Magneto-Optical Spectra and Magnetic Anisotropy of MBE-Grown CoPt Alloy Films with $L1_0$ and $L1_1$ Ordered Structure(s)

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$\text{Co}_{50}\text{Pt}_{50}$ alloy films were grown by the molecular beam epitaxy (MBE) method onto MgO(111) or (001) substrates at temperatures in the range of 40 to 500 °C. X-ray diffraction measurement demonstrated that the films grown onto the (111) substrates at 300 °C had $L1_1$ (CuPt type) ordered structure, whereas those grown onto the (111) substrates at 500 °C and onto the (001) substrates at 300 °C formed $L1_0$ (CuAu type) ordered structures. The (111) oriented $L1_1$ and the (001) oriented $L1_0$ CoPt alloy films showed large perpendicular magnetic anisotropies of $1.75 \times 10^6 \text{ J/m}^3$ and $1.8 \times 10^6 \text{ J/m}^3$, respectively. The magneto-optical Kerr spectra for the (001) and (111) oriented $L1_0$ CoPt alloy films are similar. The (111) oriented $L1_1$ CoPt film showed Kerr spectra quite different from those of the $L1_0$ CoPt films. The θ_K did not show a peak in the high energy region.

Key words: magneto-optical effect, CoPt, ordered alloy, perpendicular anisotropy, CuAu type, CuPt type

1. Introduction

Co-Pt alloys have large magneto-optical Kerr effects in the blue spectral range, and have been studied extensively because such properties are suitable for improving the recording density of the magneto-optical storage media[1]. According to the equilibrium phase diagram of the Co-Pt alloy system, there exist two kinds of ordered phase, the CoPt phase and the CoPt_3 phase, having $L1_0$ and $L1_2$ structures respectively[2]. In addition, a Co_3Pt ordered alloy having a hexagonal structure has been found recently[3, 4].

The magnetic properties of the Co-Pt system vary remarkably with respect to the order - disorder transformation. In particular, the $L1_0$ CoPt ordered alloy film having (001) orientation is reported to exhibit perpendicular magnetization due to the anisotropic crystal structure along the c axis whereas disordered CoPt alloy having (001) orientation has an easy axis of magnetization in the film plane[5]. In contrast, magneto-optical spectra of ordered and disordered CoPt alloy films having (001) orientation are similar to each other, showing large Kerr rotations θ_K in the high energy region even though spectral shape is quite sensitive to electronic band structure[6].

Recently, CoPt alloy films with an $L1_1$ ordered structure have been grown by molecular beam epitaxy (MBE) on

MgO(111) substrates maintained at 300 °C[7]. $L1_1$ CoPt, consisting of alternating stackings of Co and Pt monolayers in the (111) plane, has a different crystal structure from that of $L1_0$ CoPt. In the present paper, the Kerr spectra of the $L1_1$ ordered CoPt alloy films are reported, and the spectra of these films are compared to those of disordered and $L1_0$ ordered structures.

2. Experiment

$\text{Co}_{50}\text{Pt}_{50}$ alloy films were grown using an MBE apparatus under a pressure of less than 4×10^{-7} Pa. The constructions of these films are Pt(2 nm)/ $\text{Co}_{50}\text{Pt}_{50}$ (100 nm)/Pt(10 nm)/Ag(40 nm)/MgO(001) and Pt(2 nm)/ $\text{Co}_{50}\text{Pt}_{50}$ (100 nm)/MgO(111). Details of the sample preparation and measurements are described elsewhere[7].

3. Results and Discussion

RHEED observation confirmed that the buffer and the alloy layers were epitaxially grown on both the MgO(001) and (111) substrates. Figure 1 shows the RHEED patterns during the deposition of CoPt alloy layers onto (a) MgO(001) at 300 °C, (b) MgO(111) at 300 °C, and (c) MgO(111) at 500 °C, for which the incident electron beam was along the [100] or [110] directions for (a) and along the $[\bar{1}10]$ or the $[11\bar{2}]$ directions for (b) and (c). The presence of elongated streaks suggest that the surface of the alloy layers is very flat.

Figure 2 shows the $\theta - 2\theta$ XRD scans for samples (a) grown on MgO(001) at 300 °C, (b) (111) at 300 °C, and (c) (111) at 500 °C. In the sample grown on MgO(001) (Fig. 2 (a)), intense {002} reflections from buffer and alloy layers were seen in the region of $2\theta = 43^\circ \sim 52^\circ$. In addition, superlattice lines of {001} and {003} are clearly observed at $2\theta = 24^\circ$ and 78° , respectively, showing the formation of $L1_0$ ordered phase with (001) orientation. The lattice spacing of {002} plane d_{002} is estimated to be 0.183 nm, which agrees well with the half of lattice parameter of the c axis for the $L1_0$ CoPt alloy ($a = 0.3973 \text{ nm}$, $c = 0.3675 \text{ nm}$)[8]. The long-range order parameter S of this sample can be evaluated from the integrated intensity ratio of the superlattice {001} peak to the fundamental {002} peak, I_{001}/I_{002} in the same manner as described in Ref. 9. The results

Fig. 1 RHEED patterns during the deposition of PtCo films onto (a) MgO(001) at 300 °C, (b) MgO(111) at 300 °C, and (c) MgO(111) at 500 °C. The azimuths in the figure indicate the direction of e^- beam incidence.

of this evaluation shows that $S = 0.7 \pm 0.1$.

For the (111) substrate at 300 °C, $\{111\}$ reflection of fcc or fct structures are clearly seen at $2\theta = 42^\circ$. Furthermore, extra peaks were observed at $2\theta = 21^\circ$ and 65° as shown in Fig. 2 (b). This is attributed to the formation of an $L1_1$ ordered phase consisting of alternating stacks of Co and Pt monolayers along the $[111]$ direction as shown in Fig. 3 (b) (described in a previous study[7]). The S of this sample for the $L1_1$ ordered phase is also evaluated, and an S of 0.4 ± 0.1 is obtained. In the (111) substrate at 500 °C, the superlattice lines disappear (Fig. 2 (c)). When the sample surface is parallel to the (111) plane, the superlattice lines of the $L1_0$ ordered phase can not be detected by the θ - 2θ scan, as shown in Fig. 2 (c). Thus, the two-dimensional scan was performed in the (110) reciprocal plane for this sample, and the following results were obtained. A detailed description of the results of the reciprocal space mapping are described in Ref. 10.

- (1) CoPt alloy film forms an $L1_0$ ordered structure.
- (2) Crystal grains for which the c axis parallel to the $[001]$ and $[100]$ (or $[010]$) directions of the substrate are mixed in the film.

Figure 4 shows the hysteresis loops measured by applying a field in the film plane (solid lines) and the film normal (dashed lines) directions for CoPt alloy films having (a) (001) oriented $L1_0$ (b) (111) oriented $L1_0$ and (c) (111) oriented $L1_1$ ordered structures. The (001) oriented $L1_0$ film exhibits perpendicular magnetic anisotropy, as shown in Fig. 4 (a). This large perpendicular anisotropy is thought due to the anisotropic crystal structure along the c axis in the $L1_0$ phase (Fig. 3 (a)). This feature is not observed for the (111) oriented $L1_0$ film shown in Fig. 4 (b). For the (111) oriented

Fig. 2 θ - 2θ X-ray diffraction patterns for CoPt alloy films grown on (a) MgO(001) at 300 °C, (b) MgO(111) at 300 °C, and (c) MgO(111) at 500 °C.

Fig. 3 Images of crystal structures for (a) an $L1_0$ and (b) an $L1_1$ CoPt ordered phases.

$L1_1$ film shown in Fig. 4 (c), the easy axis of magnetization is found to be in the film normal direction. The large anisotropy is thought to be due to the monatomic layered structure of the $L1_1$ ordered phase along the $[111]$ direction, as shown in Fig. 3 (b). The (001) oriented $L1_0$ CoPt films have a large K_U of 2.4×10^6 J/m³, which is lower than 5.0×10^6 J/m³ that has been reported for the bulk alloy[11]. This may be due to the reduced chemical ordering of this sample and/

or to the imperfection of the single crystal in the present experiment. The (111) film with $L1_1$ structure also exhibits a large K_U of $2.5 \times 10^6 \text{ J/m}^3$ even though the chemical ordering of this sample is insufficient. For the (111) film grown at 500°C , a K_U of almost zero is obtained. This is thought to be attributed to the fact that the crystal anisotropy of the ordered phase is canceled among the crystal grains that have the c axis parallel to the $[100]$, $[010]$, and $[001]$ directions of the MgO substrate. In addition, the rather large coercive force of $\sim 250 \text{ kA/m}$ observed in the hysteresis loops for the (111) oriented $L1_1$ CoPt (Fig. 4 (b)) is thought to be due to the presence of these crystal grains.

Figure 5 shows the product of effective perpendicular anisotropy $K_\perp$ and the Co layer thickness t_{Co} as a function of t_{Co} for MBE Co/Pt superlattices grown on the (a) MgO(001) and (b) (111) substrates together with those for the CoPt alloy films grown at 300°C . The Co/Pt superlattices in which $t_{\text{Co}} : t_{\text{Pt}} = 1 : 4$ are fabricated by alternating deposition of Co and Pt layers at room temperature. The $t_{\text{Co}} \cdot K_\perp$ for alloy films were estimated under the assumption that these films are equivalent to Co/Pt superlattices in which $t_{\text{Co}} = 0.185 \text{ nm}$ and 0.205 nm for (001) and (111) films, respectively.

In superlattices, the effective perpendicular anisotropy $K_\perp$ is thought to originate from a surface contribution K_S

and a volume contribution K_V . Assuming the phenomenological relationship:

$$t_{\text{Co}} \cdot K_\perp = 2 K_S + t_{\text{Co}} \cdot K_V, \quad (1)$$

K_S and K_V were derived from the extrapolated line shown in the figure to be 0.45 mJ/m^2 and -3.00 MJ/m^3 , respectively, for the (001) superlattice and 0.54 mJ/m^2 and -0.40 MJ/m^3 , respectively, for the (111) superlattice. The large difference in the volume term between the (001) and (111) superlattices is thought to be attributed to magnetostriction constants along the $[100]$ and $[111]$ directions.

In the $L1_0$ CoPt(001) alloy films, $K_\perp$ satisfies roughly the linear relationship obtained from the $K_\perp$ of the superlattices. However, the $K_\perp$ of $L1_1$ CoPt(111) is approximately four times larger than that of the (111) Co/Pt superlattices. This means that the $L1_1$ CoPt prepared by MBE has good layered structure compared to superlattices fabricated by alternating deposition. Nevertheless, the $K_\perp$ of the $L1_1$ CoPt is lower than the extrapolated $K_\perp$. This may be due to an insufficient chemical ordering of the sample.

Figure 6 shows the spectra of magneto-optical Kerr rotation θ_K and Kerr ellipticity η_K for the CoPt alloy films. The

Fig. 4 Hysteresis loops for (a) $L1_0$ CoPt(001), (b) $L1_0$ CoPt(111), and (c) $L1_1$ CoPt(111) obtained by applying a field in the film plane (solid lines) and film normal (dashed lines) directions.

Fig. 5 The product of the effective perpendicular anisotropy $K_\perp$ and the Co layer thickness t_{Co} as a function of t_{Co} for MBE grown Co/Pt superlattices for which $t_{\text{Co}} : t_{\text{Pt}} = 1 : 4$ on (a) MgO(001) and (b) MgO(111). Solid circles indicate the value for the $L1_0$ and $L1_1$ CoPt alloy films grown at 300°C .

Fig. 6 Reflectivity, Kerr rotation θ_K , and ellipticity η_K spectra for the (001) and (111) oriented $L1_0$ CoPt and the (111) oriented $L1_1$ CoPt alloy films. The reflectivity, θ_K , and η_K were measured through the capping layer of 2 nm Pt.

(001) and (111) oriented $L1_0$ CoPt films exhibit similar spectral shape, indicating a maximum θ_K at around 4 eV. The slight difference in θ_K at approximately 2 eV may indicate the crystal anisotropy of the magneto-optical effect[12]. The (111) oriented $L1_1$ CoPt film shows Kerr spectra quite different from those of the $L1_0$ CoPt films as shown in the same figure. The θ_K of $L1_1$ CoPt does not show a peak in the high energy region, but rather has a maximum value of -0.48 deg at approximately 1.4 eV, where η_K changes sign. No distinct spectral difference in the reflectivity is observed between the $L1_0$ and the $L1_1$ CoPt, as shown in the upper figure. The difference in the Kerr spectra of the $L1_0$ and $L1_1$ structures may reflect the difference in the coordination number, i.e., Co atoms are surrounded by 4 Co and 8 Pt nearest neighbors for $L1_0$ type, whereas Co atoms are surrounded by 6 Co and 6 Pt for $L1_1$ type, as illustrated in Fig. 3. Like order-disorder transformation, variation in the crystal structure can influence the magneto-optical spectra, as reported

for other Co-Pt and Fe-Pt systems[6, 9, 13].

4. Summary

$\text{Co}_{50}\text{Pt}_{50}$ alloy films were grown by molecular beam epitaxy (MBE) onto MgO(111) or (001) substrates at temperatures in the range of 40 to 500 °C. X-ray measurement revealed that films grown on (111) substrates at 300 °C have $L1_1$ (CuPt type) ordered structure, whereas films grown onto (111) substrates at 500 °C and onto (001) substrates at 300 °C form $L1_0$ (CuAu type) ordered structure. The (111) oriented $L1_1$ CoPt alloy film exhibits a very large perpendicular anisotropy of $1.75 \times 10^6 \text{ J/m}^3$ due to the layered structures along the film normal direction. The magneto-optical Kerr spectra for the (111) oriented $L1_1$ CoPt film were found to be quite different from those for the $L1_0$ CoPt films. The θ_K for $L1_1$ CoPt does not show a peak in the high energy region, but rather has a maximum of -0.48 deg at approximately 1.4 eV.

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