1. Introduction

Ferromagnetic materials with strong perpendicular magnetocrystalline anisotropy (PMA) and a large coercivity ($H_c$) have been studied extensively for application to spintronic devices such as magnetoresistive random access memory, ultrahigh-density hard disk drives, and ferromagnetic single-electron transistors.\(^1\)–\(^8\) L1$_0$-ordered CoPt exhibits strong PMA and has a large $H_c$.\(^9\)–\(^11\) Hence, it is one of the promising candidates for such applications.\(^12\)–\(^15\) In most cases, L1$_0$-ordered CoPt has been prepared on single-crystal insulating substrates such as MgO, Al$_2$O$_3$, and SrTiO$_3$.\(^16\)–\(^25\) By utilizing the CoPt–substrate lattice mismatch and controlling the crystal orientations of CoPt, Graded films consisting of L1$_2$-ordered CoPt$_3$, L1$_0$-ordered CoPt, and L1$_2$-ordered CoPt were found to be formed during the interdiffusion of Pt/Co bilayer thin films with a Ti underlayer by rapid thermal annealing (RTA) at 800 °C.\(^26\)–\(^29\)

L1$_0$-ordered CoPt has been prepared by utilizing the underlayers of single-crystal insulating substrates such as MgO.\(^16\)–\(^25\) In addition, metal underlayers such as Ti,\(^26\)–\(^38\) play crucial roles in the ordering of CoPt, control of crystal orientations, and nature of magnetic properties.\(^16\)–\(^18\),\(^36\)–\(^45\) In our previous study, we prepared a Ti/Pt/Co structure by EB evaporation, where Ti was introduced as an underlayer to enhance adhesion, and demonstrated the formation of L1$_0$-ordered CoPt.\(^53\) However, the EB-deposited Ti underlayer is hypothesized to influence the ordering of CoPt on Si substrates.

In this study, we investigate the ordering of CoPt in EB-deposited (Co/Pt)$_4$ multilayer thin films with and without a Ti underlayer on Si substrates during RTA. The formation of different ordered phases of CoPt with and without the Ti underlayer is demonstrated, and these phases are analyzed by grazing incidence X-ray diffraction (GI-XRD), vibrating sample magnetometer (VSM), and scanning electron microscope (SEM). The $H_c$ and saturation magnetization ($M_s$) of these phases are also analyzed.

2. Experimental methods

2.1. Fabrication

Equiatomic (Co/Pt)$_4$ multilayer thin films with and without a Ti underlayer were fabricated by EB evaporation. To promote interdiffusion during annealing, a multilayer structure consisting of Co and Pt layers was introduced. For the films without Ti, Co (1.2 nm) was firstly deposited onto thermally oxidized Si [Si(100) (525 μm)/SiO$_2$ (50 nm)] (Si/SiO$_2$) substrates, followed by the deposition of Pt (1.6 nm). This deposition process was repeated four times to fabricate equiatomic 11.2 nm thick (Co/Pt)$_4$ multilayer thin
films. The Pt layer was chosen to be located at the top of the films to avoid Co oxidation after the deposition. For the films with a Ti underlayer, Ti (3.0 nm) was firstly deposited onto the Si/SiO2 substrates, followed by the deposition of (Co/Pt)4 multilayers using the same process described above. The thicknesses were monitored using a crystal oscillator during the deposition. The deposition process was performed under a vacuum with a base pressure of below $5.0 \times 10^{-4}$ Pa.

The fabricated films were annealed using an RTA system (MILA-5000UHV, Advance Riko). Preannealing was performed by RTA at 900 °C for 1 h at a heating rate of approximately 40 °C s$^{-1}$ under a vacuum with a base pressure of below $5.0 \times 10^{-4}$ Pa to promote the interdiffusion and alloying of the Co and Pt atoms in the films. After the preannealing, when the temperature of the RTA system reached room temperature (around 27 °C), the films were finally annealed by RTA at 900 °C for 30 s at a heating rate of approximately 40 °C s$^{-1}$ under a vacuum with a base pressure of below $5.0 \times 10^{-4}$ Pa to obtain ordered CoPt alloys.

It should be noted that when the RTA process was performed at an annealing temperature of 800 °C, the ordering of CoPt was not observed in the (Co/Pt)4 film without Ti (see Fig. S1 in the supplemental information, which is available online at stacks.iop.org/JJAP/59/075504/mmedia). Therefore, an annealing temperature of 900 °C was used in this study.

2.2. Characterization

The crystal structures of the films were characterized by two-dimensional (2D) GI-XRD at the BL-8B line of High Energy Accelerator Research Organization (KEK), Japan. The setup of GI-XRD measurement method, which was carried out using an X-ray diffractometer (R-Axis, Rigaku), is described in a previous paper.53) A monochromic synchrotron X-ray beam with a photon energy of 11.7 keV was irradiated onto the films. Because the photon energy nearly corresponded to the 3-edge X-ray absorption peak of Pt, a stronger diffraction intensity could be expected compared to that obtained in our previous study (where the photon energy was 18 keV).53)

During the measurements, the incident angle of the beam was varied from 0° to 2° and 10° to 12° by oscillating the angle of incidence of the beam. The total measurement times for the incident angles of 0° to 12° were set to 4 and 2 min, respectively. The accurate wavelength of the beam was 1.054581 Å, as determined by a CeO2 powder standard. Because the wavelength in the present study was longer than that in our previous study (0.685374 Å),53) the angular resolution of the patterns at low diffraction angles was improved, which enabled us to precisely assign superlattice peaks originating from ordered CoPt alloys. To assign and analyze the diffraction peaks originating from the ordered CoPt alloys, the intensity–20 one-dimensional (1D) GI-XRD profiles of the patterns were obtained from the 2D GI-XRD patterns using an instrument software (Display, Rigaku).

The magnetic properties of the films were measured using a superconducting quantum interference device VSM (MMPMS3, Quantum Design) by sweeping an external magnetic field perpendicular and parallel to the film plane with a maximum field of 70 kOe under a vacuum at room temperature (27 °C). The values of $M_s$ of the in-plane and out-of-plane loops differed; these values were obtained by subtracting the background signal due to the diamagnetic contribution originating from the Si/SiO2 substrates. In this study, $M_s$ was defined as the magnetization of the hard axis loops at an applied field of 70 kOe.

The surface morphologies of the films were observed using an SEM (SU8000, Hitachi High-Tech).

3. Results

3.1. Crystal structures

$L_{12}$-ordered CoPt5 and $L_{10}$-ordered CoPt were confirmed in the films with and without a Ti underlayer, respectively, after RTA at 900 °C. This can be seen from the diffraction angle differences between the CoPt5 100 and CoPt 001 peaks and between the CoPt5 110 and CoPt 110 peaks in the insets of the 2D GI-XRD patterns in Figs. 1(c) and 1(b), respectively. After RTA, the film without Ti showed spot-like superlattice peaks originating from $L_{12}$-ordered CoPt 001 and 110 at the tilted azimuthal angles with respect to the horizontal directions [red arrows in the inset of Fig. 1(b)]. In contrast, after RTA, the film with the Ti underlayer showed spot-like superlattice peaks originating from $L_{12}$-ordered CoPt 100 and 110 at tilted azimuthal angles with respect to the horizontal directions [blue arrows in the inset of Fig. 1(c)].

Fundamental peaks corresponding to $111$, $200$, $220$, and $311$ were observed for $A1$-disordered CoPt (purple arrows), $L_{12}$-ordered CoPt (red arrows), and $L_{12}$-ordered CoPt3 (blue arrows) in the films with and without the Ti underlayer before and after RTA, as shown in Figs. 1(a)–1(c). With regard to the peak corresponding to $111$, a Debye–Scherrer ring was observed for the as-deposited film [Fig. 1(a)]. After RTA at 900 °C, the azimuthal broadening of the $111$ peak became narrow for the film without Ti [Fig. 1(b)]. The $111$ peak for the film with the Ti underlayer [Fig. 1(c)] was narrower than that for the film without Ti [Fig. 1(b)], indicating that the film with the Ti underlayer after RTA had the most preferred crystal orientation. The $111$ peak separated into two, corresponding to $L_{12}$-ordered CoPt5 and $A1$-disordered CoPt from low to high diffraction angles [Fig. 1(c)]. The ascending order of the phases with respect to the diffraction angles on the $111$ planes was as follows: $L_{12}$-ordered CoPt5 (27.479°), $L_{12}$-ordered CoPt (28.254°), $A1$-disordered CoPt in the as-deposited film (28.276°), and $A1$-disordered CoPt in the film with the Ti underlayer after RTA (28.485°) (see Fig. S3 in supplemental information for details). The narrowing, separation, and ascending order of diffraction angles of the $200$, $220$, and $311$ peaks in the films with [Fig. 1(c)] and without [Fig. 1(b)] the Ti underlayer after RTA coincided well with those of the $111$ peaks.

3.2. Magnetic properties

The magnetic hysteresis loops ($M-H$ curves) of the films are shown in Fig. 2. After RTA at 900 °C, the film without Ti had an $H_c$ of 2.7 kOe [Fig. 2(b)], whereas the film with the Ti underlayer had an $H_c$ of 500 Oe [Fig. 2(d)]. For both the as-deposited films with [Fig. 2(c)] and without [Fig. 2(a)] the Ti underlayer, $H_c$ was as small as approximately 20 Oe. The easy axis of magnetization was oriented along the in-plane
Fig. 1. (Color online) Two-dimensional (2D) grazing incidence X-ray diffraction (GI-XRD) patterns of (Co/Pt)_{4} multilayer thin films (a) without Ti before annealing, (b) without Ti after rapid thermal annealing (RTA) at 900 °C, and (c) with Ti underlayer after RTA at 900 °C. The main figures show the 2D GI-XRD patterns obtained for the incident angles of 10°–12°, whereas the figure insets show the 2D GI-XRD patterns obtained for the incident angles of 0°–2°. The diffraction peaks originating from A1-disordered CoPt, L1₅-ordered CoPt, and L1₂-ordered CoPt₃ are indicated by purple, red, and blue arrows, respectively. The pair of red arrows in the inset of part (b) indicate the directions of L1₅-ordered CoPt 001 and 110 peaks. The pair of blue arrows in the inset of part (c) indicate the directions of L1₂-ordered CoPt₃ 100 and 110 peaks. The diffraction peaks were assigned using the following Powder Diffraction File cards: CoPt (03-065-8969) and CoPt₃ (00-029-0499). The full-scale 2D GI-XRD patterns of Fig. 1 are shown in Fig. S2 in supplemental information.
The shapes of both the in-plane and out-of-plane $M-H$ curves of the film without Ti after RTA exhibited slow rises and falls [Fig. 2(b)]. Moreover, the out-of-plane loop of the film without Ti after RTA [the black curve in Fig. 2(b)] had a larger coercive field than that of the film with the Ti underlayer after RTA [the black curve in Fig. 2(d)], indicating that the film without Ti after RTA showed an isotropic magnetic behavior. After RTA, $M_s$ increased from 511 to 565 emu cm$^{-3}$ for the film without Ti, whereas it decreased from 511 to 400 emu cm$^{-3}$ for the film with the Ti underlayer.

### 3.3. Surface morphologies

The SEM images of the film surfaces are shown in Fig. 3. Isolated round CoPt grains were observed in the film without Ti after RTA at 900 °C [bright regions in Fig. 3(a)]. In contrast, in the film with the Ti underlayer, an angular-outlined continuous film structure of CoPt was observed after RTA [bright regions in Fig. 3(b)]. The SiO$_2$ surface of the substrates appeared as dark regions, as shown in Figs. 3(a) and 3(b).

### 4. Discussion

To quantitatively evaluate the superlattice peaks originating from $L_{10}$-ordered CoPt and $L_{12}$-ordered CoPt$_3$, intensity–2θ 1D GI-XRD profiles were obtained from the 2D GI-XRD patterns along the directions of the $L_{10}$-ordered CoPt 001 and 110 peaks [red arrows in the inset of Fig. 1(b)] and along the directions of the $L_{12}$-ordered CoPt$_3$ 001 and 110 peaks [blue arrows in the inset of Fig. 1(c)]. These profiles along the four directions are shown in Figs. 4(a)–4(d), respectively. Each experimental superlattice peak was analyzed by one Gaussian function after subtracting the background signal. From the analysis of the film without Ti after RTA [Figs. 4(a) and 4(b)], the lattice spacings ($a$ and $c$) and $c/a$ ratio of $L_{10}$-ordered CoPt were estimated as follows: $a = 3.796$ Å, $c = 3.699$ Å, and $c/a = 0.9746$. On the other hand, from the analysis of the film with the Ti underlayer after RTA [Figs. 4(c) and 4(d)], the lattice spacings of $L_{12}$-ordered CoPt$_3$ were estimated as $a = 3.860$ and 3.847 Å. These lattice spacings of $L_{10}$-ordered CoPt and $L_{12}$-ordered CoPt$_3$ agree well with those found in previous reports.

The degree of order ($S$) for $L_{10}$-ordered CoPt was evaluated as 0.9833 using the following equation:

$$S^2 = \frac{1 - (c_{\text{exp}}/a_{\text{exp}}) \sqrt{1 - (c_{\text{cal}}/a_{\text{cal}})}}$$

where $c_{\text{exp}}$ and $a_{\text{exp}}$ are the experimental lattice spacings, and $c_{\text{cal}}$ and $a_{\text{cal}}$ are the calculated lattice spacings of fully ordered CoPt. Here, $c_{\text{cal}} = 3.700$ Å and $a_{\text{cal}} = 3.800$ Å, which are obtained from the following Powder Diffraction File card: CoPt (03-065-8969). $S$ in this study (0.9833) was higher than that of a graded film consisting of $L_{10}$-ordered CoPt in our previous study (approximately 0.54).

The value of the FWHM of the $L_{10}$-ordered CoPt 001 peak was evaluated as 1.443° [Fig. 4(a)], which was larger than that of the $L_{12}$-ordered CoPt$_3$ 100 peak (0.8640°) [Fig. 4(c)]. The same tendency of the FWHM was observed for the $L_{10}$-ordered CoPt 110 peak (1.598°) [Fig. 4(b)] and $L_{12}$-ordered CoPt$_3$ 110 peak (1.323°) [Fig. 4(d)]. The larger FWHM of $L_{10}$-ordered CoPt indicates that the size of crystalline domains of $L_{10}$-ordered CoPt was smaller than those of $L_{12}$-ordered CoPt$_3$.  

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Fig. 2. (Color online) In-plane (red curves) and out-of-plane (black curves) magnetic hysteresis loops ($M-H$ curves) of (Co/Pt)$_4$ multilayer thin films (a) without Ti before annealing, (b) without Ti after RTA at 900 °C, (c) with Ti underlayer before annealing, and (d) with Ti underlayer after RTA at 900 °C. The $M-H$ curves were obtained at room temperature (27 °C).
Fig. 3. Top-view scanning electron microscope images of (Co/Pt)_{4} multilayer thin films (a) without Ti after RTA at 900 °C and (b) with Ti underlayer after RTA at 900 °C. The bright regions correspond to CoPt alloys, whereas the dark regions correspond to SiO{sub 2} surface of Si/SiO{sub 2} substrates.

The other phases of CoPt such as metastable L{sub 11}-ordered CoPt, B{sub 2}-ordered CoPt, D{sub 019}-ordered Co_{3}Pt, and stable A3-disordered CoPt have also been reported. However, the formation of these phases in the films with and without the Ti underlayer after RTA could be ruled out in this study because no other remarkable peaks except the superlattice and fundamental peaks originating from Al-disordered CoPt, L{sub 12}-ordered CoPt, and L{sub 12}-ordered CoPt_{3} were observed in the GI-XRD results (Figs. 1, 4, and S3).

The diffraction angle of the A1-disordered CoPt 111 peak in the film with the Ti underlayer after RTA (28.485°) was shifted from that in the as-deposited film (28.276°) (Fig. S3), which suggests the presence of Co-rich CoPt. Off-stoichiometric L{sub 12}-ordered CoPt_{3} was clearly observed in the film with the Ti underlayer after RTA by GI-XRD [Fig. 1(c)].

Owing to the equiatomic composition of Co and Pt in the film, the atomic composition fraction of Co to Pt (Co/Pt) in A1-disordered CoPt should be larger than unity; this inference is well supported by the observation that the diffraction angle of the A1-disordered CoPt 111 peak in the film with the Ti underlayer after RTA is larger than that in the as-deposited film.

The two distinct phases of L{sub 12}-ordered CoPt_{3} and Co-rich A1-disordered CoPt were found to be formed in the film with the Ti underlayer after RTA [Fig. 1(c)], which would be caused by the sufficient interdiffusion between Co and Pt atoms from (Co/Pt)_{4} multilayer thin film. Recently, we have reported graded films consisting of L{sub 12}-ordered CoPt_{3}, L{sub 11}-ordered CoPt, and L{sub 12}-ordered CoPt from a Pt/Co bilayer in progress of interdiffusion by RTA for 30 s. Based on our previous result, the preannealing period was chosen as 1 h in this study. As the Ti underlayer was in contact with the first Co layer within the as-deposited (Co/Pt)_{4} multilayer, a part of the Co atoms tend to be pinned by the Ti underlayer. This pinning effect would contribute to the formation of Co-rich A1-disordered CoPt, leading to form the off-stoichiometric L{sub 12}-ordered CoPt_{3} after RTA. It can be also inferred that the film after RTA might consist of a trilayer structure of the Ti underlayer, Co-rich A1-disordered CoPt, and L{sub 12}-ordered CoPt_{3} along the thickness direction from the substrate. Consequently, these results suggest that the EB-deposited Ti underlayer could not be a buffer layer for the formation of L{sub 12}-ordered CoPt.

The diffraction angle of the CoPt 111 peak without Ti after RTA was evaluated as 28.254°, which was less than that of the A1-disordered CoPt 111 peak in the as-deposited film (28.276°) (Fig. S3), indicating a greater interplanar spacing of the (111) plane of L{sub 12}-ordered CoPt. This difference in the diffraction angle also supports the formation of tetragonal L{sub 12}-ordered CoPt.

The superlattice peaks corresponding to CoPt 001 and 110 in the GI-XRD results [Fig. 1(b)] were confirmed to be those of a single phase of L{sub 12}-ordered CoPt in the (Co/Pt)_{4} multilayer film with layer thicknesses of 1.2 nm for Co and 1.6 nm for Pt without Ti after RTA at 900 °C. We previously reported that a graded film consisting of L{sub 12}-ordered CoPt_{3}, L{sub 12}-ordered CoPt, and L{sub 12}-ordered CoPt was formed in a Pt/Co bilayer film with layer thicknesses of 6.6 nm for Pt and 4.8 nm for Co after RTA at 800 °C. The deformation of ordered phases of CoPt was observed in the bilayer film after RTA at 900 °C. As a result, the multilayered structure of the films without Ti was the key to the formation of the single phase of L{sub 12}-ordered CoPt.

An H_{c} of 2.7 kOe in the film without Ti after RTA [Fig. 2(b)] strongly suggests the formation of L{sub 12}-ordered CoPt. We reported an H_{c} of 2.1 kOe in a graded film that consisted of L{sub 12}-ordered CoPt after RTA. The larger H_{c} in the present study would be attributed to the single phase of L{sub 12}-ordered CoPt with higher S. The H_{c} of 2.7 kOe agrees with those found in previous reports related to L{sub 12}-ordered CoPt prepared by sputtering.

In the film without Ti after RTA, M_{s} increased to 565 emu cm\(^{-3}\) [Fig. 2(b)]; in the as-deposited film, M_{s} was 511 emu cm\(^{-3}\) [Fig. 2(a)]. This increase was attributed to the enhancement of the magnetic moments of Co and Pt atoms by the large spin-orbit coupling of Pt atoms and strong hybridization of Co d bands and Pt d bands in the L{sub 12}-ordered CoPt. The value of M_{s} for L{sub 12}-ordered CoPt agrees with our previously reported value of M_{s} for a graded film that consisted of L{sub 12}-ordered CoPt_{3}, L{sub 12}-ordered CoPt, and L{sub 12}-ordered CoPt_{3} (548 emu cm\(^{-3}\)).

The easy axis of magnetization of L{sub 12}-ordered CoPt in the film without Ti after RTA was oriented along the in-plane direction [Fig. 2(b)], which would be attributed to shape anisotropy. According to the GI-XRD results [Fig. 1(b)], no...
superlattice peaks were observed in the out-of-plane direction, indicating that the [001] orientation of $L_10$-ordered CoPt was tilted with respect to the film normal, which also supports the observation that the easy axis of magnetization was oriented along the in-plane direction.

The isotropic magnetic behavior was observed in the $M$–$H$ curves of the film without Ti after RTA [Fig. 1(b)], which could be attributed to the tilted [001] orientation of $L_10$-ordered CoPt.

Because of the absence of strong adhesion of the Ti underlayer, an isolated round grain structure of $L_10$-ordered CoPt was observed by SEM [Fig. 3(a)]; the isotropic $M$–$H$ curves shown in Fig. 1(b) would also be attributed to the formation of this structure. Owing to the round grain structure, Co and Pt atoms in the film could diffuse more easily for alloying and ordering during the RTA process. This morphology could also contribute to the weak magnetic anisotropy of $L_10$-ordered CoPt.

An effective anisotropy constant ($K_{eff}$) of $L_10$-ordered CoPt in the film without Ti after RTA can be estimated from the VSM results [Fig. 2(b)] using the following equation:

$$K_{eff} = H_a M_s / 2,$$

where $H_a$ is an anisotropy field of a hard axis loop in $M$–$H$ curves. The magnetization of the out-of-plane loop did not tend to saturate at a large applied field, which would be due to the diamagnetic contribution originating from the Si/SiO$_2$ substrate. $M_s$ and $H_a$ were determined as 571 emu cm$^{-3}$ and 15 kOe from the out-of-plane loop of the film without Ti after RTA, respectively [black curve in Fig. 2(b)]. As a result, $K_{eff}$ was estimated as $-4.28 \times 10^6$ erg cm$^{-3}$.

An $H_c$ of 500 Oe was observed in the film with the Ti underlayer after RTA [Fig. 2(d)]; in this film, $L_12$-ordered CoPt$_3$ and Co-rich A1-disordered CoPt were formed. The Curie temperature ($T_C$) of $L_12$-ordered CoPt$_3$ has been reported to be around room temperature, whereas that of Co-rich A1-disordered CoPt has been reported to be above 527 °C. Because the $M$–$H$ curves were obtained at room temperature (27 °C), Co-rich A1-disordered CoPt was
considered to be responsible for the measured $H_c$ of 500 Oe. The value of $H_c$ is consistent with those found in previous reports.66,75–77,87)

The in-plane easy axis of magnetization was observed in the film with the Ti underlayer after RTA [Fig. 2(d)], which was also attributed to the A1-disordered CoPt in the film. A1-disordered CoPt does not show PMA because of its isotropic structure.75 Therefore, A1-disordered CoPt could not overcome the demagnetizing energy originating from the thin film structure. Thus, the in-plane easy axis of magnetization was induced by shape anisotropy.

In the film with the Ti underlayer after RTA, $M_s$ was 400 emu cm$^{-3}$ [Fig. 2(d)], which was 0.708 times that in the film consisting of L1$_0$-ordered CoPt without Ti (565 emu cm$^{-3}$) [Fig. 2(b)]. This difference was attributed to the lattice structure and $T_c$ of L1$_0$-ordered CoPt, as explained below. In the lattice of L1$_0$-ordered CoPt$_3$, each Co atom is surrounded by neighboring Pt atoms, which prevents direct exchange interaction between Co atoms.88–90 The area of the L1$_0$-ordered CoPt$_3$ 111 peak was almost equal to that of the A1-disordered CoPt 111 peak (Fig. S3), which suggests that a quarter of the Co atoms in the film were isolated by the surrounding Pt atoms. Because $T_c$ of L1$_0$-ordered CoPt$_3$ was around room temperature,85,86 $M_s$ of L1$_0$-ordered CoPt$_3$ could not be observed at room temperature. Hence, $M_s$ was attributed to the rest of the three quarters of Co atoms in the film. Consequently, the smaller value of $M_s$ in the film with the Ti underlayer after RTA was attributed to Co-rich A1-disordered CoPt.

5. Conclusions

The ordering of CoPt in EB-deposited (CoPt)$_3$ multilayer thin films on Si/SiO$_2$ substrates by RTA depended on the presence of the Ti underlayer; L1$_0$-ordered CoPt was formed without Ti and L1$_0$-ordered CoPt$_3$ was formed with Ti. The crystal structures, magnetic properties, and surface morphologies of the films were analyzed by GI-XRD, VSM, and SEM, respectively. L1$_0$-ordered CoPt with an in-plane $H_c$ of 2.7 kOe and its isotropic magnetic behavior were confirmed in the film without Ti after RTA at 900 °C; the surface morphology of L1$_0$-ordered CoPt showed an isolated round grain structure. In contrast, L1$_0$-ordered CoPt$_3$ and Co-rich A1-disordered CoPt were confirmed in the film with the Ti underlayer after RTA at 900 °C and showed an in-plane $H_c$ of 500 Oe and an angular-outlined continuous film structure. These results suggest that the EB-deposited Ti underlayer could not be a buffer layer for the formation of L1$_0$-ordered CoPt. The three sets of experimental results from the GI-XRD, VSM, and SEM analysis of the ordered CoPt alloys coincided well with each other. These results are expected to be significant for understanding and tailoring the crystal structures, magnetic properties, and surface morphologies of ordered CoPt on Si substrates for future spintronic applications.

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ORCID iDs

Ryo Toyama https://orcid.org/0000-0002-7398-5803
Yutaka Majima https://orcid.org/0000-0002-5108-1934

1) S. Bharti, R. Shiba, A. Hirohata, H. Ohno, S. Fukami, and S. N. Piramanayagam, Mater. Today 20, 530 (2017).
2) T. Nozaki, T. Yamamoto, S. Miwa, M. Tsujikawa, M. Shirai, S. Yusa, and Y. Suzuki, Micromachines 10, 327 (2019).
3) D. Weller and A. Moser, IEEE Trans. Magn. 35, 4423 (1999).
4) D. Weller, A. Moser, L. Folks, M. E. Best, W. Lee, M. F. Toney, M. Schwickert, J.-U. Thiele, and M. F. Doerner, IEEE Trans. Magn. 36, 10 (2000).
5) C. A. Ross, Annu. Rev. Mater. Res. 31, 203 (2001).
6) A. Moser, T. Kado, D. T. Margulies, M. Albrecht, Y. Sonobe, Y. Ikeda, S. Sun, and E. E. Fullerton, J. Phys. D: Appl. Phys. 35, R155 (2002).
7) B. K. Yukushii, S. Mitani, F. Eruiti, K. Takahashi, and H. Fujimori, Phys. Rep. 451, 1 (2007).
8) J. Barnai and I. Weymann, J. Phys.: Condens. Mater. 20, 423202 (2008).
9) R. A. McCurrie and P. Gaunt, Philos. Mag. 13, 567 (1966).
10) R. A. McCurrie and P. Gaunt, Philos. Mag. 19, 339 (1969).
11) B. Zhang and W. A. Sofia, Scr. Metall. Mater. 30, 683 (1994).
12) X.-H. Xu, T. Jin, L.-L. Li, F. Wang, F.-X. Jiang, Z.-G. Yang, and H.-S. Wu, Mater. Chem. Phys. 99, 447 (2006).
13) J. Szivós, S. Pothorszky, J. Soylts, M. Serényi, H. An, T. Gao, A. Deák, J. Shi, and G. Sáfár, Surf. Sci. 435, 31 (2008).
14) G. Kim, Y. Sakuraba, M. Oogane, Y. Ando, and T. Miyazaki, Appl. Phys. Lett. 92, 172502 (2008).
15) T. Hiratooka et al., J. Appl. Phys. 107, 09C714 (2010).
16) M. B. Lainox, M. R. Visokay, E. E. Marinero, R. Sinclair, and B. M. Clemens, J. Appl. Phys. 74, 1922 (1993).
17) M. R. Visokay and R. Sinclair, Appl. Phys. Lett. 66, 1692 (1995).
18) O. Ersen, V. Parasote, V. Pierron-Bohnes, M. C. Cascadeville, and C. Ulhaq-Boullet, J. Appl. Phys. 93, 2987 (2003).
19) B. Barmak, J. Kim, L. H. Lewis, K. R. Coffey, M. F. Toney, A. J. Kellock, and J.-U. Thiele, J. Appl. Phys. 99, 033904 (2005).
20) T. Yokota, L. Gao, R. Zhang, L. Nicholl, M. L. Yan, D. J. Sellmyer, and S. H. Liu, J. Magn. Magn. Mater. 286, 301 (2005).
21) M. Ohtake, S. Ouchi, F. Kirino, and M. Futamoto, J. Appl. Phys. 111, 07A708 (2012).
22) M. Ohtake, A. Iribashi, M. Futamoto, F. Kirino, and N. Inaba, IEEE Trans. Magn. 50, 2104204 (2014).
23) S. P. Withrow, C. W. White, J. D. Budai, L. A. Boynter, K. D. Sorge, J. R. Thompson, and R. Karyananaman, J. Magn. Magn. Mater. 260, 319 (2005).
24) R. K. Rajkhit, S. K. Bose, R. Sharma, and R. C. Budhani, Appl. Phys. Lett. 89, 202511 (2006).
25) M. Yu, H. Ohguchi, A. Zambuno, I. Takachchi, J. P. Liu, D. Josell, and L. A. Bendersky, Mater. Sci. Eng. B 142, 139 (2007).
26) K. R. Coffey, M. A. Parker, and J. K. Howard, IEEE Trans. Magn. 31, 2737 (1995).
27) S. Stavroyiannis, I. Panagiopoulos, D. Niarchos, A. J. Christodoulides, Y. Zhang, and G. C. Hadjipanayis, Appl. Phys. Lett. 73, 3453 (1998).
28) R. A. Ristau, K. Barmak, L. H. Lewis, K. R. Coffey, and J. K. Howard, J. Appl. Phys. 86, 4527 (1999).
29) J. A. Christodoulides, Y. Huang, Y. Zhang, G. C. Hadjipanayis, I. Panagiopoulos, and D. Niarchos, J. Appl. Phys. 87, 6938 (2000).
30) J. Kim, K. Barmak, M. De Graef, L. H. Lewis, and D. C. Crew, J. Appl. Phys. 87, 6140 (2000).
31) S. Jeong, Y.-N. Hsu, M. E. McHenry, and D. E. Laughlin, J. Appl. Phys. 87, 6950 (2000).
32) M. Yu, Y. Liu, and D. J. Sellmyer, J. Appl. Phys. 87, 6959 (2000).
33) S. Jeong, Y.-N. Hsu, D. E. Laughlin, and M. E. McHenry, IEEE Trans. Magn. 36, 2336 (2000).
34) S. Jeong, Y.-N. Hsu, D. E. Laughlin, and M. E. McHenry, IEEE Trans. Magn. 37, 1299 (2001).
