Magnetic Anisotropy in Pd/Co Films Evaporated at Oblique Incidence

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The effect of Pd seed layer on the magnetic anisotropy in Cobalt films evaporated at oblique incidence was investigated. The deposition rate of Pd layers R(Pd) was varied from 0.1 to 1.7 Å/s and that of Co layers R(Co) was from 0.1 to 4.5 Å/s. The incidence angle of Pd vapor beam was 30° and that of Co 60°. Negatively large magnetic anisotropy and large coercive force parallel to the incidence plane appeared in Pd/Co films evaporated at low deposition rates of Pd (0.1 Å/s) and Co (0.2 Å/s) and small thicknesses of Pd(100 Å) and Co (about 140 Å) layers. In these films the anisotropy of the reflection coefficient was positive though the magnetic anisotropy was negative. Therefore, it is considered that the negative magnetic anisotropy does not originate from the shape anisotropy of the columnar grains but the magnetocrystalline anisotropy through the textural structure.

§1. Introduction

We have so far investigated the columnar grain structure in obliquely deposited films.[1),2)] The columnar grains in these films incline from the film normal towards the beam direction and generally align in the direction perpendicular to the incidence plane. This alignment of columnar grains was called a bundle of columnar grains by us[3)] or a row of columns by Dirks and Leamy.[4)] We have considered that the columnar grain structure may be modified through the practical preparatory parameters, such as deposition rate,[5)] pressure during deposition,[6)] substrate temperature,[2)] incidence angle[1)] and seed layers.[7)]

Systems like thin films and multilayers of Pd/Co with Co thickness of few monolayer have been intensively studied[8)-14)] due to their special magnetic properties such as perpendicular magnetic anisotropy (PMA) and enhanced magnetic moment at surfaces and interfaces.[15)] However, the origin of PMA and correlation between Pd/Co interface structure and magnetic properties of the system have not been understood completely yet.

On the basis of the result of our preliminary experiment it is expected that the PMA may appear in Pd/Co films with larger thicknesses of Pd and Co layers. In this paper, we prepared Pd/Co films with Co layer thickness of a few hundred Åand investigated the Pd seed effect on the magnetic anisotropy in Co films by comparing the magnetic and optical properties of Pd/Co films with those of Co films.

§2. Experimental details

The Pd/Co films were vapor deposited on glass microscope-slide substrates at the substrate temperature T_S of 293 K. The deposition rate of Pd layer R(Pd) was varied from 0.1 to 1.7 Å/s and that of Co layer R(Co) was from 0.1 to 4.5 Å/s. The nominal thickness of Pd layer t(Pd) was ranged from 40 to 160 Åand that of Co t(Co) from 25 to 500 Å. The incidence angle of Pd vapor beam was 30°, and that of Co 60°. The vacuum system used an oil diffusion pump with a liquid-nitrogen-cooled trap and its base pressure was about 2×10^{-4} Pa. The pressure during evaporation was 4.0×10^{-3} Pa, which was maintained by introducing argon gas automatically through a leak valve. The magnetization measurement was carried out using a vibrating sample magnetometer. The geometrical alignment of Co columnar grains was followed by ellipsometry,[16] where the light source was an He-Ne gas laser and its wavelength was 633 nm.

§3. Results and discussion

In Fig. 1(a), the anisotropy of the remanence $\Delta M_r/M_S$ of Pd/Co films deposited at relatively high rate is shown as a function of t(Co), where ΔM_r is the difference between the remanences in the perpendicular and parallel directions to the incidence plane and M_S is the saturation magnetization. The thickness t(Pd) was set at 100 Å, and the thickness t(Co), the deposition rates R(Pd) and R(Co) were varied in the wide ranges. The value of $\Delta M_r/M_S$ is considered to be a measure of the magnetic anisotropy in cobalt films.[17] The anisotropy $\Delta M_r/M_S$ is positive at t(Co) of 400 Å. With decreasing t(Co) $\Delta M_r/M_S$ decreases drastically below 200 Å and has a minimum at t(Co) of 140 Å. Figure 1(b) shows the coercive forces $H_C(x)$ and $H_C(y)$ of the same films as in Fig. 1(a) where x and y indicate the perpendicular and parallel directions to the incidence plane in the film plane, respectively. The change of $H_C(y)$ corresponds to that of $\Delta M_r/M_S$: $H_C(y)$ has a maximum at $t(\text{Co}) \simeq 140$ Å where $\Delta M_r/M_S$ has a minimum, though $H_C(x)$ is almost constant in the whole t(Co) range. The sign of $(H_C(x) - H_C(y))$ is similar to that of $\Delta M_r/M_S$ indicating that the magnetic easy direction in the film plane is y direction in the range $t(\text{Co}) < 180$ Å and x direction in $t(\text{Co}) > 180$ Å. The easy direction of magnetization in the incidence plane depends on the inclination angle of columnar grains and the relative gaps between them. Therefore, the change in columnar grain structure can be followed by measuring the easy direction.[18] In Fig. 1(c), the angle β, which is the angle of the easy direction from the film plane towards the beam direction in the incidence plane, of the same films in Figs. 1(a) and 1(b) is plotted as a function of t(Co). With decreasing t(Co) the angle β increases and has a maximum at about 100 Å. Figures 2 and 3 show the R(Co) and R(Pd) dependences of (a) $\Delta M_r/M_S$, (b) $H_C(x)$ and $H_C(y)$, and (c) β of the same films in Fig. 1. In Figs. 2 and 3, $\Delta M_r/M_S$ is negatively large, and $H_C(y)$ and β are large in the low R(Co) and R(Pd) ranges. The results obtained in Figs. 1–3 are as follows: (1) The easy directions of magnetization of Pd/Co films deposited at low t(Co), R(Co) and R(Pd) ranges are parallel to the

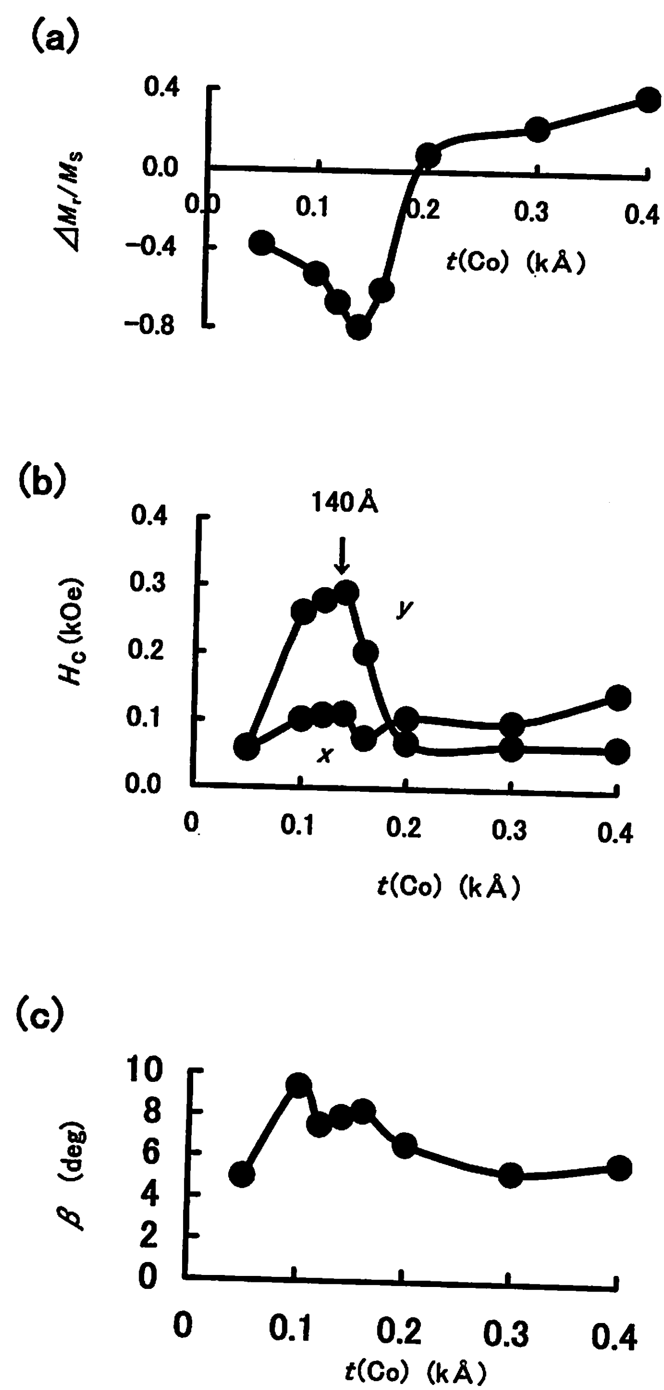

Fig. 1. The t(Co) dependences of (a) the anisotropy of the remanence $\Delta M_r/M_S$, (b) the coercive forces $H_C(x)$ and $H_C(y)$, and (c) the angle β of Pd/Co films evaporated at relatively high deposition rate.

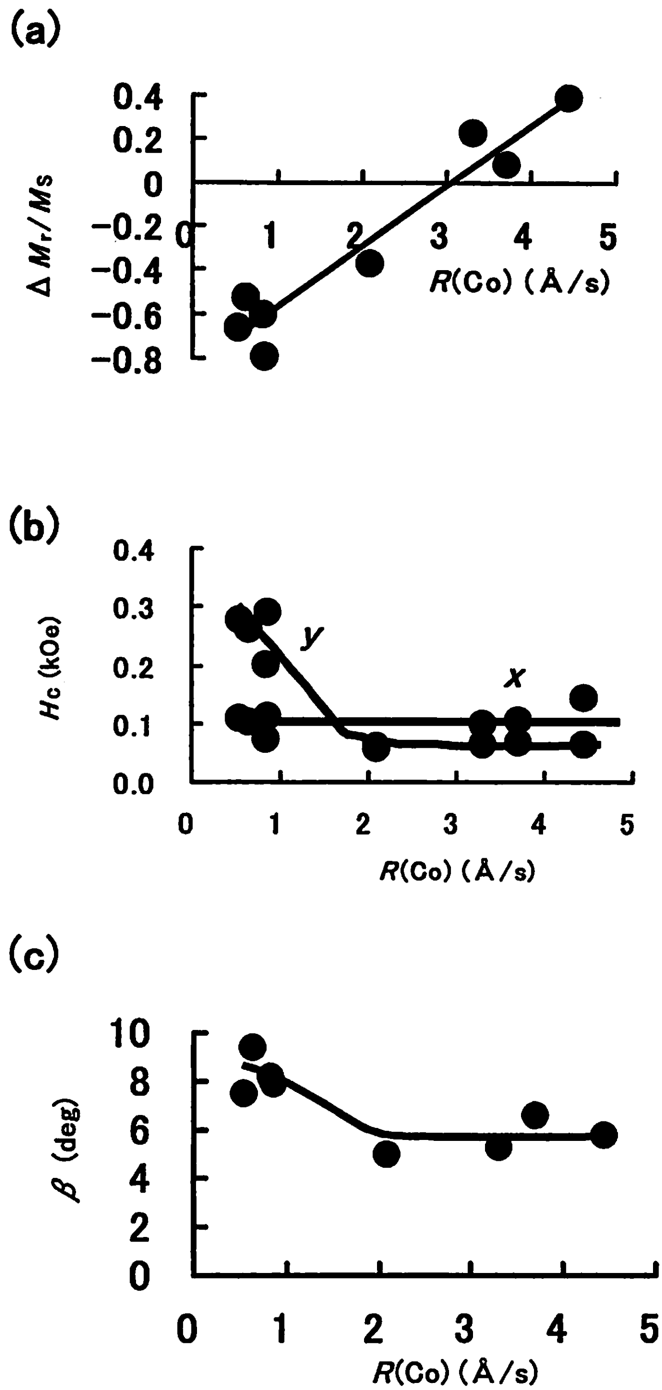

Fig. 2. The R(Co) dependences of (a) $\Delta M_r/M_S$, (b) $H_C(x)$ and $H_C(y)$, and (c) β of the same films in Fig. 1.

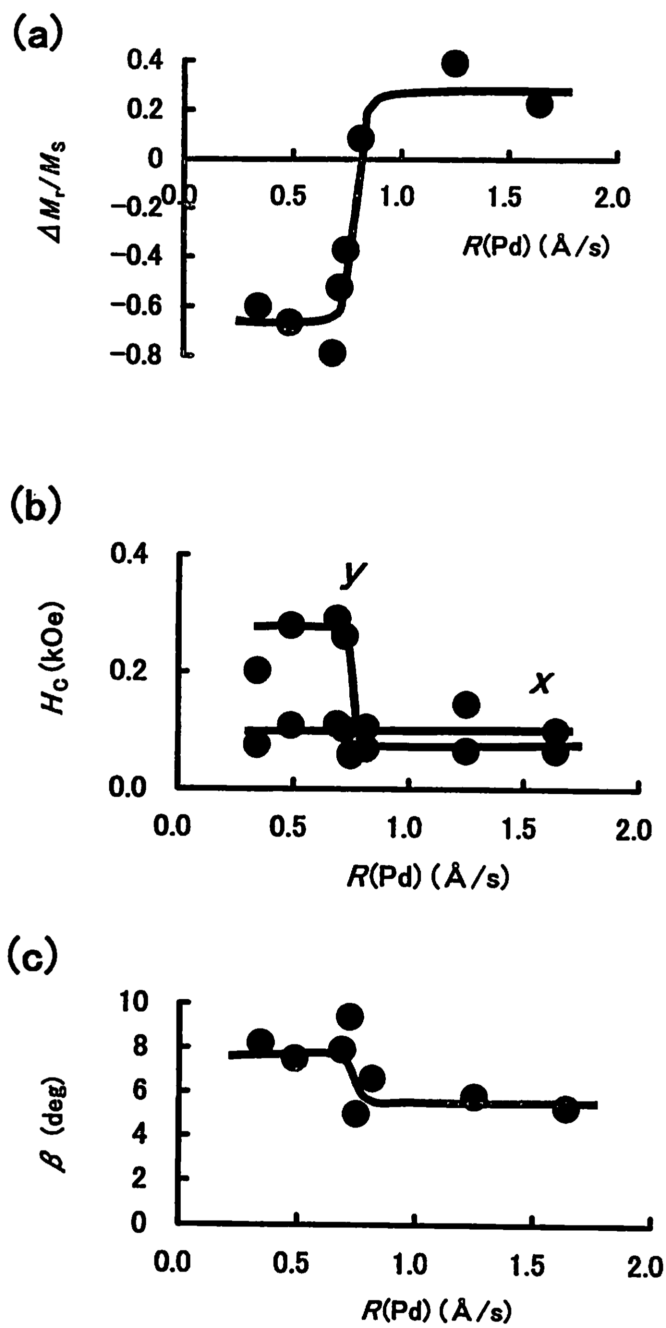

Fig. 3. The R(Pd) dependences of (a) $\Delta M_r/M_S$, (b) $H_C(x)$ and $H_C(y)$, and (c) β of the same films in Figs. 1 and 2.

incidence plane and those at high ones perpendicular to the incidence plane. (2) The angle β and the coercive force $H_C(y)$ in the low t(Co), R(Co) and R(Pd) ranges are larger than those in high ranges.

In order to elucidate the magnetic behavior of Pd/Co films in more detail we prepared Pd/Co films in the relatively lower t(Co), R(Co) and R(Pd) ranges. Figure 4 shows R(Co) dependences of (a) $\Delta M_r/M_S$, (b) $H_C(x)$ and $H_C(y)$, and (c) β of Pd/Co films evaporated at t(Pd) = 100 Å, t(Co) = 140 Å and R(Pd) = 0.7 Å/s. The anisotropy $\Delta M_r/M_S$ is negatively constant in the whole R(Co) range. Both of $H_C(y)$ and β increase monotonically with decreasing R(Co) and has a maximum at R(Co)=0.2 Å/s. Figure 5 shows R(Pd) dependences of (a) $\Delta M_r/M_S$, (b) $H_C(x)$ and $H_C(y)$, and (c) β of Pd/Co films evaporated at t(Pd) = 100 Å, t(Co) = 140 Å and R(Co) = 0.2 Å/s. The R(Pd) dependences of (a) $\Delta M_r/M_S$, (b) $H_C(x)$ and $H_C(y)$, and (c) β in Fig. 5 are similar to the R(Co) dependences of those in Fig. 4: The anisotropy $\Delta M_r/M_S$ is negative constant in the whole R(Pd) range and both of $H_C(y)$ and β increase monotonically with decreasing R(Co) and has a maximum at R(Pd) = 0.1 Å/s. The results in Figs. 4 and 5 indicate that the anisotropy $\Delta M_r/M_S$ is large negative and $H_C(y)$ and β are large at low deposition rates R(Pd) = 0.1 Å/s and R(Co) = 0.2 Å/s.

Finally we compared the magnetic behavior of Pd/Co films with that of Co films evaporated at low deposition rate. The Pd/Co films prepared at R(Pd) = 0.1 Å/s, R(Co) = 0.2 Å/s and t(Co) = 140 Å, and the deposition rate and thickness of Co films are the same as those of Pd/Co films. In Fig. 6 the t(Co) dependences of (a) $\Delta M_r/M_S$, (b) $H_C(x)$ and $H_C(y)$, and (c) β in Pd/Co films are shown with circle (●) and those in Co films with triangle (▲). The anisotropies $\Delta M_r/M_S$ in both films are negative and the magnitude of $\Delta M_r/M_S$ in Pd/Co films (●) is larger than that in Co films (▲) in t(Co) < 200 Å. The coercive force $H_C(y)$ in Pd/Co films (●) is fairly larger than that in Co films (▲) in the whole t(Co) range. The angle β of Pd/Co films (●) is also larger than that of Co films (▲). These results in Fig. 6 suggest that the Pd seed layer effect on the magnetic anisotropy in Co films exists in low R(Pd) and R(Co) regions.

The observed magnetic anisotropy in Co films has so far been analyzed by taking account of the following two anisotropies: (1) The anisotropy of the demagnetizing field due to the shape anisotropy derived from the columnar grain structure.[19] (2) The magnetocrystalline anisotropy through the textural structure.[20] The shape anisotropy due to the columnar grain structure can be detected by ellpsometry. For the geometrically aligned columnar grains the reflection of polarized light depends on the direction of the electric vector. The reflection coefficient is highest when the vector is parallel to the alignment. Figure 7(a) shows the anisotropy of the reflection coefficient $\Delta r/r$ of the same films in Fig. 6 as a function of t(Co), where Δr is the difference between the coefficients in the direction perpendicular and parallel to the incidence plane and r is the average coefficients. The circle (●) and triangle (▲) indicate Pd/Co and Co films, respectively, as in Fig. 6. The positive and negative signs of $\Delta r/r$ indicate the alignment in the perpendicular and parallel to the incidence plane. The anisotropy $\Delta r/r$ of Pd/Co films (●) is positive in the range t(Co) < 300 Å, though $\Delta M_r/M_S$ is negative in the same range as shown in Fig. 6(a).

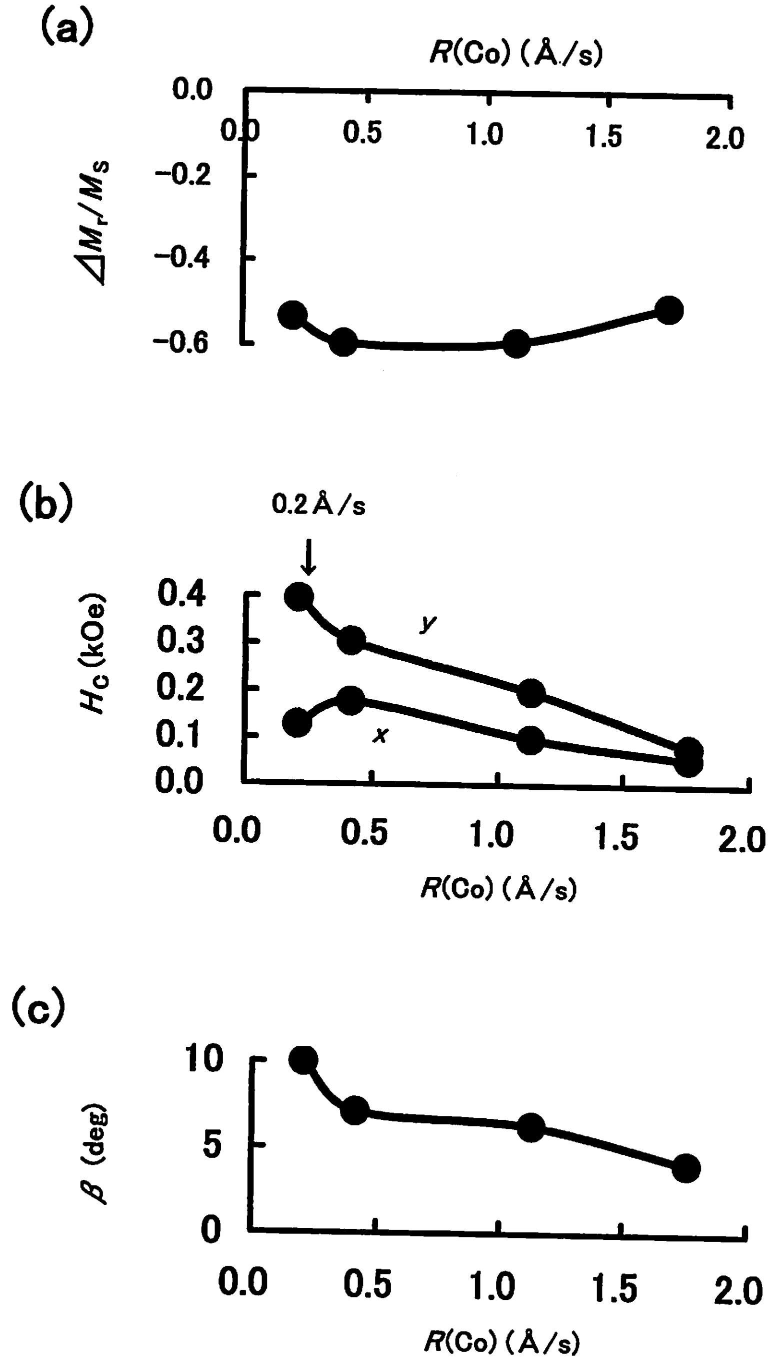

Fig. 4. The R(Co) dependences of (a) $\Delta M_r/M_S$, (b) $H_C(x)$ and $H_C(y)$, and (c) β of Pd/Co films evaporated at t(Pd) = 100 Å, t(Co) = 140 Å and R(Pd) = 0.7 Å/s.

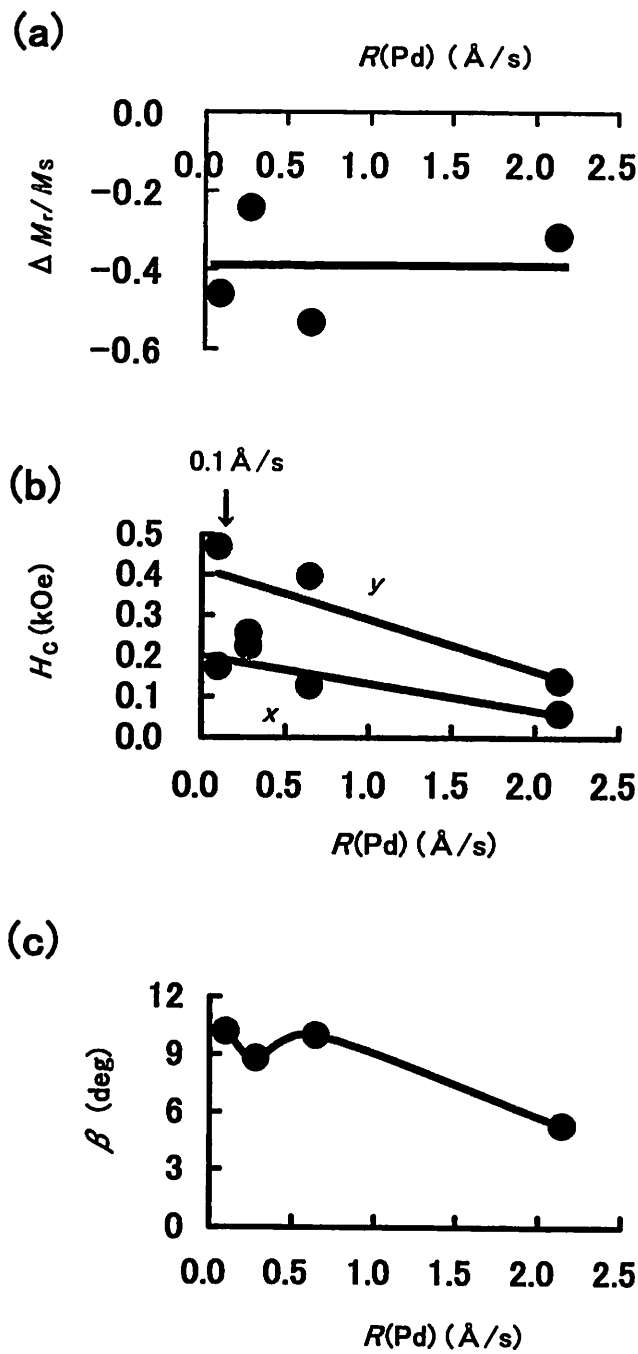

Fig. 5. The R(Pd) dependences of (a) $\Delta M_r/M_S$, (b) $H_C(x)$ and $H_C(y)$, and (c) β of Pd/Co films evaporated at t(Pd) = 100 Å, t(Co) = 140 Å and R(Pd) = 0.2 Å/s.

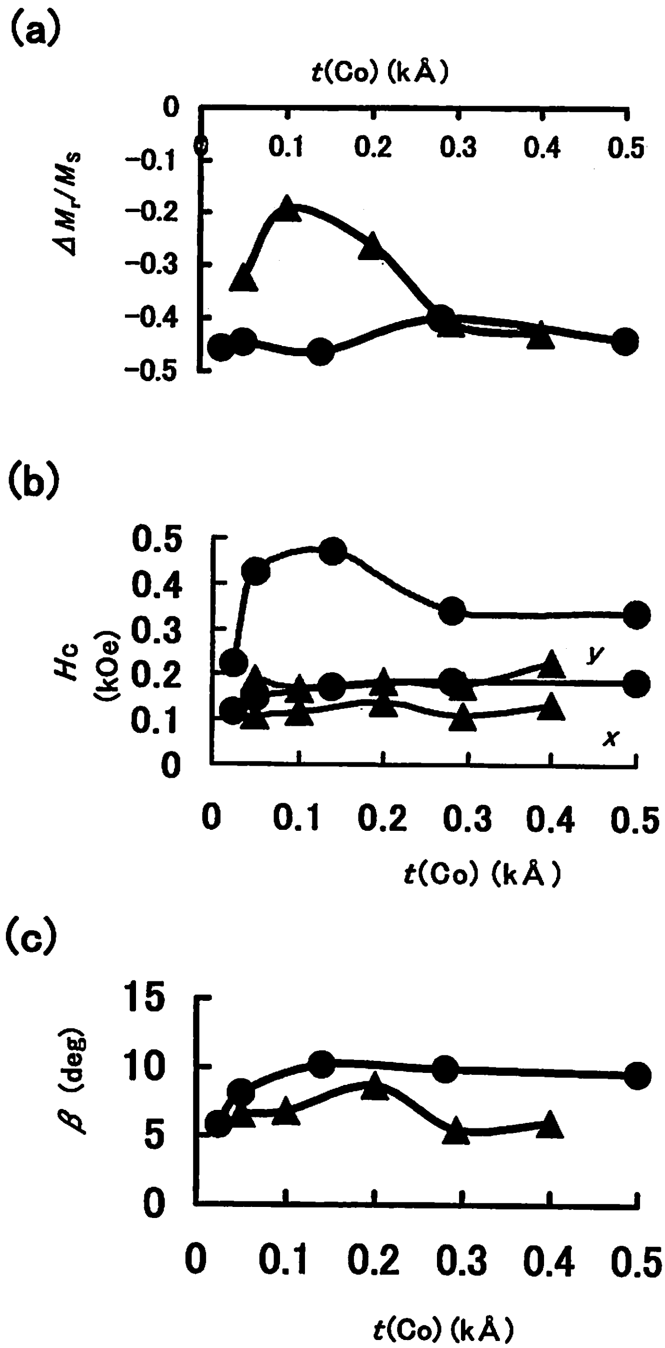

Fig. 6. The t(Co) dependences of (a) $\Delta M_r/M_S$, (b) $H_C(x)$ and $H_C(y)$, and (c) β in Pd/Co films (●) and Co films (▲) evaporated at t(Pd) = 100 Å, R(Pd) = 0.1 Å/s and R(Co) = 0.2 Å/s.

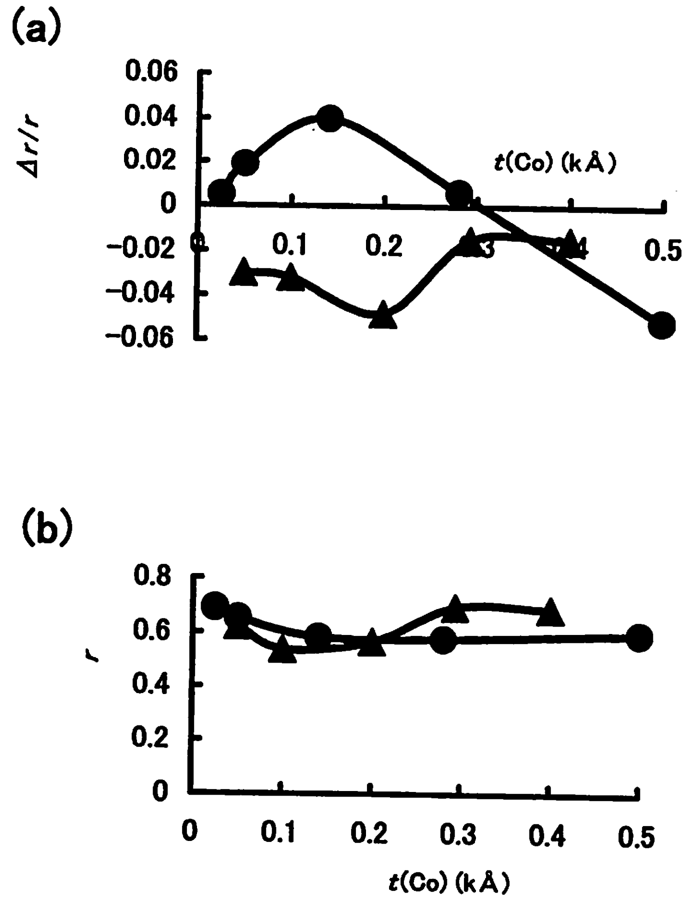

Fig. 7. The t(Co) dependences of (a) the anisotropy of the reflection coefficient $\Delta r/r$ and (b) the average coefficient r of the same films in Fig. 6. The circle (●) and triangle (▲) indicate Pd/Co and Co films, respectively, as in Fig. 6.

This result suggests that the negative magnetic anisotropy in Pd/Co films is not due to the shape anisotropy but the magnetocrystalline anisotropy. On the other hand, $\Delta r/r$ of Co films (▲) is negative in the whole t(Co) range, where $\Delta M_r/M_S$ is also negative as shown in Fig. 6(a). The negative magnetic anisotropy in Co films originates from the shape anisotropy and/or the magnetocrystalline anisotropy. Figure 7(b) is the t(Co) dependence of r of the same films in Fig. 7(a). The average coefficient r is considered to be a measure of the packing density of the columnar grains: the large value of r means the dense packing of the columnar grains. In Fig. 7(b) r of Pd/Co films is constant and almost the same value as that of Co films indicating that the degrees of the packing in both films are the same although the directions of the alignment of the columnar grains are different.

§4. Conclusions

In order to clarify the Pd seed effect on the magnetic anisotropy in Co films, the Pd/Co films were prepared at oblique incidence. The incidence angles of Pd and Co were 30° and 60°, respectively, and the substrate temperature was 293 K. The results obtained are as follows:

(1) The Pd seed effect on the magnetic anisotropy in Co films exists: Negatively large magnetic anisotropy and large coercive forces appear at low deposition rates of R(Pd) = 0.1 and R(Co) = 0.2 Å/s.

(2) The negatively large magnetic anisotropy obtained in Pd/Co films is considered not to originate from the shape anisotropy of the columnar grains but from the magnetocrystalline anisotropy through the textural structure.

In order to elucidate the result (2) further investigation of X-ray analysis etc. is required.

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