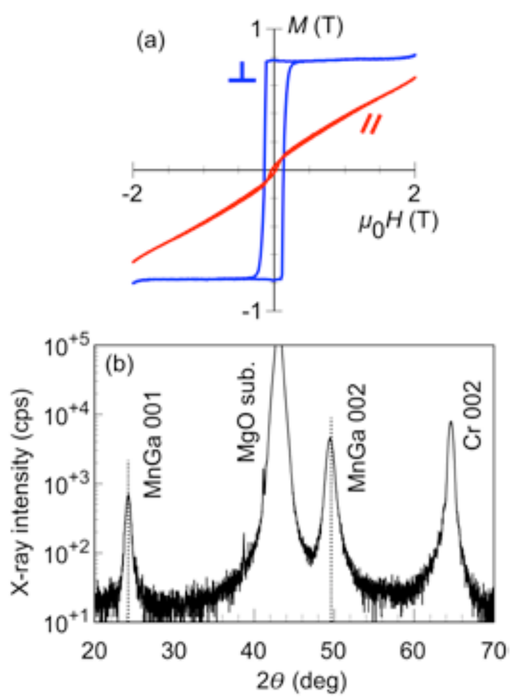

Fig. 1. (a) Out-of-plane and in-plane *M-H* curves and (b) out-of-plane XRD pattern of a MnGa film grown on a MgO substrate. The dashed lines in Fig. (b) represent diffraction angles estimated from bulk values.

III. Results and Discussions

A. MnGa epitaxial films on MgO substrates

Figure 1 (a) shows out-of-plane and in-plane *M-H* curves of the MnGa film grown on the MgO substrate. The out-of-plane curve showed a hysteresis with squareness of unity, in contrast, the in-plane curve was almost linear with small hysteresis, showing the strong perpendicular anisotropy of the MnGa film grown on the MgO substrate. The saturation magnetization M_s was ~ 0.78 T and the perpendicular magnetic anisotropy constant K_u was ~ 1 MJ/m^3 which was evaluated from the torque curve obtained applying the external field of 9 T (not shown here). M_s and K_u of the as-prepared MnGa are comparable to those reported in the literature [15]. Figure 1 (b) shows the out-of-plane XRD pattern of the MnGa film grown on the MgO substrate. MnGa 002 and Cr 002 peaks were clearly observed. Moreover, MnGa 001 superlattice peak was observed. These results indicate the (001) oriented $L1_0$ ordered phase was grown on the MgO substrate, resulting in the large perpendicular anisotropy of the MnGa film.

B. MnGa polycrystalline films on Si substrates

Before the growth of MnGa films on Si substates, we tuned the growth condition of the buffer layer with a stack of Cr (10 nm) / MgO (20 nm) / CrB (5 nm) / NiTa (25 nm) / SiO_2 / Si substrate. All the layers were deposited at R.T., and then some of the samples were post-annealed at temperatures from 200 to 800 ˚C. Figure 2 shows the annealing temperature dependence of MgO 002 and Cr 002 peak intensities obtained from XRD and average roughnesses R_a of the Cr surface estimated from AFM measurements. MgO 002 and Cr 002 peaks monotonically increased, whereas R_a of the Cr surface decreased with increasing the annealing temperature. The smooth surface of R_a = 0.3 nm and highly (001) oriented Cr buffer were obtained by the post-annealing at a temperature of 800˚C.

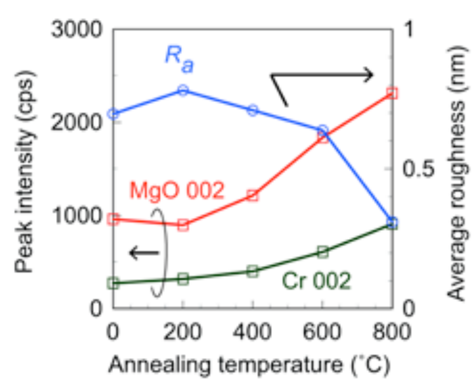

Fig. 2. MgO 002 and Cr 002 peak intensities and average surface roughness R_a of the buffer structure Cr (10 nm) / MgO (20 nm) / CrB (5 nm) / NiTa (25 nm) / SiO_2 / Si sub. as a function of the annealing temperature.

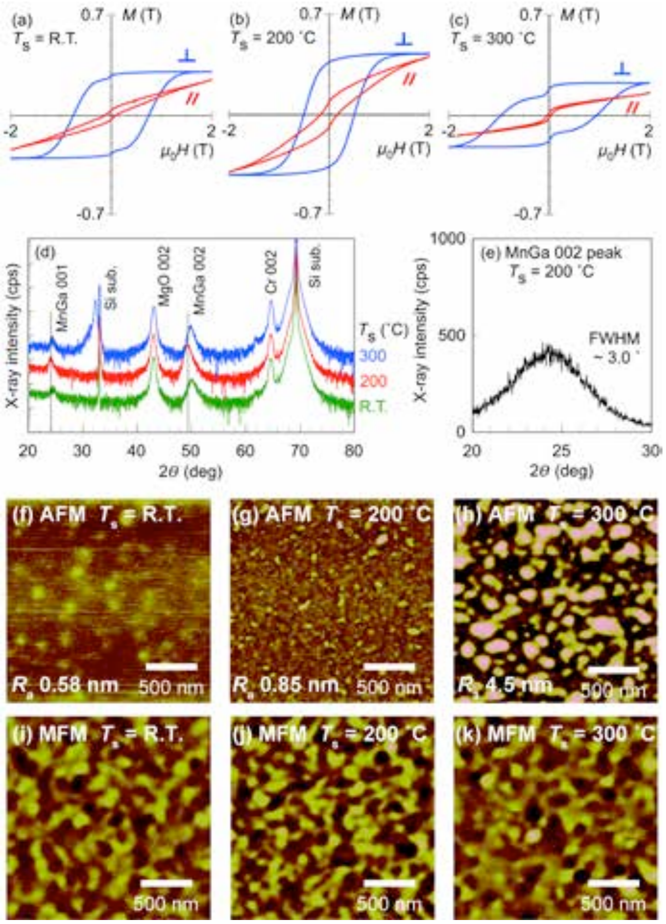

Fig. 3. (a) – (c) *M-H* curves, (d) XRD patterns, (e) rocking curve of MnGa 002 peak, (f) - (h) AFM images, and (i) - (k) MFM images of MnGa films grown on the Cr buffer layer annealed at T_a^{Cr} = 600 ˚C. The substrate temperature T_s during the growth of MnGa layer was varied at R.T., 200, and 300 ˚C. The dashed lines in Fig. (d) show the peak positions of the bulk MnGa.

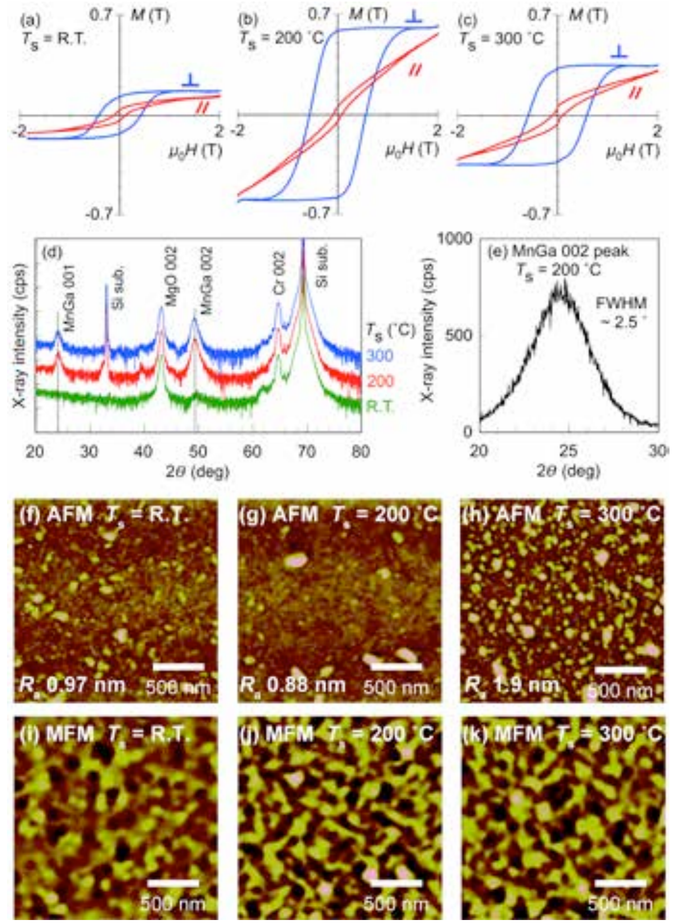

Fig. 4. (a) – (c) *M-H* curves, (d) XRD patterns, (e) rocking curve of MnGa 002 peak, (f) - (h) AFM images, and (i) - (k) MFM images of MnGa films grown on the Cr buffer layer annealed at T_a^{Cr} = 800 ˚C. The substrate temperature T_s during the growth of MnGa layer was varied at R.T., 200, and 300 ˚C. The dashed lines in Fig. (d) show the peak positions of the bulk MnGa.

Figure 3 shows (a) - (c) *M-H* curves, (d) XRD patterns, (e) rocking curve, (f) - (h) AFM images, and (j) - (k) MFM images of MnGa films grown on the buffer layer annealed at a temperature of T_a^{Cr} = 600 ˚C. The substrate temperature T_s^{MnGa} during the deposition of MnGa was varied from R.T. to 300 ˚C. Figure 4 shows the results for the MnGa grown on the buffer layer in the condition of T_a^{Cr} = 800 ˚C. From the *M-H* curves, all the samples have the easy axis of the magnetization along the film normal direction. The M_s became maximum at T_s^{MnGa} = 200 ˚C for both annealing temperatures of the Cr buffer layer, and the highest M_s ~ 0.58 T was obtained especially for T_a^{Cr} = 800 ˚C. The hysteresis of the in-plane curve of the MnGa grown on the Cr annealed at T_a^{Cr} = 800 ˚C was smaller than that for T_a^{Cr} = 600 ˚C. This means that the anisotropy distribution was smaller for T_a^{Cr} = 800 ˚C than for T_a^{Cr} = 600 ˚C.

MnGa 001 and 002, Cr 002, and MgO 002 peaks were observed in the XRD patterns of almost all the samples. This means that MnGa, Cr and MgO layers are all grown with (001) preferred orientation. Other peaks except for MnGa, Cr, MgO and substrate were not identified. At T_s^{MnGa} = 200 ˚C, the peak positions of $L1_0$-MnGa well agreed with bulk values indicated as dashed lines in the figures in both cases of T_a^{Cr} = 600 and 800 ˚C. From the rocking curves of the MnGa 002 peak, the full width at half maximum (FWHM) was estimated to be 2.5˚ and 3.0˚ for the MnGa grown on the Cr annealed at T_a^{Cr} = 600 and 800 ˚C, respectively. The FWHM for T_a^{Cr} = 800 ˚C is slightly smaller than that for T_a^{Cr} = 600 ˚C. This is closely related to the small R_a of the Cr and small hysteresis of the in-plane *M-H* loop for the condition of T_a^{Cr} = 800 ˚C shown in Figs. 2-4.

From AFM images, the surface roughness of the MnGa was rather small up to T_s^{MnGa} = 200 ˚C, and significantly increased when the T_s^{MnGa} equals to 300 ˚C for both conditions of T_a^{Cr} = 600 and 800˚C. In MFM images, bright and dark regions were observed in all samples. Since no magnetic field was applied to the sample before the observations, maze-like domain structure originated from the perpendicular anisotropy of the MnGa was seen. However, the transition between bright and dark regions was not so sharp compared to that of epitaxial MnGa film grown on MgO(001) [9], which is due to the inhomogeneity of the MnGa grown on Si substrates.

The magnetic properties of MnGa are closely related to the crystal structure, microstructure, and surface roughness of the MnGa. The film having a flat surface and highly (001) oriented structure exhibited a large perpendicular anisotropy

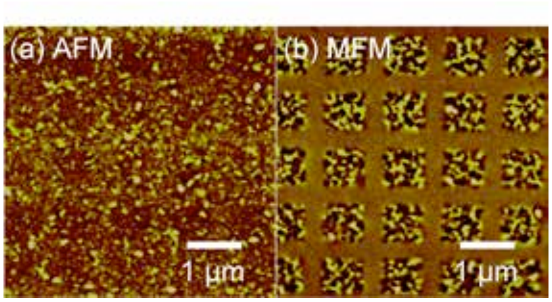

Fig. 5. (a) AFM and (b) MFM images of an ion-beam patterned MnGa film on Si substrate with a pitch size of 1000 nm.

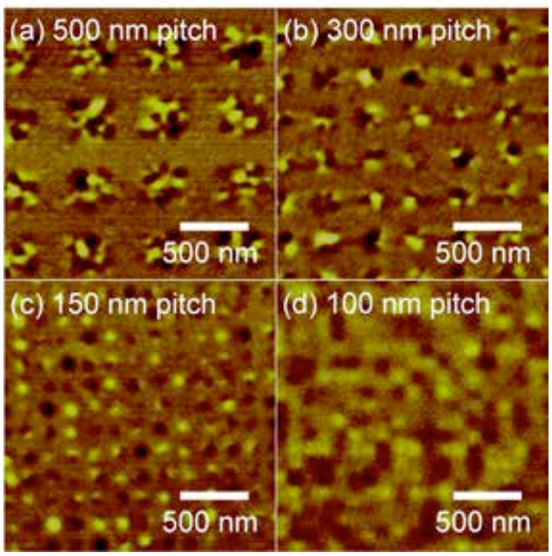

Fig. 6. MFM images of an ion-beam patterned MnGa film on Si substrate with pitch sizes of (a) 500, (b) 300, (c) 150, and (d) 100 nm.

and sharp transition between bright and dark contrasts in the MFM image. Since the structure of MnGa layer is quite sensitive to that of the buffer layer, improving the flatness and the crystal orientation of the buffer layer will be essential for the growth of MnGa films with flat surface and excellent magnetic properties.

C. Magnetic patterning of MnGa on Si substrates

Figure 5 shows AFM and MFM images of a dot patterned MnGa film by the local Kr^+ ion irradiation with a pitch size of 1000 nm. Those images were taken at the same place. In the MFM image, maze-like domain structure was seen in the dot region, in contrast no magnetic contrast was seen in the ion-irradiated regions. In the AFM image, patterned structure corresponding to the structure in MFM image did not appear. Thus, the ion irradiation into MnGa can be useful to realize a flat bit patterned structure without changing the topography of the film [8], [9]. Figure 6 shows MFM images of a dot-patterned MnGa film with various pitch sizes. The magnetic dot patterns were seen down to a pitch size of 100 nm in the MFM images. However, dot edges were not sharp even at a pitch size of 500 nm and some of the dots did not exhibit clear magnetic contrast. This is considered to be due to the poor homogeneity of the MnGa film prepared on Si substrates as discussed in Figs. 3 and 4. In the present study, we have succeeded to obtain (001) oriented MnGa with M_s ~ 460 emu/cc and large perpendicular anisotropy, however, further improvement of homogeneity of the MnGa will be necessary for the fabrication of nano-sized magnetic patterned structures.

IV. Conclusion

We have fabricated (001) textured MnGa films on thermally oxidized Si substrates. The growth condition of Cr / MgO / CrB / NiTa buffer layers were tuned and obtained (001) oriented Cr buffer layer with a flat surface of R_a = 0.3 nm after the annealing of Cr at T_a^{Cr} = 800°C. MnGa films on Si substrates exhibited large perpendicular magnetic anisotropies, and a maximum saturation magnetization of M_s ~ 0.58 T, which is 74 % of that of the MnGa grown on the MgO substrate. We also fabricated the ion beam patterned structure using the MnGa grown on Si substrates, and obtained fine magnetic patterning with a pitch size down to 100 nm without changing the surface topography. However, further improvement of the homogeneity of the (001) oriented MnGa by tuning the growth condition of the buffer layers was found to be necessary to realize high-density and flat BPM by the local ion irradiation.

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