INCIDENT ANGLE DEPENDENCE OF MAGNETIC PROPERTIES OF VACUUM DEPOSITED Co-Cr FILMS

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ABSTRACT--- Investigated was incident angle and substrate temperature dependence of magnetic properties of continuously vacuum deposited Co-Cr films. Initial incident angle ranged from 50 to 90 degrees and substrate temperature ranged from 30 to 290°C. Analyses of hysteresis loops and torque curves showed that the easy axis corrected with the demagnetization field inclined from the film normal toward the film plane in the incidence plane and that the magnetic anisotropy field of the films deposited at oblique incidence decreased with increasing substrate temperature. X-ray analysis and TEM observation showed that the magnetocrystalline anisotropy was dominant in low incident angle region and the shape magnetic anisotropy was dominant in high incident angle region. The estimation of packing factor of the films showed that the self shadowing effect promoted separation between columnar grains with decreasing substrate temperature.

INTRODUCTION

Magnetic properties and read/write characteristics of continuously vacuum deposited Co-Cr films much depend on incident angle of vapor beam to substrates [1,2].

Co-Cr films deposited at normal incidence to substrates have strong orientation of hcp c-axis in direction of the film normal and large perpendicular magnetic anisotropy [3]. These films with perpendicular anisotropy have excellent read/write performance in high linear recording density region and have such waveform as the di-pulse waveform [4,5]. The Co-Cr films deposited at incident angle from 55 to 20 degrees have higher reproduced voltage in low linear density region than the films with perpendicular anisotropy, maintaining the high read/write performance in high linear density region, having single pulse waveform with narrow width. And, for the films deposited at incident angle from 70 to 20 degrees, the

reproduced voltage in low linear density region is further high but the high read/write performance is lost in high linear density region [2,6].

The incident angle dependence of the magnetic anisotropy of the films is important to understand the results mentioned above. In the recent paper of the author et al [7], reported was the relation between incident angle and magnetic properties of Co-Cr films deposited on a substrate in a standstill. The easy axis inclines from the film normal toward the film plane with increasing incident angle. Not only the magnetocrystalline anisotropy but also the shape magnetic anisotropy contributes to the magnetic anisotropy of the films deposited at oblique incidence. For the Co-Cr film deposited at incident angle changing continuously from 70 to 40 degrees, magnetic properties are influenced by initial film growth region at incident angle above 60 degrees.

In this paper, reported is the relation between incident angle and the magnetic anisotropy of the

films deposited at incident angle changing continuously. Initial incident angle is extended up to 90 degrees. And, further reported is substrate temperature dependence of the magnetic properties of the films deposited at incident angle from 70 to 40 degrees.

EXPERIMENTAL

Co-Cr films were prepared with a web-coater type continuous vacuum deposition system which was equipped with a 270 degrees deflection type electron beam evaporator and a cylindrical can to support a substrate during deposition. The films were deposited on polyimide films of $10\mu\text{m}$ in thickness which were transported around the cylindrical can. Deposition rate was about $0.2\mu\text{m/s}$ and thickness was about $0.2\mu\text{m}$. Incident angle to the substrate, ϕ , was changed continuously from initial incident angle, ϕ_i , to final incident angle, ϕ_f . ϕ was defined with angle between incidence vapor beam and the film normal of the substrate. Substrate temperature was determined by Tcan which was measured at the surface of the can and ranged from 30 to 290°C .

Hysteresis loops were measured with the vibrating sample magnetometer (VSM). Torque curves were measured with the torque magnetometer in the film

Fig.1 Illustration of anisotropy fields.

plane and in the incidence plane to investigate on the magnetic anisotropy of the films. In Fig.1, the magnetic anisotropy fields estimated are shown schematically, where β is the angle between the easy axis of the film and the film plane, H_k is the anisotropy field in the film plane, H_{k1} is the anisotropy field corrected with the demagnetization field and α is the angle between the direction of H_{k1} and the film normal [8]. Microstructure of cross-section of the films was observed with the transmission electron microscopy (TEM). Crystallographic orientation was researched using the X-ray Shulz method [9].

RESULTS AND DISCUSSION

Incident angle dependence of magnetic properties

Fig.2 shows incident angle dependence of the perpendicular coercivity, $H_{c\perp}$, the in-plane coercivity parallel to the machine direction (MD), $H_{c\parallel}$, and

Fig.2 Incident angle dependence of $H_{c\perp}$, $H_{c\parallel}$ and $M_{r\parallel}/M_s$.

ratio of the residual magnetization in the MD to the saturation magnetization, M_r/M_s . The range of the incident angle are as follows. The couples of (ϕ_i, ϕ_r) are (50,20), (60,30), (70,30) and (90,50). All films were deposited at substrate temperature of 270°C. M_s ranged from 430 to 570kA/m. $H_{c\perp}$ increases slightly with increasing ϕ_i . $H_{c\parallel}$ and M_r/M_s increase steeply with increasing ϕ_i up to 70 degrees and are nearly constant above 70 degrees.

Fig.3 shows torque curves in the film plane (a) and in the incidence plane (b) of the film deposited at incident angle from 70 to 30 degrees. ϕ is angle of

Fig.3 Torque curves in the film plane (a) and in the incidence plane (b).

applied field from the transverse direction (TD) in Fig.3(a) and from the film normal ($\perp$) in Fig.3(b). In Fig.3(a), the easy axis in the film plane is parallel to the MD. In Fig.3(b), the easy axis of the film rises from the film plane by about 10 degrees (β).

Fig.4 shows incident angle dependence of H_k , H_{k1} , β and α . H_k increases with increasing ϕ_i . β decreases with increasing ϕ_i . α increases steeply with increasing ϕ_i up to 70 degrees. H_{k1} is considerably large at $\phi_i=50$ and decreases steeply with increasing ϕ_i and increases again above $\phi_i=70$.

To research the relation between the incident angle dependence of the magnetic anisotropy mentioned above and the crystallographic orientation, X-ray analysis was carried out with the Shulz method.

Fig.5 shows distribution of hcp c-plane of the Co-Cr films deposited at each incident angle condition. For the film deposited at incident angle from 50 to 20 degrees hcp c-axis is oriented to the film normal.

Fig.4 Incident angle dependence of H_k , H_{k1} , β and α .

Fig.5 Distribution of hcp c-plane in the incidence plane.

The dispersion of the distribution of hcp c-plane increases with increasing incident angle. At $\phi_i = 50^\circ$ the strong magnetic anisotropy is due to the magnetocrystalline anisotropy.

Substrate temperature dependence of magnetic properties

Fig.6 shows can temperature dependence of $H_{c\perp}$, $H_{c\parallel}$ and M_r/M_s of the films deposited at incident angle from 70 to 40 degrees. The can temperature, T_{can} , defines the substrate temperature. The saturation magnetization and the thickness of the films in Fig.6 ranged from 410 to 510 kA/m and from 0.15 to 0.19 μm , respectively. M_r/M_s decreases with increasing T_{can} . $H_{c\perp}$ and $H_{c\parallel}$ have the tendency to decrease with increasing T_{can} in the region of low T_{can} . This tendency differs very much from the

substrate temperature dependence of the coercivity of the films with perpendicular anisotropy. It is understood that the coercivity of the films deposited at normal incidence causes the segregation of Cr atoms into the columnar grain boundary and the segregation is promoted with increasing substrate temperature during deposition [1]. For the films deposited at oblique incidence, it is inferred that the spatial separation between the columnar grains plays the same role as the segregation of Cr atoms causing the magnetic insulation and that the self shadowing effect promoted the spatial separation with decreasing substrate temperature during deposition.

Fig.7 shows can temperature dependence of H_k , H_{k1} , β and α . β is nearly constant and is about 10 degrees. H_k , H_{k1} and α decrease with increasing T_{can} . It is supposed that the substrate temperature dependence of the magnetic anisotropy is reflected from the spatial separation between the columnar

Fig.6 Can temperature dependence of $H_{c\perp}$, $H_{c\parallel}$ and M_r/M_s .

Fig.7 Can temperature dependence of H_k , H_{k1} , β and α .

grains, the inclination of the columnar grains and/or the crystallographic orientation [10,11].

TEM observation

Fig.8 shows cross-sectional TEM views of the films. The film in Fig.8(a) was deposited at ϕ from 90 to 50 degrees and T_{can} of 270°C, the film in Fig.8(b) from 70 to 40 degrees and 30°C and the film in Fig.8(c) from 70 to 40 degrees and 290°C. All films are composed of curved columnar grains. Inclination from the film normal of the columnar grains in Fig.8(a) is larger than those in Figs.8(b) and (c). In Figs.8(b) and (c), it seems that the inclination does not change with increasing substrate temperature from 30 to 290°C.

For the three films referred in Fig.8, packing factor was estimated. The packing factor was defined with ratio $\delta_{ICP}/\delta_{TEM}$, where δ_{ICP} was the temporary thickness estimated using results of the inductively coupled

(a) $\phi = 90^\circ - 50^\circ$, $T_{can} = 270^\circ\text{C}$

(b) $\phi = 70^\circ - 40^\circ$, $T_{can} = 30^\circ\text{C}$

(c) $\phi = 70^\circ - 40^\circ$, $T_{can} = 290^\circ\text{C}$

Fig.8 Cross-sectional TEM views of films. 0.1 μm

plasma atomic emission spectrometry (ICP-AES) on the assumption that the packing factor was 1 and δ_{TEM} was the thickness obtained by TEM observation of cross-section of the films. $\delta_{ICP}/\delta_{TEM}$ is shown in Table 1. The value of $\delta_{ICP}/\delta_{TEM}$ shows that there is large spatial gap between the columnar grains and that the gap is fairly large especially in the film deposited at low substrate temperature.

Considering the results mentioned above in the magnetic anisotropy of the films deposited at oblique incidence, contribution of the shape magnetic anisotropy is considerably large owing to the spatial separation between the columnar grains because of the self shadowing effect. In order to estimate for each contribution of the magnetocrystalline anisotropy and the shape magnetic anisotropy to the anisotropy

Table 1 Estimation of packing factor of films referred in Fig.8.

films	Fig.8(a)	Fig.8(b)	Fig.8(c)
δ_{ICP}	155nm	146nm	137nm
δ_{TEM}	176nm	184nm	154nm
$\delta_{ICP}/\delta_{TEM}$	0.88	0.79	0.89

of the film, it is needed more detailed investigation on the crystallographic orientation and the morphology of the films [12,13]. Using the films with the oblique magnetic anisotropy for the magnetic recording media, it is necessary to understand the relation between the magnetic anisotropy and magnetic field of heads [6].

SUMMARY

Incident angle and substrate temperature dependence of magnetic properties of the continuously vacuum deposited Co-Cr films were investigated. The results are as follows.

The magnetocrystalline anisotropy is dominant for the films deposited at low incident angle, while the shape magnetic anisotropy is dominant for the films deposited at high incident angle.

For the films deposited at incident angle from 70 to 40 degrees, the magnetic anisotropy field of the films deposited at low substrate temperature was larger than that of the films deposited at high substrate temperature, because the self shadowing effect promoted spatial separation between the columnar grains with decreasing substrate temperature.

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