Preparation and Characterization of (0001)-Oriented Single-Crystal Co-alloy Magnetic Thin Films

Masaaki FUTAMOTO, Regular Member, Kouts TERAYAMA, Nonmember, Katsuaki SATO, and Yoshiyuki HIRAYAMA, Regular Member

SUMMARY The effect of a nonmagnetic hcp-underlayer on the epitaxial growth of CoCrPt magnetic layers on substrates of Al2O3(0001) single-crystal has been investigated. Thin films of (0001)-oriented single-crystal CoCrPt were obtained by employing non-magnetic underlayers of CoCrPt/Ti, while thin films of polycrystalline CoCrPt were grown after the deposition of underlayers of TiC/Ti and CoCr. The growth of thin film CoCrPt on a Ti(0001) underlayer was interpreted as quasi-hetero-epitaxial where the continuity of the lattice across the interface is disturbed while the overall crystallographic relationship between the two layers is maintained. A thin film of epitaxially grown CoCrPt has a compositional variation of a few percent across the film plane in terms of elements that forms the alloy.

key words: Co-alloy magnetic thin films, epitaxial growth, underlayer, single-crystal substrate

1. Introduction

Co-based alloy thin films are widely used as the magnetic recording media of hard disk drives. The areal density and data transfer rate will increase to 100–200 Gb/in2 and 500–1000 MB/s, respectively, within the next few years. The thermal stability of recorded information and magnetic switching speed under such ultra-high density magnetic recording have been investigated through computer simulation. Accurate values for the magnetic properties of the Co-based alloys such as its uniaxial magneto-crystalline anisotropy constant and Gilbert’s damping constant are essential for such an investigation. However, it has not been easy to determine these values for thin films of polycrystalline magnetic materials which consist of very small crystalline grains and have a complicated microstructure [1].

To obtain accurate results for the basic magnetic properties, it is necessary to use well-defined thin films of the material, preferably in its single-crystal forms [2]. Thin films of single-crystal have been prepared by hetero-epitaxial growth on single-crystal substrates. Thin films of Co and Co-alloy materials with (1120), (1011), (1010), and (0001) orientations have been epitaxially grown on various single-crystal substrates; the works are summarized in Table 1. Note that almost all of these films were actually grown employing some underlayer. Misfit dislocations, stacking faults, and even subgrain boundaries are generally recognizable in these thin films. These crystallographic defects are introduced to accommodate the lattice mismatch between the different materials. The crystallographic quality of an epitaxially grown thin film depends on the materials selected for the substrate and underlayer.

The effect of the substrate on the epitaxial growth of thin films of (0001)-oriented CoCrPt magnetic layer has been investigated for Al2O3(0001), LaAlO3(0001), SrTiO3(111), and MgO(111) single-crystal substrates. In each case, a nonmagnetic underlayer was employed under similar experimental conditions [16]. The best single-crystal thin film in this work was obtained on the Al2O3 substrate according to this crystallographic relationship: CoCrPt(0001)[210] // Al2O3(0001)[100].

In this study, we focus on the effect of the underlayer on the crystallographic quality of thin films of CoCrPt grown on substrates of single-crystal Al2O3(0001). Nonmagnetic underlayers that have been widely used as underlayers or intermediate layers in the preparation of strongly e-axis oriented CoCr-alloy perpendicular magnetic recording media [17–20] are employed in the epitaxial growth of the magnetic thin films. X-ray diffraction and high-resolution transmission electron microscopy (TEM) were applied to obtain structural information. The conditions under which we obtained good magnetic thin films are discussed on this basis.

2. Preparing and Characterizing the Samples

A DC sputtering system with a base pressure below 1 × 10−9 torr [17] was used to prepare the thin films. The cross-sectional structure of the sample is shown in Fig. 1(a). Figure 1(b) shows the relationship between the crystallographic orientation of a hcp-material and the Al2O3(0001) substrate on which it has been epitaxially grown. The α-axis of the hcp-material is rotated by 30 degrees with respect to the α-axis of Al2O3. In our experiments, a nonmagnetic hcp-underlayer and a CoCrPt magnetic layer were sequentially sputter-deposited on an Al2O3(0001) substrate which was kept at 200°C. The underlayer material with hcp-crystal
Table 1 The epitaxial growth of Co and Co-alloy thin films on single-crystal substrates.

<table>
<thead>
<tr>
<th>Film orientation</th>
<th>Underlayer</th>
<th>Substrate</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Co(1120)</td>
<td>Cr(001)</td>
<td>NaCl(001)</td>
<td>Daval et al., 1970 [3]</td>
</tr>
<tr>
<td>Co(1120)</td>
<td>Cr(001)</td>
<td>MgO(001), LiF(001)</td>
<td>Nakamura et al., 1994, 1995 [5, 6]</td>
</tr>
<tr>
<td>Co-alloy(1120)</td>
<td>Cr(001)</td>
<td>MgO(001)</td>
<td>Futamoto et al., 1994 [7]</td>
</tr>
<tr>
<td>Co-alloy(1120)</td>
<td>Cr(001)</td>
<td>GaAs(001)</td>
<td>Ding et al., 1994 [8]</td>
</tr>
<tr>
<td>Co-alloy(1120)</td>
<td>Cr(001)/Ag(001)</td>
<td>Si(001)</td>
<td>Yang et al., 1997 [9]</td>
</tr>
<tr>
<td></td>
<td>Mn0.5Si0.5(002)/Ag(001)</td>
<td>Si(001)</td>
<td>Hsu et al., 2000 [10]</td>
</tr>
<tr>
<td>Co-alloy(1011)</td>
<td>Cr(110)/Ag(111)</td>
<td>Cr(110)</td>
<td>Gong et al., 1999 [11]</td>
</tr>
<tr>
<td>Co-alloy(11010)</td>
<td>Cr(112)</td>
<td>MgO(110), LiF(110)</td>
<td>Nakamura et al., 1994, 1995 [5, 12]</td>
</tr>
<tr>
<td>Co-alloy(11010)</td>
<td>Cr(112)/Ag(110)</td>
<td>Si(110)</td>
<td>Yang et al., 1999 [13]</td>
</tr>
<tr>
<td>Co-alloy(0001)</td>
<td>Ti(001), Ru(001)</td>
<td>Mica(0001)</td>
<td>Krishnan et al., 1994 [14]</td>
</tr>
<tr>
<td>Co-alloy(0001)</td>
<td>Ti(001)/Ag(111)</td>
<td>Si(111)</td>
<td>Geng et al., 1999 [15]</td>
</tr>
<tr>
<td>Co-alloy(0001)</td>
<td>CoCrRu(001)</td>
<td>SrTiO3(111), LaAlO3(0001)</td>
<td>Terayama et al., 2001 [16]</td>
</tr>
</tbody>
</table>

Fig. 1 (a) Cross-sectional view of the sample structure. (b) Crystallographic relationship between the nonmagnetic hcp-underlayer and the substrate of Al2O3(0001) single crystal. Note that the a-axis of the hcp-underlayer is rotated by 30 degrees with respect to that of Al2O3 substrate.

The structure was selected from the group which consists of Ti, TiCr10, CoCr40, CoCr72Ru25, and CoCr25Ru75/Ti. The thickness of the CoCr19Pt10 magnetic layer was kept constant at 25 nm. The substrates on the chemical names above are at% and are the values for the respective sputtering targets.

The rocking curve and pole-figure techniques were employed with X-ray diffraction to investigate the sample structure. Cross-sectional views of the sample structure were obtained through a high-resolution transmission electron microscope. TEM was also used, with a chemical analysis facility, to investigate the microscopic-level distribution of elements in the alloy of a thin film of single-crystal (0001)-oriented CoCr19Pt10. A focused electron beam two nm in diameter was employed in this electron-probe micro-analysis (EPMA) to determine the distribution of elements in the cross-sectional and plan-views of the sample.

3. Results and Discussion

3.1 X-Ray Diffraction

The Δθ50 values of (0002) rocking curves measured for the underlayers and the Co-alloy layers are given in Table 2. For the nonmagnetic Co-alloy underlayers, the Δθ50 values include the effect of the Co-alloy layers, since the X-ray diffraction peaks for the CoCr40 and CoCr72Ru25 layers overlapped with those for the magnetic CoCr19Pt10 layers. The Δθ50 value for the Co-alloy layer is in the range from 0.6 to 3.5 degrees. A Δθ50 value below one degree might suggest that the thin film was grown epitaxially on the single-crystal substrate. It is clearly shown that preparation of an epitaxial layer of CoCr19Pt10 is strongly dependent on the material used for the underlayer.

Figure 2 shows the X-ray pole-figure profiles measured for the substrates, underlayers, and Co-alloy layers. The {10.1} poles for the nonmagnetic Co-alloy underlayers are overlapped with those for the CoCr19Pt10 magnetic layers. The {10.1} pole-figure for the CoCr19Pt10/Al2O3(0001) sample shows a weak intensity of 6-fold symmetry. This data indicates that the CoCr19Pt10 magnetic layer has been grown epitaxially on the Al2O3(0001) substrate but with a large texture-induced dispersion. This film presumably includes crystallographic defects such as the subgrain boundaries that were noted in previous studies [14, 15]. The CoCrRuPt10 film in the CoCr19Pt10/TiCr10/Al2O3(0001) sample is polycrystalline, even though the TiCr10 underlayer was epitaxially grown on the substrate. The circular distributions of the {10.1} poles for the CoCr19Pt10 film in the CoCr19Pt10/CoCr19Pt10/Al2O3(0001) sample, which is formed by circular and arc-like curves, indicate that it, too, is polycrystalline. The {10.1} pole-figures for Co-alloy for the CoCr19Pt10/CoCr72Ru25/Al2O3(0001) and CoCr19Pt10/CoCr25Ru75/Ti/Al2O3(0001) samples are made up of very sharp reflections in 6-fold symmetry, indicating that the growth of the CoCr19Pt10 magnetic layers on the Al2O3(0001) substrates was epitaxial.

Of the various underlayers investigated here, the CoCr25Ru75 layer produced the sharpest {10.1} pole-figure profile with the smallest dispersion, while the CoCr40 layer produced a circular {10.1} pole-figure distribution which had the largest dispersion. The or-
Table 2  $\Delta \theta_{50}$ values for thin films deposited on the Al$_2$O$_3$(0001) substrate ($\Delta \theta_{50}$: dege).

<table>
<thead>
<tr>
<th>Sample structure</th>
<th>Underlayer</th>
<th>Co-alloy layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) CoCrPt (25 nm)</td>
<td>-</td>
<td>3.5</td>
</tr>
<tr>
<td>(2) CoCrPt (25 nm)/TiCr (50 nm)</td>
<td>0.6 (TiCr)</td>
<td>3.0</td>
</tr>
<tr>
<td>(3) CoCrPt (25 nm)/CoCr (20 nm)</td>
<td>2.2 (Cr + CoCrPt)</td>
<td></td>
</tr>
<tr>
<td>(4) CoCrPt (25 nm)/CoCrRu (50 nm)</td>
<td>0.6 (CoCrRu + CoCrPt)</td>
<td></td>
</tr>
<tr>
<td>(5) CoCrPt (25 nm)/CoCrRu (10 nm)/Ti (50 nm)</td>
<td>0.6 (Ti) *</td>
<td>0.9 (CoCrRu + CoCrPt)</td>
</tr>
</tbody>
</table>

* The X-ray diffraction peak for the nonmagnetic Co-alloy layer overlapped with that for the CoCrPt layer.

Fig. 2  X-ray pole-figure profiles for 5 samples: (1) CoCr$_{19}$Pt$_{10}$ (25 nm)/Al$_2$O$_3$ (0001), (2) CoCr$_{19}$Pt$_{10}$ (25 nm)/TiCr$_{10}$ (50 nm)/Al$_2$O$_3$ (0001), (3) CoCr$_{19}$Pt$_{10}$ (25 nm)/CoCr$_{40}$ (20 nm)/Al$_2$O$_3$ (0001), (4) CoCr$_{19}$Pt$_{10}$ (25 nm)/CoCr$_{25}$Ru$_{25}$ (50 nm)/Al$_2$O$_3$ (0001), and (5) CoCr$_{19}$Pt$_{10}$ (25 nm)/CoCr$_{25}$Ru$_{25}$ (10 nm)/Ti (50 nm)/Al$_2$O$_3$ (0001).

The TiCr$_{10}$, Ti, CoCr$_{19}$Pt$_{10}$, and CoCr$_{25}$Ru$_{25}$ layers grew by epitaxy on the Al$_2$O$_3$(0001) substrate. However, the growth of the CoCr$_{40}$ layer was not epitaxial on the Al$_2$O$_3$(0001) substrate. The growth of CoCr$_{19}$Pt$_{10}$ magnetic layer was epitaxial on the CoCr$_{25}$Ru$_{25}$/Ti(0001) and CoCr$_{25}$Ru$_{25}$(0001) layers but not on the Ti(0001) layer. It is apparently necessary to take factors other than the lattice misfit into account such as chemical affinity and the diffusion properties of the deposited material on the substrate.

An underlayer material which has a large proportion of Cr atoms tends to be a poor base for epitaxial growth on the Al$_2$O$_3$(0001) substrate. One possibility is that Cr atoms may suppress the surface diffusion of the material deposited on the substrate through selective combination with the oxygen atoms on the Al$_2$O$_3$(0001) surface. Some diffusion of the deposited atoms over the substrate's surface is a necessary precondition for epitaxial growth. The addition of Ru to the CoCr-alloy is considered to facilitate surface diffusion, since the CoCrRu layer showed good hetero-epitaxy on both the Al$_2$O$_3$(0001) substrate and the Ti(0001) underlayer. It is interesting to note that hetero-epitaxy between the layers is realized with the Ti(0001) underlayer and CoCr$_{25}$Ru$_{25}$ layer, even though the misfit between the Ti ($a = 0.295$ nm) and CoCr$_{25}$Ru$_{25}$ ($a = 0.258$ nm) lattices is a large 12.5%. Surface diffusion of the deposited material over the substrate is considered to play an important role in this formation of an epitaxial thin film of CoCr$_{25}$Ru$_{25}$ on a Ti(0001) layer. However, further study will be needed to prove this interpretation.

### 3.2 Transmission Electron Microscopy

In order to investigate the microstructure of the thin films grown by epitaxy on the Al$_2$O$_3$(0001) substrates, their cross-sectional structures were observed through a high-resolution TEM. Figure 3 shows the cross-sectional structure and electron diffraction patterns for a CoCr$_{19}$Pt$_{10}$/CoCr$_{25}$Ru$_{25}$/Al$_2$O$_3$(0001) sample. The pattern of electron diffraction from the substrate, Fig. 3(b), is for the Al$_2$O$_3$(1120) plane. The electron...
Fig. 3 (a) Cross-sectional view of a CoCr19Pt10 (25 nm)/CoCr25Ru25 (50 nm)/Al2O3(0001) sample: (b), (c), and (d) show the diffraction patterns for selected areas of the Al2O3, CoCr25Ru25, and CoCr19Pt10 regions, respectively.

Fig. 4 High-resolution TEM micrographs of a CoCr19Pt10 (25 nm)/CoCr25Ru25 (50 nm)/Al2O3(0001) sample: (a) the interface between the CoCr19Pt10 and CoCr25Ru25 layers and (b) the interface between the CoCr25Ru25 layer and Al2O3(0001) substrate.

diffraction from the CoCr25Ru25 layer, Fig. 3(c), and that from the CoCr19Pt10 layer, Fig. 3(d), clearly indicate that hetero-epitaxial thin-film growth has been realized on the Al2O3(0001) substrate.

Figure 4 is a pair of high-resolution TEM images that show the interfaces between the Al2O3(0001) substrate and CoCr25Ru25 layer and between the CoCr25Ru25 and CoCr19Pt10 layers. The good hetero-epitaxy between the Al2O3(0001) substrate and the CoCr25Ru25 layer is clearly visible. The (0002) planes are parallel for both pairs of materials. Growth of the CoCr19Pt10 magnetic layer on the CoCr25Ru25 underlayer is perfectly hetero-epitaxial; the lattice misfit is only −0.8%.

Figure 5 shows the cross-sectional structure of a CoCr19Pt10/CoCr25Ru25/Ti/Al2O3(0001) sample and series of electron diffraction patterns from the respective materials. The patterns indicate that hetero-epitaxial growth is realized across the different layers. Some dark regions are recognizable in the bright field image for the Ti layer close to both of its boundaries. These are presumably result of stress and/or strain. There are no clear crystalline grain boundaries in either the Ti or the CoCr19Pt10/CoCr25Ru25 layer.

High-resolution TEM micrographs of the regions around the boundaries are shown in Fig. 6. A sharp boundary is formed between the Al2O3 substrate and the Ti underlayer. A noteworthy in Fig. 6(b) is that the Ti(0002) lattice images are not exactly parallel to those of Al2O3(0002) layers but are bending with small angles. A similar tendency is visible in the same layer near the CoCr25Ru25 layer. There is an atomically disordered region that takes up very few (0002) layers at the interface between the CoCr25Ru25 and the Ti layer; that is presumably caused by the large lattice misfit of −12.5% for these materials. The growth of a CoCr25Ru25 layer on Ti(0001) is interpreted to be based on a quasi-hetero-epitaxial mechanism where the continuity of the lattice across the boundary is disturbed but the overall crystallographic relationship between the two layers is maintained. This quasi-hetero-epitaxy between Ti and Co-alloy layers may easily be lost by modifying the composition of the thin film as was seen in the case of the CoCr19Pt10/TiCr10/Al2O3(0001) sample in this study. On the other hand, perfect hetero-epitaxy is realized
for CoCr$_{19}$Pt$_{10}$ on CoCr$_{22}$Ru$_{25}$. This is clearly visible in the upper half of high-resolution lattice image of Fig. 6(a).

3.3 Chemical Compositions

Local composition was investigated by applying an EPMA-TEM technique to a cross-section through a sample of CoCr$_{19}$Pt$_{10}$/CoCr$_{22}$Ru$_{25}$/Al$_2$O$_3$(0001). Compositional variations of the alloy elements of Co, Cr, Pt, and Ru were investigated along the sequences of points on two lines shown in Fig. 7(a). Similar proportions for the respective elements were observed along both lines. There are no large differences in elements in composition along the film growth direction in either the CoCr$_{22}$Ru$_{25}$ or the CoCr$_{19}$Pt$_{10}$ layer. Compositional fluctuations along the direction of film growth are less than 3 at.% for each of the elements in the alloys. Sharp compositional variations of a very few nanometers appear at the interface between the CoCr$_{22}$Ru$_{25}$ and CoCr$_{19}$Pt$_{10}$ layers. When we consider the electron-probe’s diameter 2 nm and the uncertainty in terms of sample thickness, we see that it is not easy to determine an accurate diffusion distance for elements when this value is a very small number of nanometers.

Figure 8 shows local concentrations of Co, Cr, and Pt for a plan-view thin film of single-crystal CoCr$_{19}$Pt$_{10}$(0001) which was extracted from a CoCr$_{22}$Pt/CoCr$_{22}$Ru/Al$_2$O$_3$(0001) sample. The compositional analysis was carried out along the two lines, A-B and C-D, indicated in Fig. 8(c). The film’s composition was determined as Co 71.2 $\pm$ 2.8(2$\sigma$)%, Cr 18.0 $\pm$ 2.3(2$\sigma$)%, and Pt 10.8 $\pm$ 1.1(2$\sigma$)%, where $\sigma$ is the standard-deviation. This thin film thus shows slight compositional variation, though it is a (0001)-oriented single-crystal. Such compositional fluctuations may be due to the effect of local stress or strain within the single-crystal thin film sample. Compositional fluctuations will readily be enhanced by the presence of crystallographic defects in a CoCr-alloy sample where the proportion of Cr exceeds the limit on solubility in the phase diagram for the Co-Cr alloy system.

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Fig. 6 High-resolution TEM micrographs of a CoCr$_{19}$Pt$_{10}$ (25 nm)/CoCr$_{22}$Ru$_{25}$ (10 nm)/Ti (30 nm)/Al$_2$O$_3$(0001) sample: (a) the interfaces of the CoCr$_{19}$Pt$_{10}$/CoCr$_{22}$Ru$_{25}$/Ti stack and (b) the interface between the Ti layer and the Al$_2$O$_3$(0001) substrate.

Fig. 7 Distributions of Co, Cr, Pt, and Ru in the alloys, as measured along the direction of thin film growth: (a) a cross-sectional TEM micrograph of CoCr$_{19}$Pt$_{10}$ (25 nm)/CoCr$_{22}$Ru$_{25}$ (50 nm)/Al$_2$O$_3$(0001) sample: white dots indicate the analysis points, and (b) distribution of the alloy elements.
either a TiCr$_{10}$ or a CoCr$_{40}$ underlayer was employed.

(2) The growth of CoCr$_{15}$Pt$_{10}$ film on Ti(0001) is
according to a quasi-hetero-epitaxial mechanism where the continuity of the lattice across the
boundary is disturbed but the overall crystallographic relationship between the two layers is main-
tained.

(3) Epitaxially grown thin films CoCr$_{15}$Pt$_{10}$ have com-
ositional variations across the film plane of a few
percent in terms of the concentrations of elements.

Acknowledgment

A part of this work was carried out under the ASET
program supported by NEDO.

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