Magnetic Properties of L1₀ Ordered FePt Films Prepared on a Fe–Si–B–Nb–Cu Soft Magnetic Underlayer

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(001)-oriented FePt films with large perpendicular magnetic anisotropy have been obtained on a soft magnetic underlayer (SUL). A nanocrystalline Fe–Si–B–Nb–Cu alloy film has been chosen as SUL, showing the coercivity H_c of less than 80 A/m after annealing at 400°C. It has been found that the crystal orientation and magnetic properties of FePt films are improved by the introduction of a MgO interlayer between FePt and Fe–Si–B–Nb–Cu. The strong (001) texture and the large coercivity of 565 kA/m have been obtained in the tri-layer structure of Fe–Si–B–Nb–Cu (200 nm)/MgO (5 nm)/FePt (10 nm).

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1. Introduction

Demand for high-density magnetic storage devices is unlimited and they have been expected to be downsized and to possess huge capacity. However, higher recording density requires smaller magnetic-particles, which faces a problem of thermal instability. L1₀-FePt ordered alloy has attracted much attention because of its high uniaxial magnetic anisotropy K_u ($= 7.0 \times 10^6$ J/m³) to solve the problem.¹⁾ In order to use the FePt alloy as the devices with a perpendicular magnetic recording system, a lot of work on the reduction of process temperature^{2–9)} and the control of the crystal orientation^{10–12)} of FePt films has extensively been investigated. Recently, several studies on the combination of an FePt layer and a soft magnetic layer (SUL) have been made.^{13–16)} In this study, nanocrystalline Fe–Si–B–Nb–Cu alloy (Finemet, abbreviated as FMT hereafter)^{17–19)} has been selected as a SUL, since it possesses a high thermal stability and low coercivity H_c . A MgO interlayer has been introduced between FePt and FMT to obtain the (001) texture in the FePt layer. First, sputtering conditions for a FMT single layer film and a MgO/FePt double layer film were separately optimized to achieve low H_c for FMT and high H_c for FePt, respectively. Then, FMT/MgO/FePt tri-layer films were prepared, and the structure and magnetic properties have been investigated.

2. Experimental Procedure

Samples were prepared in an ultra-high-vacuum system (base pressure $\sim 1 \times 10^{-8}$ Pa) using multiple dc sputtering onto glass substrates (Hoya corp., N5). FMT films were prepared at room temperature (R.T.) using a composite target, and then they were annealed at a temperature between 300 and 600°C for 1 h to improve soft magnetic properties. The composition of FMT films determined by electron probe X-ray microanalyzer (EPMA) to be Fe_{71.8}Si_{14.2}B_{10.9}Nb_{1.9}Cu_{1.2} (at%).^{18,19)} High-purity Ar with gas pressure $P_{\text{FMT}}(\text{Ar}) = 0.13$ Pa was flown during deposition, and the

film thickness t_{FMT} was varied in the range from 50 to 500 nm. RF input power E_{FMT} was fixed at 100 W. For MgO/FePt films, a MgO layer was deposited at R.T. using a sintered target followed by heating the substrate at 400°C for 1 h. The Ar gas pressure $P_{\text{MgO}}(\text{Ar})$ was changed from 0.17 to 6.7 Pa and RF input power E_{MgO} was changed from 90 to 190 W. Subsequently, an FePt layer was deposited at the Ar gas pressure $P_{\text{FePt}}(\text{Ar}) = 0.67$ Pa by co-sputtering of Fe and Pt targets. RF input power E_{Fe} was changed from 7 to 15 W, while E_{Pt} was fixed at 5 W. The composition of FePt was changed in the range from Fe₃₅Pt₆₅ to Fe₆₀Pt₄₀ (at%), which were determined by EPMA. The film thicknesses were fixed at $t_{\text{MgO}} = t_{\text{FePt}} = 10$ nm. For tri-layer films, the combination of optimized sputtering conditions for FMT and MgO/FePt films were used. Structural characterizations were performed by X-ray diffractometry (XRD) with Cu-K α radiation and transmission electron microscopy (TEM). Magnetic properties were measured by a superconducting quantum interference device (SQUID) magnetometer, a vibrating sample magnetometer (VSM), and polar magneto-optical Kerr effect (MOKE) at room temperature.

3. Results and Discussion

3.1 Optimization for FMT films

XRD patterns for FMT films in the as deposited state and in the annealed states with different temperatures T_a are shown in Fig. 1.

The broad patterns corresponding with an amorphous phase of the glass substrate at around 25° and a nanocrystalline of bcc Fe phase at both 45° and 65° are observed in the as deposited film. After annealing at 450°C, the peak corresponding with bcc Fe 110 appears. It has been found from high resolution TEM observation that Fe-based fine particles with the lateral size of about several nm are formed even for $T_a = 400^\circ\text{C}$. It is noted that this observed crystallization temperature is slightly lower than that of the liquid quenched Fe_{73.5}Si_{13.5}B₉Nb₃Cu₁ (at%) ribbon samples reported previously.¹⁷⁾ This is thought to arise from the difference in composition.

The effect of post-annealing on the coercivity H_c for FMT

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Fig. 1 XRD patterns for $\text{Fe}_{71.8}\text{Si}_{14.2}\text{B}_{10.9}\text{Nb}_{1.9}\text{Cu}_{1.2}$ thin films with different annealing temperatures; $T_a = 300, 400, 450, 500, 550$ and 600°C . The Ar pressure during deposition $P_{\text{FMT}}(\text{Ar})$ and RF input power E_{FMT} were 0.13 Pa and 100 W , respectively.

Fig. 3 XRD patterns for FePt thin films with different Ar pressures during the deposition of MgO layers; $P_{\text{MgO}}(\text{Ar}) = 0.17, 1.3, 2.7, 4.0, 5.3$, and 6.7 Pa . The RF input power E_{MgO} and the film composition were fixed at 150 W and $\text{Fe}_{43}\text{Pt}_{57}$, respectively.

Fig. 2 Annealing temperature T_a dependence of coercivity H_c for $\text{Fe}_{71.8}\text{Si}_{14.2}\text{B}_{10.9}\text{Nb}_{1.9}\text{Cu}_{1.2}$ thin films. The film thicknesses t_{FMT} were $50, 100, 200$, and 500 nm .

films with different film thicknesses t_{FMT} is shown in Fig. 2. For both $t_{\text{FMT}} = 200$ and 500 nm , H_c decreases drastically at $T_a = 300^\circ\text{C}$, possibly due to the relaxation of internal stress induced during deposition. These films annealed at $T_a = 300\text{--}550^\circ\text{C}$ also exhibit low H_c less than 80 A/m ($\approx 1\text{ Oe}$), indicating that the films possess high thermal stability. However, further annealing at the temperature

more than 550°C result in a sudden increase of H_c for $t_{\text{FMT}} = 500\text{ nm}$.

3.2 Optimization of MgO/FePt films

XRD patterns for MgO/FePt films with different $P_{\text{MgO}}(\text{Ar})$ are shown in Fig. 3. The RF input power and the film composition were fixed at $E_{\text{MgO}} = 150\text{ W}$ and $\text{Fe}_{43}\text{Pt}_{57}$, respectively. No intense peak is not observed for $P_{\text{MgO}}(\text{Ar}) = 0.17\text{ Pa}$. However, for $P_{\text{MgO}}(\text{Ar})$ more than 1.3 Pa , the fundamental 002 and superlattice 001 peaks of the L_{10} phase are clearly observed, indicating the formation of L_{10} ordered structure in the FePt layer. The most intense peak is observed for $P_{\text{MgO}}(\text{Ar}) = 5.3\text{ Pa}$.

Figure 4 also shows XRD patterns for MgO/FePt films with different E_{MgO} . $P_{\text{MgO}}(\text{Ar})$ and the film composition were fixed at 5.3 Pa and $\text{Fe}_{43}\text{Pt}_{57}$, respectively. For E_{MgO} more than 110 W , the fundamental 002 and superlattice 001 peaks of the L_{10} phase are clearly observed, indicating the formation of L_{10} ordered structure in the FePt layer. For E_{MgO} between 130 and 190 W , no remarkable change is observed.

Magnetization curves for MgO/FePt films with different E_{MgO} are shown in Fig. 5. The magnetic field was applied in the direction perpendicular to the film ($H_\perp$: solid line) and in the in-plane direction ($H_\parallel$: dotted line). For $E_{\text{MgO}} = 90\text{ W}$, only small coercivity in the perpendicular direction $H_{c\perp}$ of 250 kA/m is obtained. With increasing E_{MgO} , a large value of $H_{c\perp}$ of 550 kA/m is achieved for E_{MgO} between 110 W and 150 W . The further increase of E_{MgO} results in the decrease of $H_{c\perp}$.

The Fe concentration x (at%) dependence of K_u for MgO/ $\text{Fe}_x\text{Pt}_{100-x}$ thin films is shown in Fig. 6. $P_{\text{MgO}}(\text{Ar})$ and E_{MgO} were fixed at 5.3 Pa and 150 W , respectively. The results for

Fig. 4 XRD patterns for FePt thin films with different RF input powers; $E_{\text{MgO}} = 90, 110, 130, 150, 170$ and 190 W. $P_{\text{MgO}}(\text{Ar})$ and the film composition were fixed at 5.3 Pa and $\text{Fe}_{43}\text{Pt}_{57}$, respectively.

Fig. 5 Magnetization curves for MgO/FePt films with different RF input powers of MgO, $E_{\text{MgO}} = 90, 110, 130, 150, 170$ and 190 W. $P_{\text{MgO}}(\text{Ar})$ and the film composition were fixed at 5.3 Pa and $\text{Fe}_{43}\text{Pt}_{57}$, respectively.

Fig. 6 Fe concentration x (at%) dependence of K_u for $\text{Fe}_x\text{Pt}_{100-x}$ thin films prepared with different deposition conditions. $\blacktriangle$, $\circ$, and $\bullet$ denote the results for FePt films prepared at the substrate temperature $T_s = 400^\circ\text{C}$ on a MgO(001) substrate [Ref. 21], FePt films prepared at $T_s = 300^\circ\text{C}$ on a MgO(001) substrate [Ref. 20] and FePt films prepared at $T_s = 400^\circ\text{C}$ on a glass substrate (this work), respectively.

Fig. 7 XRD patterns for FMT (200 nm)/MgO (t_{MgO} nm)/FePt (10 nm) tri-layer films with different MgO thicknesses: $t_{\text{MgO}} = 0, 1, 3, 5, 7, 10, 20$, and 30 nm.

Fig. 8 Cross sectional TEM images for a FMT (200 nm)/MgO (5 nm)/FePt (10 nm) thin film. The enlarged image of the part marked in (a) is shown in (b). The selected area diffraction (SAD) pattern in the FMT region and the dark field image taken with the diffraction ring for bcc Fe are shown in (c) and (d), respectively.

FePt films prepared on MgO (001) single crystal substrates at different substrate temperatures T_s are also shown for references.^{20,21)} For the films prepared on MgO single crystal substrates, the optimum Fe concentration for exhibiting high K_u is shifted to a Pt-rich region from the equiatomic composition. This tendency is consistent with the present result on the films prepared on a glass substrate. The highest K_u of $1.5 \times 10^6 \text{ J/m}^3$ is obtained for $x = 43$.

3.3 Structure and magnetic properties of FMT/MgO/FePt tri-layer films

For the preparation of FMT/MgO/FePt trilayer films, FMT and MgO layers were first deposited at R.T., and then they were annealed in the UHV condition at 400°C for 1 hour. $P_{\text{MgO}}(\text{Ar})$ and E_{MgO} were set at 5.3 Pa and 150 W, respectively. Subsequently, an FePt layer was deposited at 400°C. The composition of FePt was fixed at Fe₄₃Pt₅₇. XRD patterns

Fig. 9 t_{MgO} dependence of H_c and M_r/M_s for FMT (200 nm)/MgO (t_{MgO} nm)/FePt (10 nm) tri-layer films.

for structure of FMT (200 nm)/MgO (t_{MgO} nm)/FePt (10 nm) tri-layer films with different MgO thicknesses t_{MgO} are shown in Fig. 7. The peaks of FePt 111 and FePt 222 are clearly observed for $t_{\text{MgO}} = 0$, indicating the formation of a (111) texture. However, for $t_{\text{MgO}} = 1$ nm, the intensities of FePt 111 and 222 peaks drastically decrease, and they disappear for $t_{\text{MgO}} \geq 3$ nm. Instead, the fundamental 002 and superlattice 001 peaks of the L1₀ phase are clearly observed for $t_{\text{MgO}} \geq 3$ nm, indicating that the films possess a (001) texture in the FePt layer. With further increasing t_{MgO} , the intense peak of MgO 200 starts to appear.

Figures 8 shows cross sectional TEM images for a FMT (200 nm)/MgO (5 nm)/FePt (10 nm) film. The flat interfaces between FMT and MgO layers and between MgO and FePt layers are observed. The selected area diffraction pattern in the SUL region [Fig. 8(c)] shows that it mainly consists of amorphous structure, however nano-meter scale fine particles are observed in the dark field image [Fig. 8(d)], which was taken with the diffraction ring of bcc Fe, indicating that nanocrystallines are precipitated.

$H_{c\perp}$ and the squareness ratio M_r/M_s for FMT (200 nm)/MgO (t_{MgO} nm)/FePt (10 nm) tri-layer films as a function of t_{MgO} are shown in Fig. 9. $H_{c\perp}$ increases with increasing t_{MgO} and almost saturates for $t_{\text{MgO}} \geq 5$ nm. The maximum $H_{c\perp}$ of 565 kA/m is achieved for $t_{\text{MgO}} = 5$ nm.

4. Summary

FMT/MgO/FePt thin films with a strong (001) texture in the FePt layer were prepared on glass substrates. It has been found that the (001) texture of FePt films is obtained by the introduction of a MgO interlayer and the large H_c of 565 kA/m is obtained for a FMT (200 nm)/MgO (5 nm)/FePt (10 nm) tri-layer film. This study suggests that FMT will be one of the

candidates for SUL to realize FePt perpendicular magnetic recording media with high thermal stability.

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