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Large Uniaxial Magnetic Anisotropy of Co–Pt Perpendicular Films Induced by Lattice Deformation

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A study of the thickness dependence of the uniaxial magnetic anisotropy K_u of Co–Pt perpendicular films deposited on Ru seed layers was extended over a wide range of Pt content from 10 to 30 at%, to further investigate the origin of the significant increase in K_u on reducing the film thickness, which was previously reported for $Co_{80}Pt_{20}$/Ru films. K_u increased significantly as the thickness decreased in all series of films with various Pt content. The rate of increase of K_u with reducing thickness became increasingly large as the Pt content decreased. It should be noted that the K_u of 2-nm-thick films was an almost constant 2×10^7 erg/cm^3 over the range of Pt contents studied, although K_u was maximized at 25–30at%Pt content for films thicker than 5 nm. Experimental results suggest that the increase in K_u on reducing the thickness was mostly related to a reduction of the hcp Co–Pt lattice *c/a* ratio.

***Index Terms*—Co–Pt films, fcc volume fraction, hcp lattice, lattice deformation, Ru underlayer, surface anisotropy, uniaxial magnetic anisotropy.**

I. Introduction

A LARGE uniaxial magnetic anisotropy K_u of 1.5–2×10^7 erg/cm^3 was obtained in Co–20at%Pt perpendicular films deposited on Ru seed layers with no evidence of a Co_3Pt-type ordered structure [1], [2]. K_u increased significantly as the thickness decreased, and our results suggested that the increase in K_u was mostly related to a reduction of the c/a ratio of the hcp Co–Pt lattice due to epitaxial growth of Co–Pt on the Ru layers.

In this paper we extend the study of the thickness dependence of K_u to Co–Pt films with 10, 14, 20, 25, and 30at%Pt content, to further investigate the origin of the high K_u. The lattice mismatch between Co–Pt and Ru increased as the Pt content decreased; therefore, it was expected that reducing the Pt content would result in a further enhancement of K_u. We discuss the variation of K_u as a function of crystal structure in relation to the Pt content. The lattice deformation for films thinner than 10 nm was analyzed by synchrotron radiation grazing incidence X-ray diffraction (XRD), and included in the discussion. Moreover, the thickness dependence of K_u for Co–14at%Pt films deposited on Au seed layers was also examined for comparison; the lattice mismatch between Co–Pt and Au is much larger than that between Co–Pt and Ru.

II. Experimental Procedure

Co–Pt films were deposited on 4-in SiO_x/Si substrates by the cosputtering method with Co and Pt targets using a dc-magnetron sputtering system [2]. The film thickness was varied from 2 to 60 nm. Ru (20 nm) films were used as seed layers with a pre-seed layer of Pt(10 nm)/Ta(5 nm). No substrate heating was carried out during the deposition process. Capping layers of Pt (2 nm) were deposited on top of the Co–Pt layers. For comparison, Co–14at%Pt films with Au seed and capping layers were also deposited. K_u was obtained by subtracting the shape anisotropy $2\pi M_s^2$ from the value measured by torque magnetometry. The accuracy of the measured K_u values was confirmed in our previous work [2].

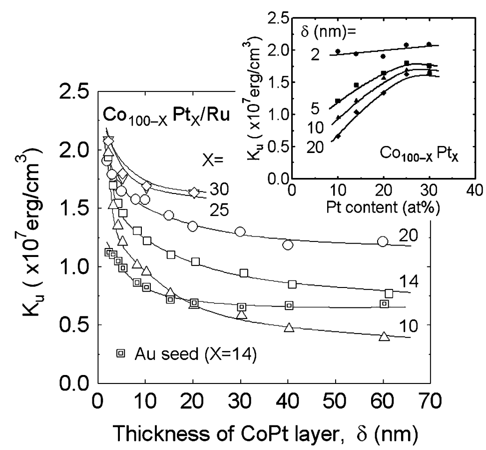

Fig. 1. K_u as a function of thickness δ for Co–Pt films with various Pt content. The inset figure shows the Pt content dependence of K_u for the same films.

III. Results and Discussions

A. K_u as Functions of Pt Content and Film Thickness

The saturation magnetization M_s was almost constant in all series of films with various Pt content, except for films thinner than 5 nm, for which M_s increased as the thickness decreased. This increase in M_s was due to polarization of the Pt capping layer [2], suggesting that no significant diffusion occurred at the top/bottom surfaces of the Co–Pt layer.

Fig. 1 shows the values of K_u for films with various Pt content as a function of film thickness δ. K_u increased as δ decreased, and reached about 2×10^7 erg/cm^3 at $\delta = 2$ nm in all series of films. The K_u values of these films were a few times larger than those of Co–20at%Pt films previously reported [3]–[6]. The K_u values of films thinner than 5 nm exceed the K_u of Co_3 Pt ordered alloy films [7]. Moreover, the rate of increase of K_u

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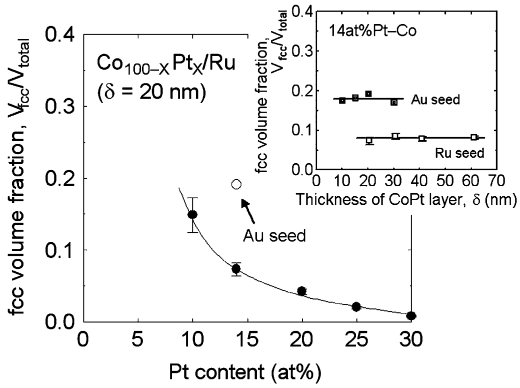

Fig. 2. The fcc volume ratio, $V_{\rm fcc}/V_{\rm total}$, for 20 nm-thick films as a function of Pt content. The inset figure shows the thickness dependence of $V_{\rm fcc}/V_{\rm total}$ for films with 14at%Pt content.

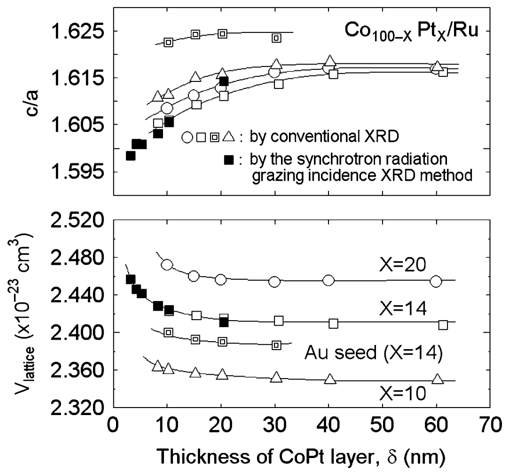

Fig. 3. Values of c/a ratios and $V_{\rm lattice}$ of the hcp Co–Pt lattice as a function of thickness. Symbols: $\rm X = 20$ (circle), 14 (square), and 10 (triangle).

with reducing δ became increasingly large as the Pt content decreased, as expected. The $K_{\rm u}$ of films of $\delta = 2$ nm was almost constant for films with Pt content from 10 to 30at%, as seen in the inset figure, although $K_{\rm u}$ was maximized at 25–30at%Pt content for films thicker than 5 nm. Our investigation of the first- and second-order energy terms of the uniaxial anisotropy, K_{u1} and K_{u2}, for Co–20at%Pt films revealed [1], [2] that the ratio of K_{u2} to K_{u1} was 0.16 for films with $\delta = 40$ nm, but reduced to less than 0.03 on decreasing δ to 5 nm. The K_{u2} values of these films were particularly small, unlike in previous reports [5], [6]. A similar thickness dependence of $K_{\rm u}$ was also observed in Co–14at%Pt films deposited on Au seed layers, as shown in the figure; however, the $K_{\rm u}$ values were smaller than those of Co–14at%Pt films deposited on Ru seed layers.

B. Structure

X-ray diffraction patterns revealed that the Co–Pt films with Ru seed layers had good c-axis orientation perpendicular to the film plane, with a c-axis distribution $\Delta\theta_{50}$ of about 2.8°, independent of Pt composition. No evidence of a Co_3Pt type ordered structure was found in the X-ray diffraction patterns. The diffraction of the fcc(111) plane was weakly observed by tilting the sample an angle $\chi = 70.5°$. χ is the angle between the normal axis to the film plane and the optical plane. This means that hcp Co–Pt lattice of grains contains a small number of fcc layers. We measured the diffraction intensities for the hcp(101) and fcc(111) planes, respectively, and calculated the fcc volume fraction, $V_{\rm fcc}/V_{\rm total}$, taking account of the preferred grain orientation, the multiplicity, form factor, Lorentz-polarization factor, and Debye–Waller factor [8]. Fig. 2 shows the values of $V_{\rm fcc}/V_{\rm total}$ as a function of Pt content for films with $\delta = 20$ nm. $V_{\rm fcc}/V_{\rm total}$ could not be estimated for films thinner than about 10 nm because of the very low diffraction intensities. $V_{\rm fcc}/V_{\rm total}$ was about 0.15 for films with a 10at%Pt content; however, $V_{\rm fcc}/V_{\rm total}$ decreased significantly as the Pt content increased, becoming less than 0.02 at 30at%Pt content. It should be noted that the value of $V_{\rm fcc}/V_{\rm total}$ was nearly constant as a function of δ, as shown in the inset figure for Co–14at%Pt films. This was supported by cross section (dark field) transmission electron microscopy (TEM) images; thin fcc layers form nearly independently of the film thickness. The use of Au instead of Ru seed layers resulted in $V_{\rm fcc}/V_{\rm total}$ nearly doubling.

C. Appearance of High $K_{\rm u}$ in Relation to Structure

The magnetic anisotropy of fcc Co–Pt should be negligibly small compared to that of hcp Co–Pt, and the Pt content dependence of $V_{\rm fcc}/V_{\rm total}$ was qualitatively in good agreement with that for $K_{\rm u}$, shown Fig. 1. This result suggests that an increase in $V_{\rm fcc}/V_{\rm total}$ plays a role in reducing $K_{\rm u}$ in the low Pt content region. However, the change in $K_{\rm u}$ was significantly large compared to that in $V_{\rm fcc}/V_{\rm total}$. Moreover, the value of $V_{\rm fcc}/V_{\rm total}$ was nearly constant as a function of δ. It is likely that the thickness dependence of $K_{\rm u}$ was mainly caused by other factors.

The surface anisotropy should be taken into account when discussing the value of $K_{\rm u}$ in the thin film region. Assuming that the increase in $K_{\rm u}$ was caused by the surface anisotropy, we tried to estimate the surface anisotropies at the top and the bottom surfaces, $K_{\rm s1}$ and $K_{\rm s2}$. However, the $K_{\rm u} \sim 1/\delta$ curve was not linear in all series of films, similar a series of Co–20at%Pt films [2]. Moreover, the calculated values of $K_{\rm s1} + K_{\rm s2}$ in these films ranged from 5 to 8 erg/cm^2, which are much larger than the surface anisotropy of Co-based alloy films [9]. These results indicate that the thickness dependence of $K_{\rm u}$ cannot be explained only by the surface anisotropy.

The lattice mismatch between Co–Pt and Ru increased as the Pt content decreased; therefore, it was expected that reducing the Pt content would result in an enhancement of lattice deformation. We measured the hcp-CoPt lattice spacings of the (002), (004), and (112) planes of these films, and used them to calculate the lattice constants a and c. The diffraction of the hcp (112) plane was measured by tilting the sample at an angle $\chi = 58$–$59°$. Fig. 3 shows the values of the c/a ratio and the lattice volume, $V_{\rm lattice}, (= (3^{1/2}/2)ca^2)$ as a function of δ for films with 10, 14, and 20at%Pt content. In the fig, the results for Co–14at%Pt films in the very thin film region (from 3 to 20 nm), analyzed by synchrotron radiation grazing incidence XRD method, are also shown. The c/a value decreased as δ decreased for all series of media. This c/a reduction was mainly caused by

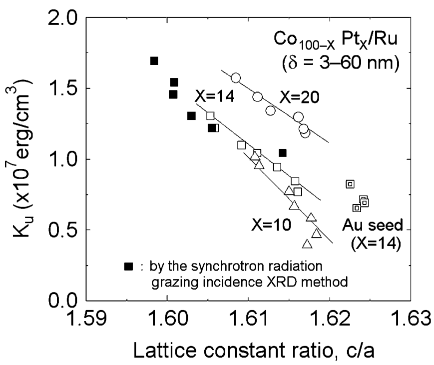

Fig. 4. Relationship between the c/a ratio of the hcp Co–Pt lattice and K_u. Symbols: $X = 20$ (circle), 14 (square), and 10 (triangle).

an increase in the a value (the lattice spacing in the lateral direction), probably due to epitaxial growth of Co–Pt on the Ru layers. The c/a reduction in Co–14at%Pt films reached 1% on decreasing δ from 60 to 3 nm. We expected that increasing the lattice mismatch by reducing the Pt content would enhance the lattice deformation. However, the c/a values for the 10at%Pt films were large relative to the others, which may be related to the formation of a small number of fcc layers in the hcp-lattice. Moreover, it should be noted that $V_{\rm lattice}$ increased significantly, especially in the δ region less than 20 nm. The increase in $V_{\rm lattice}$ for Co–14at%Pt films reached 2% on decreasing δ from 60 to 3 nm. Co–14at%Pt films with Au seed layers showed larger c/a and smaller $V_{\rm lattice}$ compared to films with Ru seed layers.

Fig. 4 shows the relationship between the c/a ratios of the hcp Co–Pt and K_u. The increase in K_u on reducing δ was coincident with a reduction of the c/a ratio. This relationship between the c/a ratio and K_u was qualitatively in good agreement with theoretical predictions [10]–[13]. The rate of increase of K_u with reducing c/a value was slightly larger in series of films with low Pt content; however, no significant difference was found.

Experimental results suggested that the increase in K_u on reducing the thickness was mostly related to a reduction of the hcp Co–Pt lattice c/a ratio. The results for Co–14at%Pt films with Au seed layers are located in the extrapolated area of the $K_u - c/a$ plot for the films with Ru seed layers. We deposited Co–25at%Pt binary alloy films (10-nm thickness) on various seed layer materials, and found [14] that K_u and the c/a ratio showed a greater dependence on the seed layer materials used, and K_u increased significantly as the c/a ratio decreased. This result supports our conclusion. Moreover, it is likely that a huge increase in the lattice volume enhances the increase in K_u on reducing the thickness especially below 10 nm; however, more intensive effort is required to clarify the relationship between the lattice deformation and K_u.

IV. Conclusion

The rate of increase of K_u of Co–Pt films with reducing thickness becomes increasingly large as the Pt content decreases as we expected, and K_u of 2-nm-thick films was almost a constant 2×10^7 erg/cm^3, independent of Pt content in the region from 10 to 30at%Pt. Our results suggest that the increase in K_u on reducing the thickness was mostly related to a reduction of the hcp Co–Pt lattice c/a ratio.

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