THE EFFECT OF THE INITIAL LAYER ON THE REVERSAL MECHANISM IN CoCr FILMS

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ABSTRACT: It is well known that the initial layer of sputtered CoCr films can have quite different magnetic properties compared with the succeeding growth of the perpendicular anisotropic "top layer". To understand the influence of the initial layer on the magnetic behaviour we have measured the dependence of OR, Hc and hysteresis loss as functions of the angle with the applied field (H_a) as a parameter [5]. In this paper we report that with increasing H_{c1}/H_k values the orientation direction of the magnetization gradually changes from in-plane ($OR_i=0.7$) to perpendicular ($OR_i=3.9$). The angular dependence of Hc is closely related to the value of H_a . It was found that H_c/H_{c1} drastically decreases at $H_a=H_{c1}$ max (159 kA/m) with decreasing H_a . The change of amplitude for H_{c1} is much smaller than for Hc therefore we introduce a critical field H_{co} where $H_{c1}=H_{co}$. If H_a is changed from $H_a>H_{co}$ to $H_a<H_{co}$ the magnetic behaviour will be changed from a typical perpendicular to an in-plane anisotropy. From this we can assume that in the high field range ($H_a>H_{co}$) the Hc of CoCr mainly results from the perpendicular "top layer", but in the low field range Hc basically depends on the behaviour of the initial layer having in-plane anisotropy. If $H_a>H_{co}$ the H_c/H_{c1} decreases monotonically with the angle and for $H_a=H_{c1}$ max the H_c/H_{c1} vs θ curve follows approximately the calculated inverse $\cos(90-\theta)$ line. However, for $H_a=H_{co}$ (=80 kA/m) the measured curves deviate from this calculated one. This can be explained by measuring the normalized demagnetizing factor N vs. θ curve. For several films we found that if $\theta<30^\circ$, there is a sharp increase of N .

INTRODUCTION

It is generally agreed that sputtered CoCr films having perpendicular anisotropy are in a compositionally segregated state [1,12] and have a typical columnar microstructure [7]. Recently it was discovered from a lot of experimental data [1,7,9] that the initial layer shows a quite different crystalline orientation and magnetic behaviour, compared with the succeeding growth of a perpendicular anisotropic "top layer". The initial layer can exhibit a significantly different orientation of the easy axis from a random to a rather good in-plane orientation, depending on various deposition conditions. In general, the coercivity of the initial layer is much less than that of the "top layer". It can be expected that the initial layer will exert a tremendous influence on the magnetization reversal mechanism of CoCr films. It was proposed that the magnetization reversal process in an initial layer seems to take place exclusively through the in-plane domain-wall motion [2,3], and the presence of an in-plane magnetization component is favourable for forming stripe-domain configurations of CoCr films [5]. Therefore, the reversal mechanism is complicated by the contributions from both incoherent rotation with perpendicular orientation of the magnetization (top layer) and domain-wall motion with either in-plane or random orientation of the magnetization (initial layer). In order to investigate the precise magnetization process, this paper reports on the dependence of OR, coercivity and hysteresis loss of CoCr films on the angle, which is the angle between the applied field and the film normal, with the applied field as parameter. In addition, the influence of the demagnetizing field on the angular dependence of the magnetic behaviour in CoCr films is also examined.

EXPERIMENTAL PROCEDURE

The CoCr films are RF magnetron sputtered on silicon and RF sputtered on polyimide (no.6) substrates. For the latter $A_{90}=9\sim 10^\circ$. X-ray fluorescence was used to check the composition and thickness of the CoCr films. Both planimeter and numeral integrals were used to calculate the hysteresis loss of these films. We paid particular attention to investigating a typical CoCr film (no. 6), which has a very high coercivity (159 kA/m) with a quite obvious in-plane magnetization component, because it is very advantageous to study the relation between the microstructure and magnetization reversal mechanism of CoCr films. In order to

compare the experimental data with the calculated curve of the domain-wall motion, a pure nickel specimen was also examined. The related magnetic properties obtained from the VSM and Torque Magnetometer are summarized in table 1.

No.	thickness nm	M_s KA/m	H_{c1} KA/m	H_{c1}/H_k %	$R_s(0)$	OR_i	Wh_i J/m ² * 10 ⁴
1	493	334	8.35	1.78	0.03	0.7	1.21
2	1230	424	9.15	1.59	0.03	0.75	1.43
3	650	461	35.0	5.65	0.104	2.6	4.4
4	1220	468	46.2	7.5	0.126	3.9	5.5
5	650	321	73.2	14.1	0.212	3.6	6.0
6	265	467	159.2	29.8	0.39	2.6	24.2
7	5417	484	8.75	1.0	0.014	0.032	0.02

Note: Specimen 7 is pure nickel sheet ($10^{-4} \times 0.005417$ mm);

The definitions of some parameters used are as follows: 1) The squareness ratio $R_s(\theta)=M_r(\theta)/M_s$ (uncorrected for the demagnetizing field). 2) Relative orientation ratio $OR(\theta)=R_{s1}/R_s(\theta)$. 3) The measured coercivity at 800 kA/m is considered to be the film's coercivity H_{c1} max. Due to the influence of the demagnetizing field, the deviation of the magnetization from the film normal will take place by varying degrees. The larger the $R_s(0)$ the less the deviation of magnetization from the easy axis of a CoCr film in the remanent state will be. Therefore, in a certain sense the amplitude of $R_s(0)$ reflects the ability of CoCr films to resist or weaken the influence of the demagnetizing field. Due to the influence of the columnar microstructure and perpendicular anisotropy, the N_i factor of CoCr films (the demagnetizing factor along the film normal direction) is not necessarily equal to 1. Sometimes, the N_i is much less than 1. In order to simplify matters, all the demagnetizing factors N were normalized by those at 0° .

EXPERIMENTAL RESULTS AND DISCUSSION

The results listed in table 1 show that as the H_{c1}/H_k values of CoCr films increase, all the $R_s(0)$, OR_i and Wh_i values also increase almost monotonically. With increasing H_{c1}/H_k , the orientation direction of the magnetization gradually changes from the in-plane direction ($OR_i=0.7$) to the perpendicular direction ($OR_i=3.9$). This means the degree of orientation of the magnetization along the perpendicular direction increases with the H_{c1}/H_k . At the same time with increasing H_{c1}/H_k , the absolute values of $R_s(0)$ increase from 0.03 to 0.39. This fact clearly shows that the higher the H_{c1}/H_k , the less the influence of the demagnetizing field on the magnetization orientation will be, so that a CoCr film with a high H_{c1}/H_k is advantageous for improving the stability of magnetic recording media. This is supported by the following arguments: for a CoCr magnetic disk the reproduced signal E_p is in direct proportion to H_{c1} and the recording density D_{50} is in inverse proportion to H_{c1} [10]. It was known that for a CoCr film the magnetization reversal mechanism strongly depends on the amplitude and direction of the applied field [5], so that the angular dependences of $H_c(\theta)/H_{c1}$, $OR(\theta)$ and $Wh(\theta)/Wh$ with the field as a parameter were measured. In order to have a thorough investigation of the magnetization behaviour of CoCr films, a 265 nm specimen (no.6), which has a very high coercivity ($H_c=159$ kA/m), was chosen.

Orientation ratio, hysteresis loss and critical coercivity

The angular dependence of $OR(\theta)$ with the field as parameter is shown in Fig.1. It is very interesting to see that when the applied field is higher than H_{c1} max (159 kA/m), the behaviour of the OR vs. θ curves is that usually seen for perpendicular oriented media, but in the low field range (about <159 kA/m) the OR_i vs. θ curves will be changed from larger than 1 to less than 1. This fact clearly suggests that the orientation direction of the magnetization will be changed from the perpendicular to the in-plane direction if $H_a<H_{c1}$ max. It is clearly shown from Fig.2 that H_{c1} drastically decreases at $H_a=H_{c1}$ max (159 kA/m) with

decreasing applied field. Although both H_{c1} and $H_{c//}$ decrease with decreasing field, the change in magnitude of H_{c1} is much larger than that of $H_{c//}$. If $H_a = H_{c0}$ (80 kA/m), the H_{c1} is just equal to $H_{c//}$. Hereafter this coercivity H_{c0} is referred to as the critical coercivity. As the applied field is changed from $H_a > H_{c0}$ to $H_a < H_{c0}$ the magnetic behaviour of a CoCr film will be changed from a typical perpendicular anisotropic one to an in-plane anisotropic media. It is because the $H_{c1}/H_{c//}$ of a CoCr film is larger or smaller than 1 that this indicates whether the film has the characteristics of perpendicular or in-plane anisotropy. Perhaps it is reasonable from this result to assume that in the high field range ($H_a > H_{c0}$) the coercivity of this type of CoCr films mainly results from the "top layer" of CoCr having perpendicular anisotropy, but in the low field range the coercivity basically depends on the behaviour of the initial layer having in-plane anisotropy. In addition, if $H_a < H_{c0}$, the absolute value of H_{c1} will

Fig. 1 The dependence of the orientation ratio OR_1 on the angle and typical hysteresis loops for different applied fields

Fig. 2 The dependence of coercivity and hysteresis loss on the angle for different applied fields

drastically decrease from 159 kA/m to a very small value of about 3 kA/m, but the $H_{c//}$ only reduces from 16 kA/m to 7.2 kA/m. It is noticeable that this value is almost identical with the coercivity of low $H_{c1}/H_{c//}$ films (8 kA/m) and similar values of the initial layer [9]. It can be also seen from Fig. 1 that the hysteresis loop of this specimen has a typical characteristic of perpendicular anisotropy if $H_a > H_{c0}$. However, if the applied field is lower than the critical coercivity, it seems that the main perpendicular oriented layer no longer switches. Only the in-plane oriented layer with low coercivity (about 8 kA/m) can respond to the applied field. At this time its hysteresis loop becomes a typical one of in-plane anisotropy. Therefore, it could be reasonable to assume that the magnetization reversal for this "top layer" has rather sharp switching properties, in the low applied field the magnetic behaviour seems to only depend on the initial layer. According to the amplitude of the discontinuous magnetization jump in the in-plane hysteresis loop, the thickness of this in-plane oriented layer is roughly estimated at about 50 nm [4].

The dependences of Wh_1 and $Wh_{//}$ on the applied field, as seen in Fig. 2, reveal that: 1) if the applied field is higher than H_{c0} , the CoCr film exhibits a typical perpendicularly anisotropic behaviour ($Wh_1/Wh_{//} > 1$). The angular dependence of $Wh_1/Wh_{//}$ monotonically decrease with increasing θ , which basically follows the change tendency of incoherent rotation reversal [6]. However, this film will become an in-plane oriented media ($Wh_1/Wh_{//} < 1$) if $H_a < H_{c0}$. The change pattern obviously deviates from a straight line, which considered as an important indication of domain-wall motion [6]. The reason to cause such discrepancy have been described elsewhere. 2) Although the Wh_1 and $Wh_{//}$ decrease monotonically with decreasing H_a , the change in magnitude of

Wh_1 is far larger than that of $Wh_{//}$. As H_a decreases from 800 to 16 kA/m, $Wh_{//}$ decrease by a factor of 5.3×10^4 , but the decrease in amplitude of Wh_1 is as high as a factor of 5.1×10^4 . Especially in the field ranges between H_{c1} max and H_{c0} a small change in amplitude of H_a can cause the hysteresis loss to change enormously. Therefore, in order to ensure that the CoCr films exhibit a stable perpendicular property $H_a > H_{c1}$ max is an indispensable condition.

Relative in-plane coercivity.

All the above results suggest that, as a whole, this CoCr film has strong perpendicular anisotropy and consists of two quite different layers, one a typical main perpendicularly oriented top layer, the other an in-plane oriented layer with rather low coercivity. It is reasonable to infer that the response of the whole film can be considered as the superposition of the response of each layer to the applied field. In order to investigate the correlation between the magnetization reversal mechanism of CoCr film and H_a , the $H_c/H_{c//}$ vs. θ curves are plotted against H_a in Fig. 3. As is seen from this figure the effect of the applied field on the angular dependence of the coercivity is quite remarkable. If the applied field is higher than the H_{c1} max (159 kA/m), the $H_c/H_{c//}$ vs. θ curves decrease monotonically with increasing angle. This behaviour is qualitatively consistent with the characteristic of the incoherent rotation $\cos \theta$ law [5]. As the applied field is continuously decreased and approaches

Fig. 3 The angular dependence of $H_c(\theta)/H_{c//}$ with H_a as parameter for CoCr film (specimen no. 6) and Ni sheet

H_{c1} max, the experimental form of the relative coercivity will gradually change from following the $\cos \theta$ to the inverse $\cos(90-\theta)$ law. It is well known [11] that the form of $H_c/H_{c//}$ will follow the inverse $\cos$ law if its magnetization is reversed by domain-wall motion. However, if H_a is further decreased, becoming lower than H_{c0} , the form of $H_c/H_{c//}$ will again deviates from the inverse $\cos$ law. It can be easily seen from Fig. 3 that at different H_a for each $H_c/H_{c//}$ vs. θ curve there is a critical angle θ_c or above which the form of $H_c/H_{c//}$ is almost identical with the inverse $\cos$ curve, but below this angle the $H_c/H_{c//}$ drastically decreases with a decreasing angle. With decreasing H_a , this angle is gradually moved towards a higher value.

Normalized demagnetizing factor.

In order to clarify the physical meaning of the critical angle, the normalized demagnetizing factor N vs. θ curves are shown in Fig. 4. for specimen no. 6. If the angle is below

Fig. 4 The angular dependence of the normalized demagnetizing factor ($N(\theta)$) for CoCr films

about 30° , the demagnetizing factor sharply increases. On the contrary, if the angle is changed to approach the in-plane direction, it only causes N to increase slightly. Therefore, it may be inferred that if the direction of H_a is very close to the film normal, the internal field will become so small that the working point of the magnetization

will move to the declining minor loop in the field range below H_{co} . Hence it results in a sharp decrease of H_c/H_{co} . According to the same viewpoint, it is easily understood why the shape of the ORL vs. θ curves in the field range of $H_a < H_{co}$ (seen in Fig. 1) is similar to the variation of the coercivity, if the angle is decreased, starting from the in-plane direction. At first ORL decreases very slowly, but once the angle is lower than some of the critical angles, the ORL value will increase sharply and the critical angle will gradually move to a larger angle with decreasing field. For isotropic recording films the angular dependence of the normalized demagnetizing factor follows the $N(\theta) = \sin^2(90 - \theta)$ [13]. Comparing the calculated curve drawn by the solid line with the measured ones for CoCr films, it is clearly seen from Fig. 4 that for low coercivity films the N vs. θ curve is quite consistent with the calculated one. This fact suggests that the characteristic of this film approaches that of the isotropic recording media. This argument is supported by that for low coercivity films; their several magnetic parameters (such as OR, H_c etc.) are almost independent of the angle [5]. However, as the H_{ci}/H_k value of CoCr films increases, the deviation of the N vs. θ curves from the calculated one will gradually increase.

Relative hysteresis loss.

The dependence of the measured hysteresis loss for specimen 6 is plotted against different H_a in Figs. 5a, b, representing the applied field respectively higher and lower than the $H_{ci,max}$ of 159 kA/m. It can be seen from Fig. 5a that the hysteresis loss Wh/Wh_i vs. θ curves for four different fields without exception decrease monotonically with increasing angle, and qualitatively follow the same change pattern expected by the incoherent rotation models in fields above 159 kA/m. However, if H_a is continuously decreased to be below this, the hysteresis loss Wh/Wh_i vs. θ curves follow quite different variations. If the angle increases, the hysteresis loss first increases, reaching a maximum value at an appropriate critical angle; further increase of the angle results in a diminished hysteresis loss. This fact suggests that at present the magnetization reversal mechanism of CoCr films must differ from that of the rotation reversal model.

Fig. 5 The angular dependence of hysteresis loss along perpendicular (Fig. 5a) and in-plane (Fig. 5b) direction with H_a as parameter for CoCr film (specimen no. 6) and Ni sheet.

In order to present a more clear image the angular dependence of the hysteresis loss Wh/Wh_i with respect to different fields is also shown in Fig. 5b, because the orientation direction of the magnetization has already changed from the film normal to an in-plane direction in the field below 159 kA/m. According to previous analyses of H_c/H_{co} behaviour for CoCr films, we have learnt that if H_a is lower than 159 kA/m, the magnetization reversal occurs by domain-wall motion and if this is so the characteristics of the hysteresis loss should be independent of the angle, but a very drastic angular dependence of the measured hysteresis loss appears instead of a straight line. In order to explain the relatively large discrepancy between the experimental and theoretical results based on the domain-wall displacement, a pure nickel sheet was also examined because it is well known that its magnetization reversal mechanism belongs to domain-wall motion and the magnetization aligns in the in-plane direction. Compared with the angular dependencies of hysteresis loss Wh/Wh_i drawn with a dashed line for the nickel specimen, it is clear that the angular dependencies of Wh/Wh_i for CoCr films is strikingly similar

to the behaviour of the nickel specimen. As the applied field decreases, the critical angle, which corresponds to the the maximum hysteresis loss Wh/Wh_i , gradually moves to a larger angle. It is shown in Fig. 5b that above this critical angle, the Wh/Wh_i vs. θ curves ascend in varying degrees with decreasing angle, starting from the in-plane direction, and below it descend drastically with decreasing angle. This latter behaviour is due to the strong influence of the demagnetizing field. In the presence of the demagnetizing field the Wh/Wh_i vs. θ curves no longer follow the straight-line law for a thin film having in-plane anisotropy. In view of the same consideration, the H_c/H_{co} vs. θ curves for both the nickel specimens drawn with dashed lines (H_a ranging from 8 to 800 kA/m) and the CoCr film (no. 6, in the field range below 159 kA/m) are shown in Fig. 3. The change tendencies of the H_c/H_{co} vs. θ curves again show that there is a striking similarity between the two specimens. Above the critical angle the angular dependencies almost coincide with the inverse $\cos(90 - \theta)$ curve, which is thought to be a strong indication of domain-wall motion. Therefore, it is perhaps reasonable to conclude that in the low field range $H_a < H_{co}$ a CoCr film presents an in-plane orientation of the magnetization and its magnetization is reversed by in-plane domain-wall motion. In the vicinity of the film normal (θ about 30°) the angular dependence for both Wh/Wh_i and H_c/H_{co} are strongly influenced by the demagnetizing field. It is very interesting that a similar behaviour of H_c/H_{co} and hysteresis loss also appears in the bulk CoCr sample (its H_c is about 1.3 kA/m) [8].

CONCLUSIONS

1) This type of CoCr films are composed of an initial layer with a succeeding grown perpendicularly anisotropic "top layer". The magnetization reversal mechanism of CoCr films consisting mainly of an initial layer is controlled by domain-wall motion and its orientation of the magnetization aligns along the in-plane direction. However, these films exhibit a strong perpendicular anisotropy as a whole and the incoherent rotation reversal dominates. The response of the CoCr films can be qualitatively interpreted as the superposition of the response of each layer to the applied field. 2) The magnetization reversal mechanism strongly depends on the amplitude and direction of the field. If the applied field is larger than $H_{ci,max}$, the incoherent rotation process dominates. In the low field ranges below it, the magnetization reversal is controlled by the in-plane domain-wall motion. 3) In the range of low H_a the demagnetizing field exerts a tremendous influence on the magnetic behaviour of CoCr films, especially in the vicinity of the film normal direction. 4) With increasing H_{ci}/H_k values, the degree of magnetization orientation along the film normal will increase. The higher the coercivity, the more pronounced the perpendicularly anisotropic characteristic. According to the angular dependence of OR, H_c and the demagnetizing factor for low H_{ci}/H_k CoCr films the magnetic behaviour approaches an isotropic recording medium.

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