Magnetic and structural properties of $L_1$ type CoPt-C ordered alloy perpendicular films as a function of C content

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Abstract. Magnetic and structural properties of $L_1$ type (Co$_{0.5}$Pt$_{0.5}$)$_{100-X}$C$_X$ ordered alloy perpendicular films, fabricated on 2.5 inch size glass disks by sputter deposition, were examined as a function of C content, X. $L_1$ type Co$_{0.5}$Pt$_{0.5}$-C polycrystalline films (10 nm thickness), with $<111>$ axis (the easy axis) perpendicular to the film plane, were successfully fabricated even for a 30 vol% C content. Structural analysis indicated the segregation of C to the grain boundaries. Uniaxial magnetic anisotropy, $K_u$, of Co$_{0.5}$Pt$_{0.5}$ films without C addition was relatively low, about 1.5x10$^7$ erg/cm$^3$ under the present deposition conditions. However, the addition of 5 vol.% C to Co-Pt films enhanced the ordering, resulting in an increase in $K_u$ to around 2.5 x10$^7$ erg/cm$^3$. A further increase in C content reduced $K_u$; however, $K_u$ maintained a relatively large value of about 1.8x10$^7$ erg/cm$^3$ even for a 20vol% C content, without degrading the easy axis orientation perpendicular to the film plane. Experimental results demonstrated the potential of the $L_1$ type Co$_{0.5}$Pt$_{0.5}$-C films for use in granular media applications, due to their very high $K_u$, the relatively low fabrication temperature, and good controllability of the grain orientation.

1. Introduction

$L_1$ type Co$_{50}$Pt$_{50}$ ordered films [1-3] are promising candidates for high density recording media because of their large magnetocrystalline anisotropy, $K_u$, of the order of 10$^7$ erg/cm$^3$ and relatively low fabrication temperature (300-400 °C). However the $L_1$ phase is quasi-stable, and in all previous reports $L_1$ type Co$_{50}$Pt$_{50}$ films were fabricated on single crystal substrates using molecular beam epitaxy. We successfully fabricated $L_1$ type Co-Pt ordered alloy films, with the easy axis of magnetization perpendicular to the film plane, using ultra-high vacuum (UHV) sputter film deposition [4,5]. The values of the order parameter, S, and $K_u$ for $L_1$ type Co$_{50}$Pt$_{50}$ films increased as the substrate temperature, $T_s$, increased. $K_u$ reached about 3.7x10$^7$ erg/cm$^3$ ($S=0.54$) at $T_s=360$ °C for single crystal films deposited on MgO(111) substrates, indicating the potential increase in $K_u$ on enhancing the ordering. The $K_u$ values of polycrystalline films deposited on glass disks were smaller than those of single crystal films on MgO(111) substrates, however, $K_u$ reached 1.9x10$^7$ erg/cm$^3$ at $T_s=360$ °C. Moreover, these films had a preferred crystal orientation with the close-packed plane
parallel to the film plane, and the easy axis distribution, estimated from the rocking curves of the $L1_1$-(222) diffraction line, was 3.4 degrees, even for polycrystalline films deposited on glass disks. The experimental results demonstrated the potential of $L1_1$ type Co-Pt ordered films for use in data storage applications, due to their very high $K_u$, comparable to $L1_0$-type Fe$_{50}$Pt$_{50}$ films, the relatively low fabrication temperature, and good controllability of the grain orientation.

In this study, we added some carbon to $L1_1$ type Co$_{50}$Pt$_{50}$ ordered alloy films. We examined the structural and magnetic properties of $L1_1$ type ($Co_{0.5}Pt_{0.5})_{100-X}$-$C_X$ films as a function of C content, X, and demonstrate their fundamental potential for use in high density granular media applications.

2. Experimental procedure
Films were deposited using an UHV DC magnetron sputtering system (ANELVA, E8001). The base pressure prior to film deposition was less than 7x10$^{-7}$ Pa. Films were deposited on 2.5 inch-size glass disks for hard disk applications. CoPt-C films were deposited by the co-sputter method. The composition of CoPt was fixed at Co$_{50}$Pt$_{50}$ (at %), and C was added to this CoPt composition by controlling the deposition rate. The C content was expresses as the volume percent of C, which was calculated using deposition rates of CoPt and C films. The film thickness was 10 nm. 20 nm thick Ru underlayers with 5 nm thick Ta pre-underlayers were used for the CoPt-C layers. The substrate temperature for the deposition of the CoPt-C layers was 360 °C, which is the temperature where the values of the saturation magnetization of the grains, $M_s$, as a function of C content. In the figure, the values of $M_s$, calculated by taking account of the volume fraction of CoPt grains, are also shown for comparison. The value of $M_s$ for $L1_1$-CoPt films without C addition was about 900 emu/cm$^3$, and decreased gradually as the C content increased. However, it should be noted that the value of $M_s$ was nearly saturated for $L1_1$ type Co-Pt binary alloy films [4,5]. It should be noted that the substrate was not heated up for the depositions of Ru and Ta underlayers in the present study, because of a technical problem, which was different to in our previous work [4,5]. The values of $K_u$ (= $K_{u1}$+$K_{u2}$) were measured by the GST method [6], with a maximum applied field of 7 T.

3. Results and discussion
Fig.1 (a) and (b) show the X-ray diffraction (XRD) patterns for CoPt-C films with various C content, X. All films had a preferred crystal orientation with the close-packed plane parallel to the film plane. Diffraction lines of CoPt-$L1_1$(111) planes were observed in all patterns, even at 30 vol% C addition, indicating the successful formation of a $L1_1$ type ordered structure, although the diffraction line width was relatively large due to the reduction of crystalline coherence length.

The intensity of the $L1_1$-(111) line for a CoPt film without C addition was low compared to our previous work [4,5] due to the difference in the deposition conditions mentioned above. However, the addition of 2-5 vol% C to Co-Pt polycrystalline films enhanced the intensity, indicating an enhancement of the ordering. A further increase in C content reduced the intensity of the $L1_1$-(111) line. The $L1_1$-(111) lines were weak and broad in these films, which made it difficult to calculate the order parameter, S.

Fig.2 shows the values of the saturation magnetization, $M_s$, as a function of C content. In the figure, the values of the saturation magnetization of the grains, $M_s^g$, calculated by taking account of the volume fraction of CoPt grains, are also shown for comparison. The value of $M_s$ for $L1_1$-CoPt films without C addition was about 900 emu/cm$^3$, and decreased gradually as the C content increased. However, it should be noted that the value of $M_s^g$ maintained the original value of 900 emu/cm$^3$ even at 30 vol% C addition. This result suggested that almost all carbon was segregated to the grain boundaries of $L1_1$-CoPt.

Fig.3 shows the values of $K_u$ as a function of C content. In the figure, the values of the magnetostructural anisotropy of the grains, $K_u^g$, calculated by taking account of the volume fraction of CoPt grains, is also shown for comparison. The value of $K_u$ for $L1_1$-CoPt films without C was relatively low, about 1.5x10$^7$ erg/cm$^3$ under the present deposition conditions. The addition of 5 vol% C to the Co-Pt polycrystalline films enhanced the values of $K_u$ and $K_u^g$ to around 2.4 x10$^7$ erg/cm$^3$ and 2.5 x10$^7$ erg/cm$^3$, respectively. A further increase in C content reduced $K_u$ and $K_u^g$. However, it should be noted that $K_u^g$ maintained a relatively large value of about 1.8x10$^7$ erg/cm$^3$ even at 20vol% C addition, which is about 3 times larger than the maximum value of $K_u^g$ of CoPtCr-SiO$_2$ perpendicular media [7]. The variations of $K_u$ and $K_u^g$ were in qualitative agreement with the intensities of the $L1_1$-
(111) lines shown in Fig.1. The values of $S$, estimated from the relationship between $K_u$ and $S$ for single crystal $L_11$-CoPt films [4,5], were about 0.35 and 0.25 for films with 5 and 20 vol% C additions, respectively.

Figure 1. X-ray diffraction patterns for $L_11$ type ordered CoPt-C films with various C contents.

Figure 2. Values of $M_s$ and $M_{s\parallel}$ for CoPt-C films as a function of C content.

Figure 3. Values of $K_u$ and $K_{u\parallel}$ for CoPt-C films as a function of C content.

Fig.4 shows images of CoPt-20vol% C films observed by (a) bright field scanning transmission electron microscopy (BF-STEM) and (b) high-angle annular dark-field scanning transmission electron microscopy (HAADF-STEM). Dark (indicating light atoms) and thick grain boundaries were clearly observed in Fig.4(b), suggesting C segregation at these grain boundaries. This result is qualitatively consistent with the variation in $M_s$ shown in Fig.2. However, the C was not homogeneously segregated at all grain boundaries, suggesting a very strong intergranular exchange coupling remained. Fig.5 shows magnetic force microscopy (MFM) images of $L_11$-CoPt films (a) without and (b) with 20vol% C addition. The domain size decreased on the C addition, but was large compared to the metallurgical structure shown in Fig.4, supporting this assumption.
4. Conclusion

We successfully fabricated $L_1_1$ type CoPt-C ordered alloy perpendicular films on glass disks using ultra-high vacuum sputter film deposition. $K_u$ maintained a relatively large value of about $1.8 \times 10^7$ erg/cm$^3$ even at 20vol% C addition, without degrading the orientation of $<111>$ axis (the easy axis) perpendicular to the film plane. Experimental results demonstrated the potential of the CoPt-C ordered films for use in granular media applications, due to their very high $K_u$, the relatively low fabrication temperature, and good controllability of the grain orientation, although more intensive efforts are required to fabricate films with a homogeneous C segregation at the grain boundaries for use in granular media applications. It is expected that a homogeneous segregation structure could be formed by the use of adequate seed layers and tuning the deposition conditions.

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