Effects of substrate bias on magnetocrystalline anisotropy K_u of CoPt thin films with increasing Pt content

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The magnetocrystalline anisotropy (K_u) of continuous $Co_{1-x}Pt_x$ alloy films peaks at ~30 at. % of Pt. Further increase in Pt at. % decreases K_u quickly probably due to the increasing density of stacking faults (SFs) and the fcc phases. The effect of substrate bias has been studied in various compositions of CoPt films. K_u increases from 8×10^6 to 1.1×10^7 ergs/cm^3 when −50 V bias was applied to $Co_{60}Pt_{40}$ films and decreases with further increase in bias. Pt at. % slightly increases from 40 to 43 at. %, which is opposed to the initial K_u increase. However, the SF density and the fcc content are greatly reduced in the biased samples. The transmission electron microscopy images of the biased films show less faulted atomic planes in the hcp CoPt grains. Such improvement in structural defects helps increase K_u in magnetic thin films. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3067558]

I. INTRODUCTION

CoPt thin film with perpendicular anisotropy has been widely studied for the sake of superior Pt induced high magnetocrystalline anisotropy energy (K_u). However, due to the large atomic size of Pt atoms, high Pt content causes Co lattice expansion and resultant internal stress and crystallographic defects such as stacking faults (SFs). Pt also stabilizes the face-centered-cubic (fcc) phase relative to the hexagonal-closed-packed (hcp) phase for Pt contents greater than 12 at. %. It is known that the grains containing SFs and fcc phases along the c axis of a hcp crystal structure will cause a K_u reduction due to the magnetic soft nature of these defects.[1–6] This explains the trend that the K_u of continuous $Co_{1-x}Pt_x$ alloy films peaks at ~30 at. % of Pt and decreases quickly with further increase in Pt at. %.[7–9] Studying the relationship between the crystallographic defects and the resultant magnetic parameters provides a unified understanding of the effect of crystallographic defects on the magnetic behavior of the materials. The lattice match is usually good between the commonly used (00.2) textured Ru underlayer and the (00.2) textured CoPt magnetic layer at the heteroepitaxial growth interface. However, such constraint no longer exists through the rest of the film once beyond that critical thickness. Producing SFs or fcc phase free perpendicular CoPt thin film is not very controllable.

This study focused on how K_u varies in CoPt films by varying the substrate bias voltage with different Pt content levels. We found the trend of K_u increase at high Pt concentration regions by applying a proper substrate voltage. In-plane x-ray diffraction (XRD) has been used to study the texture, SFs, and lattice constants of the thin films quantitatively. The results are discussed in detail in the following text.

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II. EXPERIMENT

Thin films $Co_{1-x}Pt_x$(15 nm)/Ru(30 nm)/Ta(3 nm) (x =8, 25, and 40 at. %) were deposited on the naturally oxidized 1 in. Si substrates by rf diode sputtering from the Leybold-Heraeus Z-400 system. The base pressure was about 5×10^{-7} Torr and the argon pressure for CoPt film deposition was fixed at 45 mTorr. The CoPt magnetic layers were fabricated by using a Co target with bonded Pt chips. The composition varies by changing the relative surface area of Pt chips and Co target. Substrate bias has been applied to the CoPt film from 0 to −125 V. All the layers were deposited at room temperature. XRD was utilized to study crystallographic properties of the thin films. High resolution transmission electron microscopy (TEM) was used to study the microstructure, SFs, or fcc regions in the (00.2) textured CoPt thin films from the cross sectional view. The vibrating sample magnetometer (VSM) has been used to measure K_u from hard axis MH loops. Torque magnetometer was utilized to verify the K_u results from the VSM measurements.

III. RESULTS AND DISCUSSION

The space groups of the fcc and hcp structures are $Fm\bar{3}m$ and $P6_3/mmc$, respectively. When (111) textured fcc and (00.2) textured hcp phases are mixed in the thin films, the $(220)_{fcc}$ and $(10.0)_{hcp}$, $(11.0)_{hcp}$, etc., are the planes perpendicular to the film surface. $(11.0)_{hcp}$ and $(220)_{fcc}$ have similar d spacings due to the arrangement of the atoms. By measuring the intensity of mixed $(11.0)_{hcp}$ and $(220)_{fcc}$ over the intensity of the diffractions due to hcp structures only, relative SFs or fcc phase amount could be obtained quantitatively. In this study, we measured the value of $I(10.0)_{hcp}/[I(11.0)_{hcp}+I(220)_{fcc}]$ from in-plane XRD $\theta/2\theta$ scans. The higher this value, the larger the hcp fraction, and vice versa.

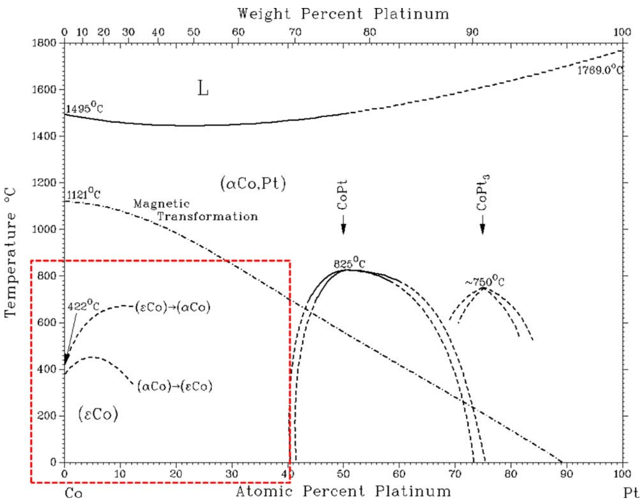

FIG. 1. (Color online) Phase diagram of binary CoPt alloy from Ref. 10.

Figure 1 is the binary phase diagram of CoPt alloy.[10] The region of interest is emphasized within the red dot frame. For pure Co, the stable phase is ε (hcp) below 422 °C and α(fcc) above. With increasing Pt content from 0 to $\sim$12 at. %, the curve shows the stabilization of the ε (hcp) phase over the fcc phase. Further increase in Pt might cause the preference of the fcc phase but is not clearly shown in the diagram.

Figure 2 is the plot of K_u of the CoPt films as a function of Pt content (8, 25, and 40 at. %) and substrate bias voltage. Under each bias voltage applied from 0 to -125 V, it is noticeable that K_u increases monotonously with increasing Pt content, which is consistent with literature reports cited earlier. Also under all these three levels of Pt content alloying, increasing bias eventually leads to a continuous K_u drop. This is probably due to the fact that applying substrate bias not only provides the extra momentum to the atoms or species on the surface of the growing film but also accelerates the deposition process toward the thin film equilibrium low energy fcc phase state with most closed packed structure, but with low magnetocrystalline anisotropy. However, with high 40 at. % Pt content, K_u increases from 8×10^6 to 1.1×10^7 ergs/cm^3 when -50 V bias is applied to CoPt films, although K_u decreases with further increase in bias. The cause of such K_u increase is of interest.

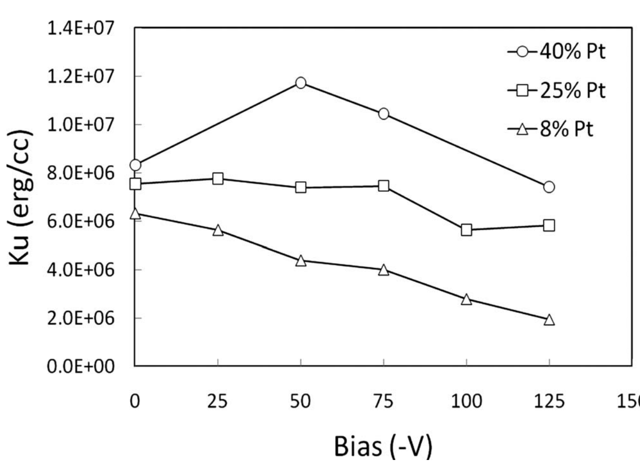

FIG. 2. Magnetocrystalline anisotropy K_u of CoPt films as a function of Pt content and substrate bias voltage.

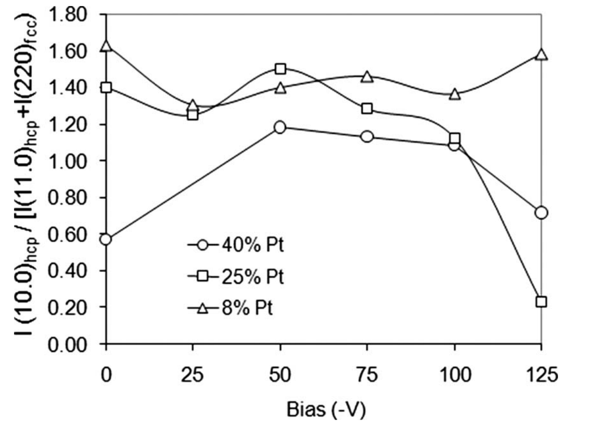

FIG. 3. $I(10.0)_{hcp}/[I(11.0)_{hcp}+I(220)_{fcc}]$ ratio of CoPt peaks from $\theta/2\theta$ in-plane XRD scans as a function of Pt content and substrate bias voltage.

Figure 3 is the plot of the $I(10.0)_{hcp}/[I(11.0)_{hcp}+I(220)_{fcc}]$ value of the CoPt films as a function of Pt content (8, 25, and 40 at. %) and substrate bias voltage. It shows that this ratio is kept around 1.5 with lowest 8 at. % Pt addition and increasing bias voltage. Usually, applying substrate bias will reduce the amount of low mass atom (e.g., Co in this case) due to the preferential resputter phenomena on the surface of growing film, which effectively causes the slight Pt content increase with increasing substrate bias (e.g., Pt at. % content increases from 40 to 43 at. % by varying bias from 0 to -125 V analyzed from EDX). This indicates that because of low Pt content in the CoPt thin films, a large amount of hcp phases maintains, although Pt content slightly increases. It shows the consistency with the phase diagram as discussed earlier. However, K_u is kept low due to the insufficient Pt content regardless of relative high purity of the present hcp phase. In the case of 25 at. % Pt, the ratio stays at a lower value of around 1.4 with increasing bias up to -75 V and drops quickly toward 0.2 with -125 V bias, which implies the potential high SFs or fcc amount present in the film. It is obvious that it has a strong relationship with K_u drop in Fig. 2, showing that such crystallographic defects are harmful to the magnetic properties. In the case of 40 at. % Pt, the ratio increases from 0.6 to 1.1 with increasing bias from 0 to -50 V, maintained around 1.1 up to -100 V, followed by a drop to 0.7 with -125 V bias applied. It is not surprising that very high density of SFs and fcc are currently present in the 0 V biased film due to high Pt content and the resultant large degree of lattice distortion. However, the increasing ratio by means of applying substrate bias between -50 and -100 V implies a reduction in defects amount in such biased samples. In particular, this seems to have the similar increase as K_u increases in Fig. 2, which could be strongly related.

Figure 4 shows the plot of lattice constants c, a, c/a ratio of CoPt films as a function of Pt content (8, 25, and 40 at. %), and substrate bias voltage from 0 to -125 V. It is obvious that c has a steady increase from 4.14 to 4.33 Å with increasing Pt content from 8 and 25 to 40 at. % and a slight increase with increasing bias voltage. On the other hand, a has a steady increase from 2.53 to 2.63 Å with increasing Pt content from 8 and 25, to 40 at. %. However, a varies little

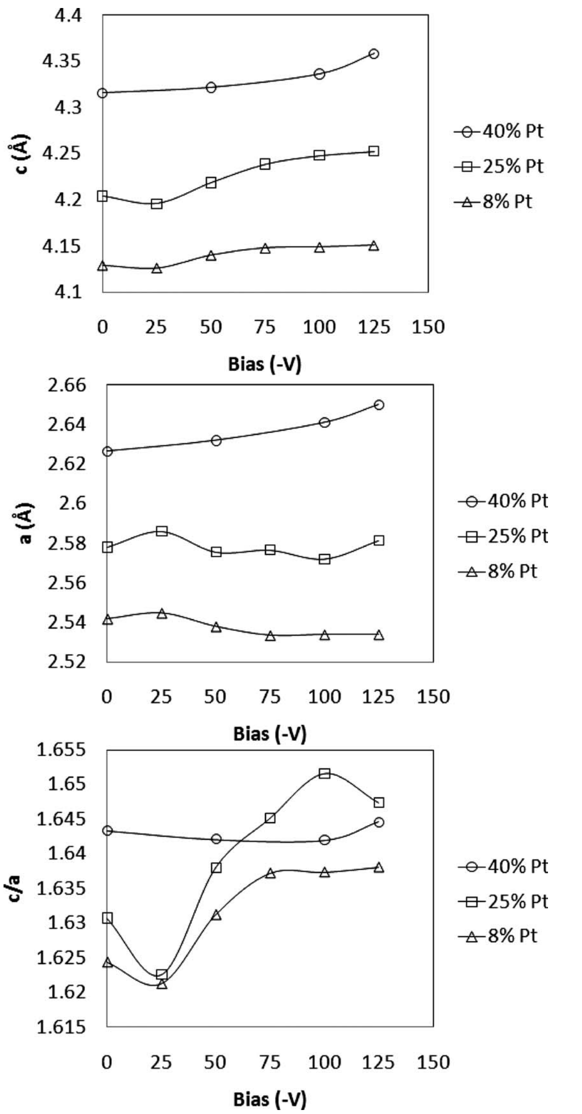

FIG. 4. c, a, c/a ratio of CoPt films as a function of Pt content and substrate bias voltage.

with increasing bias for the cases of 8 and 25 at. % Pt addition, but has a continuous increase with increasing bias voltage from 0 to -125 V with 40 at. % Pt addition. Therefore, the resultant c/a ratio increases greatly from 1.623 to 1.635 with 8 at. % Pt addition and from 1.630 to 1.647 with 25 at. % Pt addition with increasing bias, but c/a is kept around 1.643 for 40 at. % Pt addition. It has been empirically observed that low c/a is accompanied by the stabilization of hcp phase and high c/a for the fcc phase. Therefore, such c/a trend as a function of substrate bias has a good fit with the variation in $I(10.0)_{\mathrm{hcp}}/[I(11.0)_{\mathrm{hcp}}+I(220)_{\mathrm{fcc}}]$ value as a function of substrate bias in Fig. 3 for 8 and 25 at. % Pt additions. On the other hand, probably due to the high 40 at. % Pt addition, c/a does not change much.

Figure 5 is the cross sectional TEM image of $Co_{60}Pt_{40}$ films deposited at -100 V substrate bias at room temperature. Due to the limited grains in the TEM experiments, counting SFs or fcc phases is not a very ideal method for the purpose of quantification. However, this technique can help

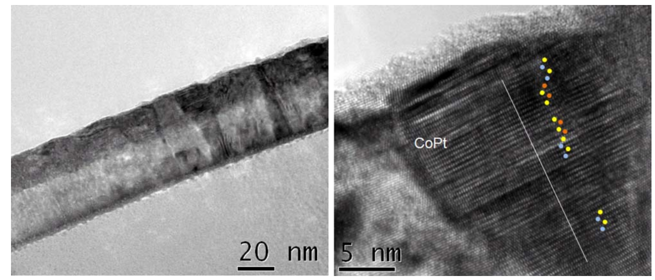

FIG. 5. (Color online) Cross sectional TEM image of $Co_{60}Pt_{40}$ films deposited at -100 V substrate bias at room temperature.

observe the microstructure in the thin films and SFs directly. From the figure, both growth and deformation faults can be clearly seen. Moreover, the correction or healing of faulted atomic planes in the hcp CoPt grains has been observed as indicated beside by the schematic of the magnified arrangement of atoms. Such improvement in the structural defects helps increase K_u in the high Pt content magnetic CoPt thin films by means of applying proper substrate bias voltage.

IV. CONCLUSIONS

In the present study, we measured K_u of CoPt films as a function of substrate bias with different Pt content levels. High Pt additions gave rise to higher perpendicular K_u, although it also increases the SFs or fcc content. However, applying a proper substrate bias probably decreases the SFs or fcc amount and increases K_u at high Pt content level. CoPt thin films with both high Pt addition and low SFs or fcc content are desired to produce high K_u properties. In-plane XRD $\theta/2\theta$ scan is a very useful technique to measure the relative SFs or fcc amount quantitatively.

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