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Magnetic Anisotropies of Obliquely Evaporated Co Films

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The magnetic anisotropies of obliquely evaporated Co films were studied using ferromagnetic resonance. The coerceive force (H_c) increases rapidly beyond the incidence angle of $\eta = 60°$. The remanence ratio (M_r/M_s) along the parallel axis at 0° is 0.55–0.7 and comes to a minimum at $\eta = 30$–$60°$. For 1000-Å films deposited at $\eta = 75°$, oblique anisotropy field of $H_{k1} = 4.9$ kOe, in-plane anisotropy field of $H_{k2} = 3$ kOe and tilt angle of $\alpha = 28°$ were observed; this film has $H_c = 800$ Oe and $M_r/M_s = 0.95$.

***Index Terms*—Anisotropy, cobalt, evaporation, ferromagnetic resonance.**

I. Introduction

LARGE coercive forces are obtained by oblique evaporation [1]. The evaporation technique is utilized for the production of the magnetic recording tapes such as Hi8ME and DVC tapes. In the thin film, in-plane anisotropy is known to be induced as well as oblique anisotropy [2], [3].

Magnetic anisotropy is usually determined by torque technique. Also, the anisotropy can be determined by ferromagnetic resonance (FMR). Although Kittel formula is useful to determine the anisotropy [4], the model is inadequate for the vertical plane of thin films because the magnetization direction differs from that of the static field [5]. Therefore, we used strict solutions to analyze FMR data for Hi8ME and DVC tapes [6], [7]. However, the fitting along the tape-width direction is poor. These results suggest introducing in-plane anisotropy is necessary. In this paper, we study two magnetic anisotropies of pure Co films obliquely evaporated.

II. Theoretical

The resonance relation follows the energy method [8]. We assume the film is magnetically saturated. We set up the coordinate system as shown in Fig. 1. The film is in the $x-y$ plane. The attitude of magnetization M is set by the polar angle θ and the azimuth ϕ ; the attitude of magnetic field H is set by the polar angle β and the azimuth ψ. The oblique anisotropy k_1 is in the $x-z$ plane and makes an angle α with respect to the z-axis. We also set the easy axis of in-plane anisotropy (k_2) along the y-axis. Therefore, the free energy per unit volume G is

$$\begin{aligned} G = K_{u1}[&\sin^2\theta(\cos 2\alpha + \sin^2\alpha \sin^2\phi) \\ &- (1/2)\sin 2\theta \sin 2\alpha \cos\phi] - K_{u2}\sin^2\theta \sin^2\phi \\ &- MH[\cos\theta\cos\beta + \sin\theta\sin\beta\cos(\phi-\psi)] \\ &- 2\pi M^2 \sin^2\theta. \end{aligned} \quad (1)$$

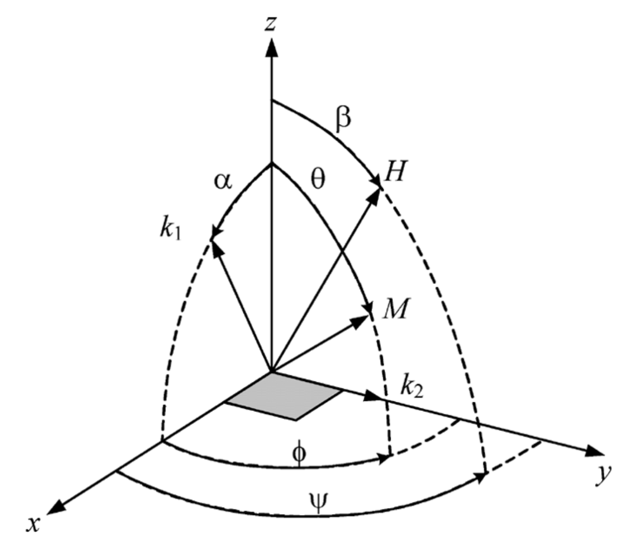

Fig. 1. Geometrical coordinates. The magnetic film is in the $x-y$ plane and the oblique anisotropy k_1 is in the x-z plane and makes an angle of α. In-plane anisotropy k_2 is along the y-axis.

Here, K_{u1} and K_{u2} are oblique anisotropy and in-plane anisotropy constants, respectively. The basic resonance condition is given by

$$\begin{aligned} (\omega/\gamma)^2 = [&(\partial^2 \mathrm{G}/\partial\theta^2) \\ &\times(\partial^2 \mathrm{G}/\partial\phi^2) - (\partial^2 \mathrm{G}/\partial\theta\partial\phi)^2]/M^2\sin^2\theta \end{aligned} \quad (2)$$

where ω and γ denote the angular frequency $(= 2\pi f)$ and gyromagnetic ratio, respectively.

In the vertical plane containing the oblique anisotropy axis $(\Psi = 0)$, the resonance equation is

$$\begin{aligned} (\omega/\gamma)^2 = [&(2K_{u1}/M)\cos(2\theta - 2\alpha) \\ &+ H\cos(\theta-\beta) - 4\pi M\cos 2\theta] \\ &\times\{(2K_{u1}/M)[\sin^2\alpha + (1/2)\cos\theta\sin 2\alpha/\sin\theta] \\ &- (2k_{u2}/M)\sin^2\theta + (H\sin\beta/\sin\theta)\} \end{aligned} \quad (3)$$

with

$$K_{u1}\sin(2\theta - 2\alpha) + MH\sin(\theta-\beta) - 2\pi M^2\sin 2\theta = 0. \quad (4)$$

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In the film plane ($\beta = \pi/2$), the resonance equation is

$$\begin{aligned}(\omega/\gamma)^2 = \{&(2K_{u1}/M)[\cos 2\theta(\cos 2\alpha + \sin^2\alpha \sin^2\phi) \\ &+ \sin 2\theta \sin 2\alpha \cos\phi] - (2K_{u2}/M)\cos 2\theta \sin^2\phi \\ &+ H\sin\theta\cos(\phi-\psi) - 4\pi M\cos 2\theta\} \\ &\times \{(2K_{u1}/M)[\sin^2\alpha\cos 2\phi \\ &+ (1/2)\sin 2\alpha\cos\phi\cos\theta/\sin\theta] \\ &- (2K_{u2}/M)\cos 2\phi + H\cos(\phi-\psi)/\sin\theta\} \\ &- \{(2K_{u1}/M)[\cos\theta\sin^2\alpha\sin 2\phi \\ &+ (1/2)\sin 2\alpha\sin\phi\cos 2\theta/\sin\theta] \\ &- (2K_{u2}/M)\cos\theta\sin 2varphi \\ &+ H\sin(\phi-\psi)\cos\theta/\sin\theta\}^2 \end{aligned} \tag{5}$$

with

$$\begin{aligned}&(2K_{u1}/M)[\sin 2\theta(\cos 2\alpha + \sin^2\alpha\sin^2\phi) \\ &\quad - \cos 2\theta\sin 2\alpha\cos\phi] \\ &\quad - (2K_{u2}/M)\sin 2\theta\sin^2\phi - 2H\cos\theta \\ &\quad \times\cos(\phi-\psi) - 4\pi M\sin 2\theta = 0\end{aligned} \tag{6}$$

and

$$\begin{aligned}&(2K_{u1}/M)(\sin\theta\sin^2\alpha\sin 2\phi + \cos\theta\sin 2\alpha\sin\phi) \\ &\quad - (2K_{u2}/M)\sin\varphi\sin 2\theta + 2H\sin(\varphi-\psi) = 0.\end{aligned} \tag{7}$$

III. Experiment

Co films with thicknesses of 500 Å and 1000 Å were evaporated on glass substrate, which was kept at 150°C. Incidence angle (η) was varied from 0° (normal) to 80°. Oblique anisotropy field ($H_{k1} = 2K_{u1}/M_s$) and in-plane anisotropy field ($H_{k2} = 2K_{u2}/M_s$) were determined by 34 GHz ferromagnetic resonance. The applied static field is rotated in two planes: the plane containing the evaporation-beam direction and the film normal (x-z plane), and the film plane (x-y plane). For fitting of the resonance fields, we used $\gamma/2\pi = 3.11$ GHz/kOe. The in-plane magnetic properties are measured using vibrating sample magnetometer (VSM); the static fields are applied in the film plane. We refer to the x-axis and the y-axis as the parallel (//) axis and transverse axis ($\perp$), respectively, for the VSM measurements (see Fig. 1). The film thicknesses were measured by a scanning white-light interferometer (Zygo, New View 200).

IV. Results and Discussion

The coerceive forces (H_c) in both parallel and transverse axes are shown in Fig. 2. Although H_c at $\eta = 0°$ are 20 Oe for 500 Å, it increases to 230 Oe for 1000 Å. The values remain unchanged until $\eta = 60°$, however, H_c tends to increase slightly for 500 Å and to decrease slightly for 1000 Å. For $\eta = 60°, H_c$ along the parallel axis is larger than that of the transverse axis for 1000 Å film. H_c along the parallel axis upturns at $\eta > 60°$ and reaches 1650 Oe for the $\eta = 80°$. The H_c values of 1000 Å are larger than those of 500 Å films due to the increased crystallite size, which was observed by x-ray diffraction linewidth. With increasing the crystallite size, the average anisotropy increases [9], consequently H_c increases. The H_c values are larger than that obtained by Speliotis *et al.* [1].

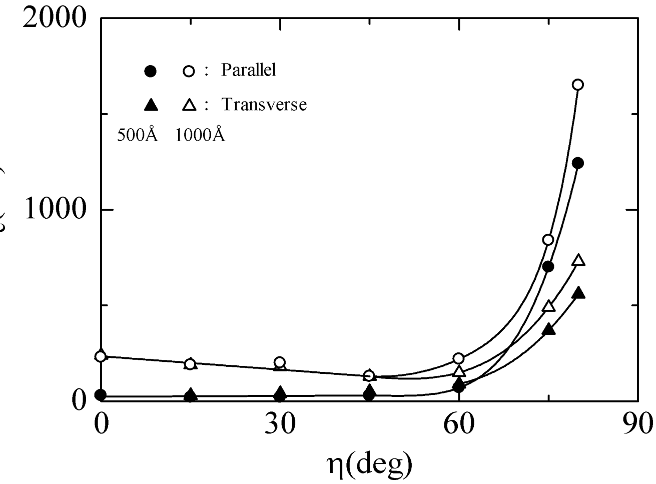

Fig. 2. Variation of coercive force (H_c) with incidence angle (η).

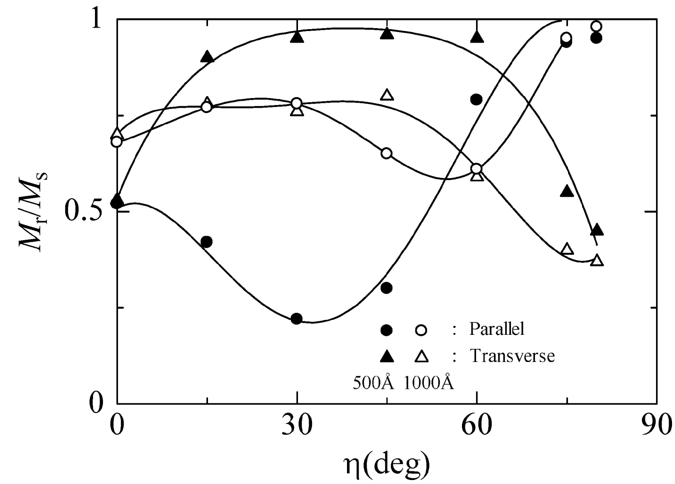

Fig. 3. Variation of remanence ratio (M_r/M_s) with incidence angle (η).

The remanence ratio (M_r/M_s) is 0.55–0.7 at $\eta = 0°$ and initially increases with increasing η as shown in Fig. 3. However, it comes to a minimum between $\eta = 30°$ and 60° for the parallel axis, indicating an easy axis along the transverse axis. At $\eta = 75°$ and 80°, M_r/M_s shows a large value of 0.95, indicating a large anisotropy along the parallel axis. The change in M_r/M_s is explained by an apparent anisotropy in the film plane as was observed using torque measurements by Tasaki *et al.* [3]. The apparent in-plane anisotropy was observed to be along the transverse axis for $\eta < 45°$ and is along the parallel axis for $\eta > 45°$. However, in our films, the apparent anisotropy is not large for 1000 Å films with $\eta < 45°$, because the difference in M_r/M_s between the parallel and transverse axes is small for 1000 Å films compared with 500 Å films. The saturation magnetization (M_s) is 1400 G at $\eta = 0°$ and decreases with increased η ; at $\eta = 75° M_s$ drops to 700–800 G as shown in Fig. 4. The decrease in M_s is due to self-shadowing effect [10]; consequently, spacing between columns and/or obliquely-stacked scales increases with η.

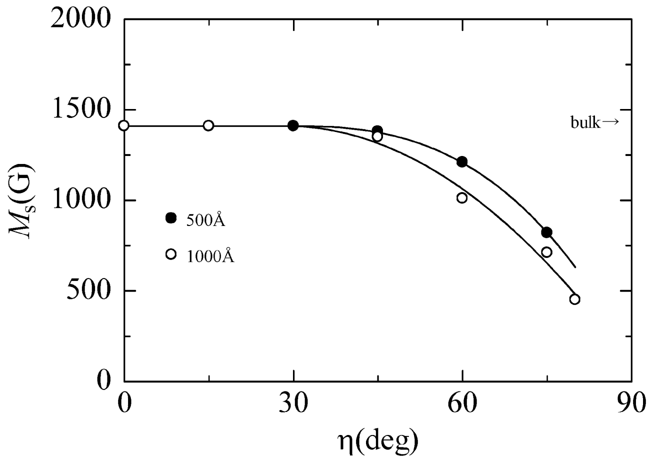

Fig. 4. Variation of saturation magnetization (M_s) with incidence angle (η).

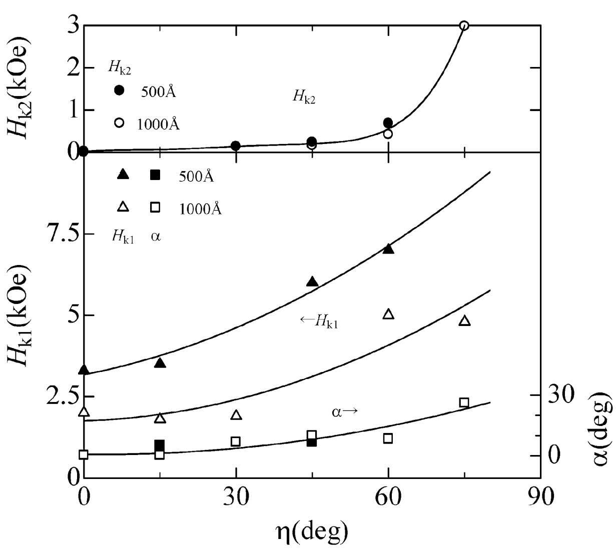

Fig. 5. Variation of anisotropy fields (H_{k1}, H_{k2}) and tilt angle (α) with incidence angle (η).

Fig. 5 shows the anisotropy fields (H_{k1}, H_{k2}) and tilt angle (α) as a function of incidence angle η. The $\eta = 0^\circ$ film has a perpendicular anisotropy field $(H_{k1} = 2K_{u1}/M_s)$ of 2–3 kOe. The tilt angle α increases slightly with increasing angle η. H_{k2} is as small as 0.1 kOe for $\eta =$ 30–45°. However, small H_{k2} strongly influences M_r/M_s value because α is small. The effects of H_{k1} and H_{k2} to the in-plane magnetization are comparable. Note that the 1000 Å films have smaller H_{k1} than the 500 Å films, resulting in the smaller difference in M_r/M_s for 1000 Å films. Although H_{k2} increases to 0.5 kOe at $\eta = 60^\circ, H_{k1}$ also increases; consequently the films become close to apparently isotropic in the film plane $(M_r/M_s \sim$ 0.6–0.9$)$ as was observed [3]. Torque measurements were done in the film-plane; apparent anisotropy in the film plane becomes zero at around $\eta = 45^\circ$ [3]. For $\eta > 60^\circ, H_{k1}$ increases to ~5 kOe and α increases to 28° for the $\eta = 75^\circ$ film. The anisotropies are due to an obliquely-stacked-scale structure similar to the one observed in Hi8ME [6]. The behavior of H_{k2} is the same that reported by Keitoku [10], however, our values are smaller than those by Keitoku. We could not obtain clear FMR signals for the $\eta = 80^\circ$ films. We estimate the easy axis is not clearly fixed to a direction during the film growth. Further study of thickness dependence of the magnetic properties is needed.

V. Conclusion

Oblique anisotropy field H_{k1} as well as in-plane anisotropy field H_{k2} were determined by FMR. H_c is small for $\eta = 0^\circ$ and perpendicular anisotropy of $H_{k1} =$ 2–3 kOe was induced. H_c and H_{k1} increase rapidly beyond $\eta > 60^\circ$. For the 1000 Å film by an incident angle of $\eta = 75^\circ, H_{k1} = 5$ kOe, $H_{k2} = 3$ kOe and $\alpha = 25^\circ$ were observed.

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