MAGNETIZATION REVERSAL MECHANISM IN CoCr MEDIA FOR PERPENDICULAR RECORDING

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Abstract: It has recently been shown[1] that hysteresis loss as a function of the direction of the applied field can be used as a criteria to determine the reversal mechanism in CoCr films. In this paper we present hysteresis loss ($W_h/W_{h\perp}$) and orientation ratio (OR) as function of the amplitude and direction of the applied field for low and high $H_{c\perp}/H_k$ sputtered CoCr films. The reversal behaviour depends strongly on the amplitude and direction of the field. The presence of an initial layer has an important influence on the type of reversal. The rotational mechanism governs the switching in high $H_{c\perp}/H_k$ films while the domain-wall reversal acts in the low coercivity film.

INTRODUCTION

Much work has been carried out on the magnetic properties and microstructure of deposited CoCr films, but at present the essential question about the nature of the magnetization reversal process is not very clear. In the literature two different approaches to solve the problem were mainly proposed: a) the microscopic method by Lorentz electron microscope and Kerr microscope, b) The macroscopic method by angle dependent hysteresis measurements. The type of reversal mechanism depends on the morphology of the layer which can lead to a particle (no exchange through the column boundaries) or a continuous behaviour In the case of a particulate character the magnetization can be rotated either coherently or incoherently for single-domain particles as well as by domain-wall motion for multidomain particles. In the so-called continuous layers the magnetization is reversed by domain-wall motion. Chemical etching techniques and Auger Electron Spectroscopy have already confirmed that for some CoCr films the Cr segregation exists in the boundaries between the columnar grains[3,4]. It was known that the Cr segregation not only occurs at the column boundaries but also via the so-called CP structure[17]. Of course, the Cr segregated boundaries will result in the pinning to domain-wall motion or weaken and even break down the exchange coupling between the neighbouring grains. Another type of inhomogeneity comes form the initial layer, which is generally poorly oriented and even forms a transition layer with longitudinal magnetization and low Hc depending on the structure of the films and deposition conditions[18,19]. The origin of the perpendicular anisotropy is closely correlated with the crystalline anisotropy, the microstructure as well as their related inhomogeneities. The rotational reversal mechanism of the magnetization was proposed to explain the behaviour of CoCr films. Basic arguments are as follows:

(1) The Hc decreases monotonically with increasing angle, which qualitatively is quite consistent with the S-W coherent rotation or the curling model($S<1.47$) [4,5]. (2) Each columnar grain is surounded by nonmagnetic Cr-rich thin layers, so that each columnar grain can be thought to be a single-domain particle[3,4, 6]. (3) The rotational hysteresis integral Rh is about 0.7, which suggests that a rotation reversal of magnetization dominates [4,7]. (4) For most films the hysteresis loss angular variation is in better agreement with the curling model if the in-plane magnetization component is considered[1]. (5) Lorentz microscope and the digitally enhanced Kerr microscope show a dot-like domain structure for some films. This means that in the remanent state the magnetization in the adjacent grain or columnar cluster is oriented parallel or antiparallel to the film normal[6,8]. One of the knotty problems, which is encountered in employing a rotational reversal model is that the Hc of CoCr films is much less than Hk. Therefore, the domain-wall motion was also proposed to explain the reversal mechanism. The main arguments are as follows: (1) The experimental relation between the initial slope of the easy loop [$T=(dM/dH)_{M=0}$] and the film thickness is in good agreement with the theoretical curves, which are calculated according to the domain-wall model[9]. (2) Another important feature of the perpendicular loop is the presence of the typical "shoulder"[8] (3) For low $H_{c\perp}/H_k$ films the measured domain period vs. the applied field curves are in good agreement with the calculated curves, according to the theory of the stripe-domain model[10]. (5) On assuming that the distribution of the Cr concentration follows a Gaussian distribution[11], the related magnetic parameters such as the Ms and Hc as function of the Cr content were calculated. It was concluded that the most feasible reversal mechanism for CoCr films is domain-wall displacement.

However, comparing the measured and calculated data between the domain-wall theory and magnetic properties, it can be clearly seen that this good agreement is only found in low coercivity films, which often show a pronounced "shoulder" and stripe-domain structure. For high coercivity films the domain-wall model cannot be valid [10]. Moreover, both initial slope and measured domain density belong to the characteristics in the remanent state[8]. They do not reflect the magnetization reversal mechanism in the high applied field.

Here we have primarily based our study of the magnetization process on the VSM hysteresis-loop behaviour of CoCr films. The numeral differential and integral methods were used to investigate the dependence of $H_{cr}(\theta)/H_{cr\perp}$, $H_c(\theta)/H_{c\perp}$, OR and Wh on the angle with the applied field Ha as a parameter. The angle is that between Ha and the film normal. Changing the angle and amplitude of the applied field is more related with the actual recording process, namely the media passing the recording head will experience a field which varies in both magnitude and direction. Combining the $H_{c\perp}/H_k$ values with the experimental results on the observed domain configuration [8], we can classify the CoCr films(see No 2,3,6 in Table 1) in the three types, namely: (1) low $H_{c\perp}/H_k$ values (1.5~1.7%) showing long stripe-domain configurations and pronounced "shoulder" loop (2) medium $H_{c\perp}/H_k$ values(about 6%) with short stripe-domain configurations (3) high $H_{c\perp}/H_k$ values (above 10%) showing typical dot-like domain configurations.

EXPERIMENTAL PROCEDURE

The CoCr films used are RF magnetron sputtered on silicon substrates with a background pressure of $1.5*10^{-7}$ mbar and Par= $6*10^{-3}$ mbar. The sputter power is varied from 250-550 Watt. X-ray fluoresence is used to check the composition and thickness of the films. The related magnetic properties obtained from the VSM and Torque Magnetometer are summarized in Table 1.

Table 1: The relevant parameters (Ha=800 kA/m)

No	thickness nm	Ms kA/m	$H_{c\perp}$ kA/m	$H_{c\perp}/H_k$ %	OR(90°)	Rh	$H_{c\perp}/H_{c\parallel}$
1	493	334	8.35	1.78	0.70	0.29	1.24
2	1230	423	9.15	1.59	0.56	0.29	1.3
3	650	461	35.0	5.65	2.6	0.55	4.0
4	1100	293	59.7	10.1	4.1	0.81	4.4
5	1950	294	59.3	9.6	5.1	0.83	4.6
6	650	321	73.2	14.1	3.6	0.78	5.2
7	1010	344	77.2	13.3	3.6	0.74	5.7

The definition of some parameters used are as follows:
(a) The squareness ratio $S=M_r/M_s$;(uncorrected for the demagnetizing effect); (b) Relative orientation ratio $OR(\theta)=S_\perp/S(\theta)$; (c) Hysteresis loss $W_h=\int_{-H_m}^{H_m} dM1*dH-\int_{-H_m}^{H_m} dM2*dH$; the M1 and M2 represent the magnetization of the descending and ascending loop respectively. Hm is the measured applied field. For an ideal perpendicular anisotropy film, the squareness along the easy-axis equals one and along the hard axis it must be 0. Therefore OR(90°) will be infinite. Of course the larger OR(90°) is, the better the degree of orientation of the magnetization. The direction having a minimum $OR(\theta)$ is the preferred oriented direction of the magnetization.

RESULTS AND DISCUSSION

It is seen from Table 1 that OR(90°) increases with increasing $H_{c\perp}/H_k$ values. This means that the degree of orientation of the

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magnetization along the perpendicular direction increases with the $H_{c\perp}/H_k$ values. It is very interesting that for low $H_{c\perp}/H_k$ films, the OR(90°) value is less than, but almost approaches one. This fact suggests that the degree of orientation is very poor in the remanent state. At the same time, minimum OR(θ) does not appear at the film normal (see Fig 6). This indicates that the magnetization obviously deviates from the film normal due to the influence of the demagnetizing field and magnetostriction, although these films have excellent crystalline orientation. In general, their $\Delta\theta_{50}$ are rather small, i.e. the lower the $H_{c\perp}/H_k$ value, the larger the deviation of the magnetization orientation from the crystalline orientation. In Figs. 1,2 the dependence of $H_c/H_{c\perp}$ on the angle are plotted as a parameter Ha for low and high $H_{c\perp}/H_k$ films. It can be seen from these Figs. that for low $H_{c\perp}/H_k$ films the change of amplitude of the $H_c/H_{c\perp}$ vs. θ curve is rather smaller and the $H_c/H_{c\perp}$ values are almost independent of the angle, which is considered as an indication of domain-wall motion. This is supported by the stripe-domain configuration of low $H_{c\perp}/H_k$ films in the remanent state[8] and the opinion that the coercivity hardly changes when the applied field is at an angle to the domain wall[12].

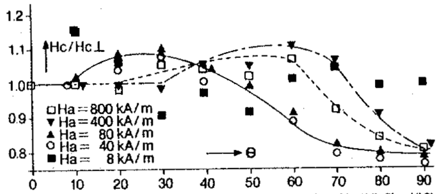

Fig. 1 Relative coercivity measured vs. angle of a low Hc/Hk film (#2).

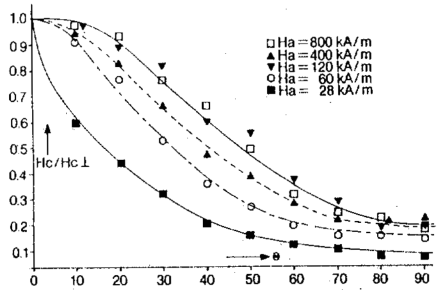

Fig. 2 Relative coercivity measured vs. angle of a high Hc/Hk film (#6).

In fact, their $H_c/H_{c\perp}$ and $H_{cr}/H_{cr\perp}$ are almost independent of the angle in the range of 0-50°(see Figs.1,3). This fact again shows that the degree of orientation of the magnetization is very poor for low $H_{c\perp}/H_k$ films. On the contrary, for high $H_{c\perp}/H_k$ films, no matter how the applied field changes, the $H_c/H_{c\perp}$ decreases almost monotonically with an increase of the angle. Only the shape of the $H_c/H_{c\perp}$ vs. θ curve becomes steeper in the low-field than in the high-field range. The OR values for high $H_{c\perp}/H_k$ films far exceed those for low $H_{c\perp}/H_k$ films.

For an incoherent rotation $H_c(\theta)=H_{c\perp}\cos\theta$ and $H_{cr}(\theta)=H_{cr\perp}/\cos\theta$ can be used to describe the related characteristics of CoCr[13] In Fig. 4 the dependence of $H_c/H_{c\perp}$ on $\cos\theta$ is shown for several films with coercivities ranging from 8 to 85 KA/m. In order to compare the experimental data with the coherent (S W model) and incoherent rotation (Cos type model), the theoretical curves[14] drawn with solid lines are also shown in Fig.4.

It is clear that the change tendencies of $H_c/H_{c\perp}$ vs. θ are quite different from the S W model. However, in general the measured values are in fairly good agreement with theoretical values in the range of 0-40°, except for low $H_{c\perp}/H_k$ film. The relatively large discrepancy between the measured and theoretical values for a low $H_{c\perp}/H_k$ film suggests that its magnetization reversal process is quite different from the incoherent model. On the contrary, for high and medium $H_{c\perp}/H_k$ films that basically follow this model, in the range of 80-90°the measured $H_c/H_{c\perp}$ values are obviously higher than the theoretical one. This deviation is caused by the presence of the in-plane magnetization component of the hysteresis loop, which is also supported by other arguments: (1) the small jump of the magnetization on the in-plane loop, (2) the presence of an obvious peak of distribution of the Wh vs. applied field curves in the vicinity of 90°[15], (3) several measured magnetic parameters (OR(θ), $W_h/W_{h\perp}$, $H_c/H_{c\perp}$) are almost independent of the angle in the range of 75~90°.

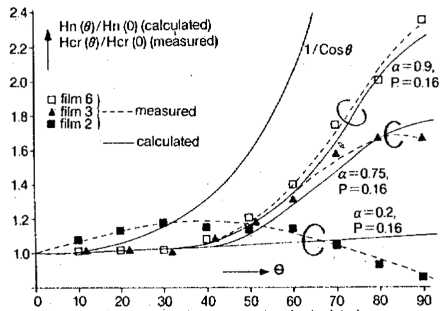

Fig. 3 The relation between the measured and calculated curves.

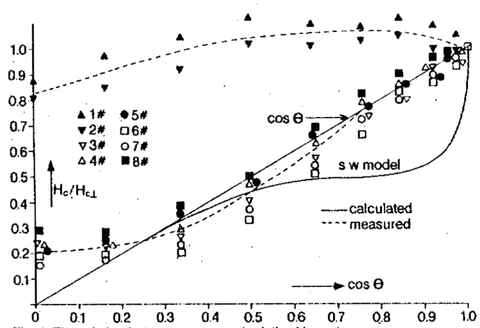

Fig. 4 The relation between measured relative Hc and several theoretical models.

The remanent coercivity is closely related to the nucleation field since, in contrast to the Hc, no reversible rotation is involved in this switch process. For most of the specimens the values of the angular dependence of remanent coercivity are almost constant up to 30-40°, which significantly deviates from the inverse cosine curve (see Fig.3). A modified relation was recently proposed: $H_n(\theta)/H_{n\perp}=(1-\alpha\sin^2\theta)^{-1/2}$, derived from the theoretical nucleation field for curling in an infinite chain of spheres or an ellipsoid, where the α is considered to be an

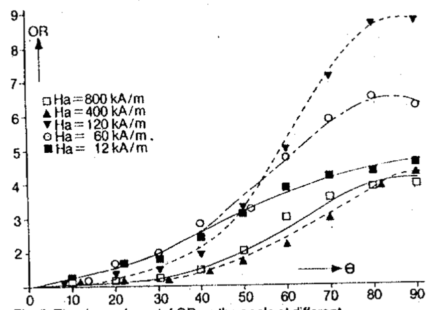

Fig. 5 The dependence of OR on the angle at different fields for a high Hc/Hk film (#6).

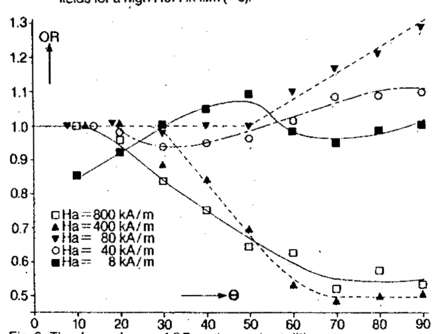

Fig. 6 The dependence of OR on the angle at different fields for a low Hc/Hk film (#2).

adjustable parameter[16]. If we assume that P is the ratio of the in-plane magnetization component to the total magnetization, the above formula can be changed in:

$$H_n(\theta)/H_{n\perp}=(1-\alpha\sin^2\theta)^{-1/2}*(1-p)+(1-\alpha\cos^2\theta)^{-1/2}*p \qquad (1)$$

Typical calculated results for P=0.16 are shown in Fig.3 with α=0.9,0.75 and 0.2. It can be seen that the calculated values are quite consistent with the measured ones for high and medium $H_{c\perp}/H_k$ films,except those of medium $H_{c\perp}/H_k$ films.in the range of 80-90°, which again verifies the fact that the influence of the in-plane component does exist. However, the large discrepancy between the calculated and measured $H_{cr}/H_{cr\perp}$ data for low $H_{c\perp}/H_k$ films again shows its magnetization reversal differs from that of the incoherent rotation model. In Figs. 5,6 the dependence of OR on the angle is plotted as a parameter of the applied field. It was found that no matter how the applied field changes, all the OR vs. θ curves have a similar tendency to change for high $H_{c\perp}/H_k$ films. These curves prove the magnetization aligns along the film normal and the degree of the orientation is very good. On the contrary for low $H_{c\perp}/H_k$ films most of the OR values are less than one. As Ha decreases, their change of amplitude decreases with the applied field and the OR vs. θ curve gradually becomes a flat line. It may be inferred from this fact that in the remanent state the easy-axis direction of such a film will deviate from the normal and leads to the appearance of a very large in-plane magnetization component Of course, this pronounced in-plane component is favourable for forming a stripe-domain structure, which is controlled by the initial layer. Since the crystal grain in this layer has various crystallographic orientations, it is expected that it will have more or less in-plane anisotropy.

We think that the characteristics of Wh can be used as one of the criteria for establishing reversal mechanisms. In Figs. 7,8 the dependence of Wh on the angle is plotted as a parameter of Ha. It can be seen that the curves for two typical CoCr films

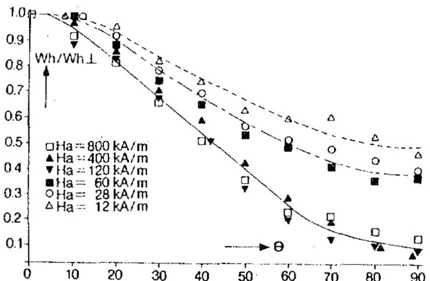

Fig. 7 Angular dependence of Wh at different applied fields for a high Hc/Hk film (#6).

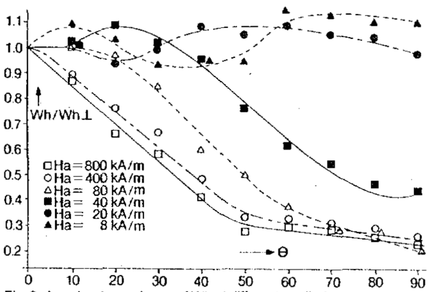

Fig. 8 Angular dependence of Wh at different applied fields for a low Hc/Hk film (#2).

without any exception decrease with the angle and qualitatively follow the same change pattern expected by the S W model in the 800 kA/m field. There is a linear relation between the $W_h/W_{h\perp}$ and the angle in the 10-70° interval for high $H_{c\perp}/H_k$ as well as in the 0-60° for low $H_{c\perp}/H_k$ films. Similarly, due to the influence of the in-plane magnetization component for low $H_{c\perp}/H_k$ films the $W_h/W_{h\perp}$ values are almost constant in the 60-90° interval.

It can seen from Fig.7 that although for high $H_{c\perp}/H_k$ films the field changes from 800 to 12 kA/m, all the $W_h/W_{h\perp}$ vs. θ curves still maintain a monotonically decreasing tendency. Only when Ha is lower than the coercivity of the film, the absolute values of $W_h/W_{h\perp}$ increase to some extent. This point suggests that no matter how the applied field changes, the incoherent rotation reversal occupies a dominant position. In contrast to this, in the case of low $H_{c\perp}/H_k$ films as the applied field is decreased close to the coercivity the $W_h/W_{h\perp}$ vs. θ curves gradually change from monotonically decreasing curves to rather flat ones, which are very close to the straight line ($W_h/W_{h\perp}$=1) (see Fig.8). It is well known that this line is an important indication of domain-wall motion. Therefore, it may be reasonable to assume that for low $H_{c\perp}/H_k$ films the incoherent rotation dominates in the strong field and the domain-wall reversal is the dominant mechanism in the weak field. The latter point is in agreement with the previous conclusion about domain-wall reversal, which is derived from the consistencies between the calculated and measured values of the relation between the initial slope and film thickness[9]. This is also true for the observed and theoretical values of domain density for low $H_{c\perp}/H_k$ films having a long stripe-domain configuration [10]. Both the slope and domain density belong to the magnetic parameters in the weak field area. According to this, it is easily understood why Rh increases with the coercivity(see Table 1).

CONCLUSION

1) The method, which differentiates magnetization reversal mechanisms according to their $H_{c\perp}/H_k$ values, is an efficient measure. 2) For a CoCr film the magnetization reversal mechanism strongly depends on the amplitude and direction of the applied field. In the low field range(below about 24 kA/m) the domain-wall motion easily takes place prior to the rotation process, but in the high field range the rotation reversal will be dominant. 3) The magnetic properties of our CoCr films are strongly influenced by the initial layer, because this has a rather poor degree of orientation of the magnetization along the perpendicular direction. It is reasonable to consider the initial layer as an important source of reversed magnetization nucleation. The pronounced in-plane component will be favourable for forming the stripe-domain configuration. Domain-wall reversal holds a dominant position in the low $H_{c\perp}/H_k$ films. 4) For low $H_{c\perp}/H_k$ films in the remanent state their easy-axes of the magnetization obviously deviate from the film normal, even though these films have excellent crystalline orientation($\Delta\theta_{50}$ very small). On the contrary, for high $H_{c\perp}/H_k$ films no matter how the applied field changes, their easy-axes of the magnetization always stay in the film normal. Therefore, a high $H_{c\perp}/H_k$ value is favourable for restraining domain-wall motion. The rotation magnetization reversal governs the magnetization switch in high $H_{c\perp}/H_k$ films. 5) The characteristics of hysteresis loss can be used as one of the criteria for establishing the reversal mechanism.

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