MAGNETIC PROPERTIES OF VACUUM EVAPORATED Co-O THIN FILM FOR PERPENDICULAR MAGNETIC RECORDING MEDIA

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Abstract

A study of the microstructure of and the origin of magnetic anisotropy in evaporated Co-O thin film has been carried out. It was found that the strong perpendicular magnetic anisotropy of Co-O thin film can be attributed to the magnetocrystalline anisotropy along the c-axis preferred orientation of Co and the shape anisotropy of each Co particle.

INTRODUCTION

We previously reported the magnetic properties and the recording and playback characteristics of a perpendicular magnetic film of Co-O prepared by evaporation [1][2]. The Co-O thin film, prepared using a high deposition rate of 3000 Å/s and a high incident angle of $20^\circ < \theta < 40^\circ$, exhibits good recording and playback characteristics in the short wavelength region. It is widely considered that a columnar structure is essential if a perpendicular magnetic recording medium is to have good recording and playback characteristics [3][4]. The columnar structure observed in the previously reported Co-O thin film [4] was not so clear as that of the CoCr thin film, however, so, the good recording and playback characteristics of the Co-O thin film may be attributed to the strong perpendicular magnetic anisotropy of the film.

In this paper, we report the results of a systematic study of the origin of the magnetic anisotropy of Co-O thin film.

EXPERIMENTAL PROCEDURE

The Co-O thin films investigated in

this work were deposited by electron-beam evaporation from an ingot of Co onto a polyamide substrate in a continuously varying incident angle vacuum coater. The minimum and the maximum angle of incidence were 20° and 40° , respectively. During the deposition, Co was partially oxidized by oxygen gas introduced into the vacuum chamber, and the composition of the films was controlled by the flow rate of the oxygen gas. The average deposition rate was 3000 Å/s and the thickness of the films was maintained at 2000 Å.

The crystal structure of the film was observed using a transmission electron microscope, TEM. A cross section sample for TEM was cut down to about 300 Å in thickness by ultramicrotomy in a plane normal to the film and along the direction of deposition. The magnetic anisotropy constant was measured by the torque magnetometer in the temperature range between -196°C and 242°C .

RESULTS AND DISCUSSION

A. Microstructural characterization

Figures 1(a) and 1(b) are TEM micrographs of the Co-O thin film, showing a dark field image of a cross section and electron diffraction pattern from the cross section, respectively. The

Co-O thin film consisted of h.c.p. Co and CoO fine crystallites less than 100 Å in diameter. The film developed a curved and slanted columnar structure which is not so clear as that of CoCr thin film [5][6] or that of the magnetic film of ME tape [7][8]. The columnar axis of the film is about 18° at the center of the film. The tangent rule [9], which connects the columnar axis with the incidence direction, is valid for the present Co-O thin film. As shown in Fig.1(b), the electron diffraction pattern from the cross section shows that the Co (00·2) reflections are clustered in arcs oriented along the columnar axis, indicating a c-axis crystallographic preferred orientation along that direction. From Fig.1(b), the angle of the c-axis preferred orientation is estimated to be about 19°.

From these results, we suppose that magnetocrystalline anisotropy exists along the c-axis preferred orientation of Co in the Co-O thin film.

Fig. 1 (a) Dark field image of a cross section.
(b) Electron diffraction pattern from the cross section.

B. Magnetic properties

Figure 2 shows the torque curves measured at various temperatures between -196°C and 242°C. In these measurements, a magnetic field of 15 KOe was applied in

Fig. 2. Torque curves measured at various temperature between -196°C and 242°C.

a plane normal to the film and along the direction of deposition. In this figure, θ represents the angle between the normal of the film and the direction of the applied field. As shown in Fig.2, the torque curves are not saturated below room temperature and a rotational hysteresis loss appears on the lowering of the temperature. This phenomenon is caused by exchange anisotropy [10], which results from an exchange interaction between the antiferromagnetic CoO and the ferromagnetic Co, and appears below the Néel temperature, T_N [11], of CoO.

In order to analyze the torque curves of the present Co-O thin film, a new method is adopted in this paper. When intrinsic perpendicular magnetic anisotropy is not exactly normal to the film plane, magnetic anisotropy energy, E_A , may be written as

$$E_A = K_I^* \cdot \sin^2(\theta - \alpha) + 2\pi M_s^2 \cdot \cos^2 \theta \quad (1)$$

The torque, L , is then

$$L = -K_I^* \cdot \sin 2(\theta - \alpha) + 2\pi M_s^2 \cdot \sin 2\theta \quad (2)$$

where K_I^* is the intrinsic perpendicular anisotropy energy, $2\pi M_s^2$ is the shape anisotropy energy of the film and α is the angle between the orientation of K_I^* and the normal of the film. From equation (2), the torque L at $\theta = 45^\circ$, $L(\theta = 45^\circ)$, and at $\theta = 90^\circ$, $L(\theta = 90^\circ)$, are expressed, respectively, as

$$L(\theta = 45^\circ) = -K_I^* \cdot \cos 2\alpha + 2\pi M_s^2 \quad (3)$$

and

$$L(\theta = 90^\circ) = -K_I^* \cdot \sin 2\alpha \quad (4)$$

From these two relations, K_I^* and α are given by

$$K_I^* = - \frac{L(\theta = 90^\circ)}{\sin 2\alpha} \quad (5)$$

and

$$\alpha = \frac{1}{2} \left[\tan^{-1} \left\{ \frac{L(\theta = 90^\circ)}{L(\theta = 45^\circ) - 2\pi M_s^2} \right\} \right] \quad (6)$$

Therefore, K_I^* and α of a sample are determined by the values of $L(\theta = 45^\circ)$ and $L(\theta = 90^\circ)$ measured from the corresponding torque curve.

The values of K_I^* obtained at various temperatures are found in Fig.3, where they can be compared with the temperature dependence of the magnetocrystalline anisotropy energy, K_{u1}^* , which is estimated from K_{u1} of Co [12] in proportion to the volume fraction of Co in the film, that is equivalent to the ratio of M_s of the film to that of Co. As you can see from Fig.3, the temperature dependence of K_I^* , which decreases with increasing temperature, is suggestive of the existence of magnetocrystalline anisotropy. At the same time, another form of magnetic anisotropy should be considered in addition to the magnetocrystalline anisotropy, because the value of K_I^* at the room temperature, $3.01 \times 10^6 \text{ erg/cm}^3$, is larger than the estimated K_{u1}^* , $2.01 \times 10^6 \text{ erg/cm}^3$.

Fig. 3. Temperature dependence of K_I^* and K_{u1}^*

Figure 4 shows the temperature dependence of α and an easy axis direction, θ_E , measured from the torque curve. Though θ_E increases with increasing temperature, α is only slightly dependent on temperature. That is to say, the orientation of the intrinsic perpendicular anisotropy is almost constant. The value of α at room temperature is 15° , which on the whole

agrees with the angle of the columnar axis and the c-axis preferred orientation.

Based on these results, we conclude that the intrinsic perpendicular anisotropy of the Co-O thin film consists of the magnetocrystalline anisotropy of Co along the c-axis preferred orientation and another anisotropy possibly along the columnar axis.

Fig. 4. Temperature dependence of α and θ_E .

When the intrinsic perpendicular anisotropy energy K_I^* is assumed to be composed of the magnetocrystalline anisotropy energy K_{u1}^* along the c-axis preferred orientation and unknown magnetic anisotropy energy K' , the total magnetic anisotropy energy E_A^* may be written as

$$E_A^* = K_{u1}^* \cdot \sin^2(\theta - \gamma) + K' \cdot \sin^2(\theta - \beta) \quad (7)$$

and then

$$\frac{\partial E_A^*}{\partial \theta} = K_{u1}^* \cdot \sin 2(\theta - \gamma) + K' \cdot \sin 2(\theta - \beta) \quad (8)$$

where β is the direction of K' and γ is the direction of K_{u1}^* , that is 19° . Figure 5 shows the definition of the angle α , β and γ as the angle between the normal of the film and the orientations of K_I^* , K' and K_{u1}^* , respectively. Since the intrinsic easy axis is α , as mentioned above, E_A^* is minimized at $\theta = \alpha$ and maximized at $\theta = \alpha + 90^\circ$. The maximum value of E_A^* is K_I^* . These two conditions can be

expressed from equation (7) and (8) as

$$K_{u1}^* \cdot \sin 2(\alpha - \gamma) + K' \cdot \sin 2(\alpha - \beta) = 0 \quad (9)$$

and

$$K_{u1}^* \cdot \cos^2(\alpha - \gamma) + K' \cdot \cos^2(\alpha - \beta) = K_I^* \quad (10)$$

From these two relations, K' and β are given by

$$K' = \frac{K_I^* - K_{u1}^* \cdot \cos^2(\alpha - \gamma)}{\cos^2(\alpha - \beta)} \quad (11)$$

and

$$\beta = \alpha - \tan^{-1} \left[\frac{1}{2} \left\{ \frac{K_{u1}^* \cdot \sin 2(\alpha - \gamma)}{K_{u1}^* \cdot \cos^2(\alpha - \gamma) - K_I^*} \right\} \right] \quad (12)$$

Therefore, K' and β are determined by the value of K_I^* , K_{u1}^* and α shown in Fig.3 and 4, and γ .

Fig. 5. Definition of the angle α , β and γ .

The temperature dependence of K' and β is found in Fig.6 and 7, respectively. As can be seen from these figures, both K' and β are only slightly depend on temperature. The value of β at room temperature is about 5° . The orientation of K' seems to be more perpendicular to the film than the c-axis preferred orientation.

Consequently, we can conclude that K' is either the shape anisotropy of each Co particle or that of the column composed of Co and CoO fine crystallites. The value of K' at the room temperature, $1.23 \times 10^6 \text{ erg/cm}^3$, can be explained either by the shape anisotropy of a ellipsoidal

Co particle whose dimensional ratio is about 1.7 or that of a ellipsoidal column whose dimensional ratio is about 8.0. Neither of these two propositions may be discounted, judging from Fig.1(a).

Fig. 6. Temperature dependence of K_{u1}^* , K' and $2\pi M_s^2$.

Fig. 7. Temperature dependence of β , γ and θ_E .

In order to understand the origin of the magnetic anisotropy of the Co-O thin film, it should be clarified whether the smallest indivisible unit of

magnetization corresponds to a Co particle or to the column as a whole. If the magnetic moment of a Co particle can act independently, the shape anisotropy is due to the Co particle. On the other hand, if the magnetic moment of a Co particle is coupled, the unit of magnetization should be regarded as referring to the column, and the shape anisotropy due to the column.

Figure 8 shows the saturation magnetization dependence of K_i^* and K' . Both K_i^* and K' increase linearly with increasing saturation magnetization, M_s , up to 750emu/cc. If the shape anisotropy is due to the column, K' is proportional to M_s^2 , as is well known. The increasing of M_s of the Co-O thin film, which is composed of Co and CoO fine crystallites, is equivalent to an increase of in the volume fraction of Co. Then, if the shape anisotropy is due to the Co particles, the anisotropy energy per unit volume, K' , should increase linearly with increasing M_s , on the condition that the dimensional ratio of the Co particles does not depend on M_s at all. Therefore, temperature-independent anisotropy, K' , of the Co-O thin film may be attributed to the shape anisotropy of each Co particle. This inference may also be supported by

Fig. 8. Saturation magnetization dependence of K_i^* and K' .

the fact that the columnar structure in the Co-O thin film is not clear and the fact that the orientation of the shape anisotropy is more perpendicular than the columnar axis.

Consequently, we can conclude that the origin of the strong perpendicular magnetic anisotropy of the present Co-O thin film can be attributed to the magnetocrystalline anisotropy of Co along the c-axis preferred orientation and the shape anisotropy of each Co particle. The columnar structure in the film does not seem to play a significant role in the perpendicular magnetic anisotropy of the Co-O thin film.

CONCLUSION

The perpendicular magnetic anisotropy of the Co-O thin film can be attributed to the magnetocrystalline anisotropy of Co along the c-axis preferred orientation and the shape anisotropy of each Co particle.

Total intrinsic perpendicular magnetic anisotropy energy, K_i^* , of the Co-O thin film of M_s 660emu/cc is 3.01×10^6 erg/cm³ at room temperature. About two-thirds of K_i^* is derived from the magnetocrystalline anisotropy energy, K_u^* , and the rest is derived from the shape anisotropy energy, K' , of each Co particle. The values of K_u^* and K' at room temperature are 2.01×10^6 erg/cm³ and 1.23×10^6 erg/cm³, respectively.

Consequently, the columnar structure in the present Co-O thin film does not play a significant role in the perpendicular magnetic anisotropy of the film.

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