Abstract. Surface magnetic hysteresis, measured by Polar M.O. Kerr effect on RF and Magnetron sputtered CoCr (81/19 at%) films in the range 20 - 4000 nm is compared with volume hysteresis measured by VSM, both with external field perpendicular to the surface. The surface coercivity \( H_{\text{C}} \) was found to decrease below the volume coercivity at a critical thickness of 125 nm for RF films [1] and at about 1000 and 800 nm for centre and off-centre Magnetron samples respectively. The slope of the Kerr loop at \( \theta_k = 0 \) increased slightly again deviating from the VSM slope at a film thickness of about 100, 500 and 500 nm for RF, centre and off-centre Magnetron CoCr samples respectively. These results are consistent with the formation of small splices from the surface for films thicker than a critical value. Order of magnitude calculations do not oppose the formation of such small reversed domains and the higher critical thickness for Magnetron samples is also in qualitative agreement with these calculations, due to a higher perpendicular anisotropy by a factor 2 for these films. If spike domains do exist in CoCr the reversal mechanism is most likely one in which the reversed domains grow at the expense of the main domains.

INTRODUCTION

The reversal mechanism and associated with it the domain structure of CoCr thin films for perpendicular magnetic recording is not clear at present. There are two main models, namely the particulate and the continuous model. In the particulate one the CoCr columns that are formed during film deposition are believed to interact only through magnetostatic interaction. No exchange force acts over the column boundaries due to e.g. a higher concentration of Cr there. In the continuous model the reversal mechanism is thought to take place by Bloch walls as in isotropic domains hindered by the column boundaries [3]. On the base of Neutron Deformation and Magneto-Optic Kerr measurements a third intermediate model has been proposed, in which the magnetization reversal takes place by spike domain wall motion within the columns [1,4].

Using the Magneto-Optic Kerr Effect (MOKE) the hysteresis loop of the surface of CoCr can be measured, since the penetration depth of light (\( \lambda = 632 \text{ nm} \)) into CoCr is about 15 nm. Comparison of surface and volume coercivity would give a possible inhomogeneity in the magnetization distribution throughout the thickness of the film and thus more insight can be gained in the domain structure and reversal mechanism of the CoCr films.

Earlier we reported on the surface coercivity \( H_{\text{C}} \) and the coercivity ratio \( H_{\text{C}} / H_{\text{V}} \) for a CoCr target as a function of film thickness [1]. A rotating analyser apparatus was used to measure the Kerr rotation as a function of the applied field. The experimental set up is described in [1]. Using a multi-reflection sample holder the Kerr rotation could be measured with an accuracy of 0.002 deg. A maximum \( H_k \) was found at \( t = 88 \text{ nm} \) for RF-films and at about 1000 nm for Magnetron films (both 81/19 at%). The coercivity ratio \( H_{\text{C}} / H_{\text{V}} \) is defined by \( H_{\text{C}} / H_{\text{V}} \). For RF-films a critical film thickness \( t_{\text{c}} = 125 \text{ nm} \) was found, so that if \( t < t_{\text{c}} \) then \( H_{\text{C}} > 1 \) and if \( t > t_{\text{c}} \) then \( H_{\text{C}} < 1 \).

The presence of a critical thickness in Magnetron films was not clear from the reported data, therefore additional samples were Magnetron sputtered, also to cover the thicker films region, and results are reported here. Secondly we will compare the slope of the easy-axis hysteresis loop measured with the Kerr effect and VSM at \( \theta_k = 0 \) and \( M = 0 \) respectively.

The functional dependence of the VSM slope on film thickness for RF-films was explained by Willings using a continuous domain model [2]. Hubert expanded the theoretical basis of this analysis to branched domain structures in CoCr [3].

SAMPLE PREPARATION AND CHARACTERIZATION

The CoCr samples were sputtered from alloyed CoCr (81/19 at%) targets of 4" and 3" inch diameter respectively, on Si (100) substrates in a Leybold Heraeus RF-sputter apparatus (2400) either with or without Magnetron facilities. We will distinguish here between RF- and Magnetron films. RF-films were sputtered in batches of 4 samples under the optimized sputter parameters: \( R_{\text{RF}} = 4 \text{ sbar} \) and \( V_{\text{RF}} = -1.5 \text{kV} \) [5] while for Magnetron films the optimum parameters for obtaining good perpendicular anisotropy were determined at \( R_{\text{M}} = 6 \times 10^{-3} \text{ mbar} \) and \( V_{\text{M}} = -250 \text{ V} \). The target substate distance was 5 and 3 cm respectively. As is well known from literature sputter rate and film properties in Magnetron sputtering depend quite on the position of the samples on the substrate. The homogeneity groups were made by the use of the film thickness and coercivity that calculated with a substrate position near the centre and off-centre. Here they will be referred to as group 1 and 2. The previously reported [1] Magnetron samples all belong to group 1 (near the centre). In addition to these, 5 series of 23 samples were Magnetron sputtered to cover thickness range of 1000 to 4200 nm. Of each series 8 samples fell in group 1 and 15 samples in group 2. X-ray fluorescence was used to check the composition and film thickness. The saturation magnetization \( M_s \) could be determined at 488 kA/m from these measurements together with VSM results, and was found to be almost independent of film thickness. Also a constant Kerr rotation of about 0.1 degree was found for all films, indicating that \( M_s \) and composition do not change in the field range of 1000 to 4200 nm. As the magnetic film thickness is determined from the magnetic field of the sample \( (M_s,H) \) determined by VSM (± 3%) the sample surface (1 cm²) and \( M_s = 468 \text{ kA/m} \). The perpendicular anisotropy constant \( K_1 \) was corrected for the sheet demagnetization factor \( 1/2 \mu_0 M_s^2 \) was determined from torque measurements at 90 kOe² for RF-films [6] and now found for Magnetron films. No dependence on film thickness was found nor did \( K_1 \) differ significantly for Magnetron samples from group 1 or 2. In preparing thick Magnetron samples we were faced with the problem that the CoCr spontaneously peeled of the Si substrate due to internal stress. Premagnetizing the substrates at \( V_{\text{M}} = 1 \text{kV} \) for 15 minutes prevented this problem. The thickest films however had to be measured quickly after preparation and still only 8 samples could be measured with both MOKE and VSM. Before peeling off occurred the metallic appearance of the CoCr disappeared probably due to the formation of microcracks. VSM hysteresis curves were measured both with applied field in-plane and perpendicular to the surface. For all films \( S/H \) definitions as \( (M_s,H)\) was smaller than 0.12 and typically 0.09 for Magnetron and 0.06 for RF-films, indicating good perpendicular anisotropy of the CoCr films.

COERCIVITY

The surface coercivity \( H_{\text{C}} \) for RF-films was found to decrease almost discontinuously at a critical film thickness of 125 nm after a maximum was reached at 125 kA/m at a film thickness of 88 nm. For Magnetron films the results are blurred due to the intrinsic spread in the samples (depending on substrate position). But also for Magnetron films it is found that \( H_{\text{C}} \) decreases more rapidly with increasing film thickness than the volume coercivity \( H_{\text{V}} \) after a maximum is reached. In Fig. 1. \( H_{\text{C}} \) (Kerr) and \( H_{\text{V}} \) (VSM) are plotted as a function of film thickness. Symbols without error bars were previously published [1] each representing a single sample. The symbols with error bars indicate the average values of film thickness and coercivity per group and the bars show the standard deviations of the coercivity. A maximum coercivity of 180 kA/m (1250 Oe) is found for group 1 samples at a film thickness of about 1000 nm. The maximum for group 2 is about 90 kA/m (1100 Oe) at a film thickness of 1000 nm approximately. Again the surface coercivity \( H_{\text{C}} \) decreases faster than \( H_{\text{V}} \).

This can be seen more clearly in Fig. 1b were the coercivity ratio (CR) is plotted as a function of film thickness. Here the averages of the samples from group 1 and 2 are plotted with...
different symbols to distinguish them from the previously reported samples. A critical thickness is found at about 1100 nm for group 1 and for group 2 (off-centre) samples the critical thickness must certainly lie between 400 and 1000 nm, but probably between 700 and 1000 nm, after the maximum \( H_c \) is reached. So also for Magnetron films a critical thickness (defined by the coercivity ratio) is found. The maximum coercivity is about the same for RF and Magnetron samples, only the thickness at which it is reached is shifted to thicker films together with the critical thickness for Magnetron films.

![Graph 1a](image1.png)

*Fig. 1a.* \( H_{cv} \) (VSM) and \( H_{cb} \) (Kerr) as a function of film thickness for Magnetron sputtered CoCr. (see text).

![Graph 1b](image2.png)

*Fig. 1b.* The Coercivity Ratio (C.R) versus film thickness calculated from the data in Fig. 1a (see text).

**Slope of the Perpendicular Loop.**

RF-sputtered CoCr films.

The slope of the perpendicular hysteresis curve at \( M = 0 \) as a function of film thickness for RF-films was explained by Wielinga [2] using the Roy & Enz model. Also in the particulate model an increased slope was predicted for the thinnest films \( t < 1000 \) nm but this increase was not large enough to fit the experimental results. In the light of this discussion it is interesting to note, that the slope of the perpendicular hysteresis curve measured with HKE deviates from the bulk value. In determining the Kerr slope the physical state of saturation \( \theta_E(\text{sat}) \) is set equal to \( H_E \). In Fig. 2 both the slope of the Kerr and VSM curves are shown as a function of film thickness for RF-films. The VSM slope reproduces the results by Wielinga, but the Kerr-slope again increases, deviating from the VSM slope, for films thicker than about 1000 nm.

![Graph 2](image3.png)

*Fig. 2.* The slope of the perpendicular surface (Kerr) and volume (VSM) hysteresis curve near the origin for RF-films as a function of film thickness. Each point represents the average of 4 samples.

![Graph 3](image4.png)

*Fig. 3a.* The slope of the perpendicular surface (Kerr) and volume (VSM) hysteresis curve for Magnetron films as a function of film thickness. (see text).

![Graph 3b](image5.png)

*Fig. 3b.* The slope ratio calculated from the data Fig. 3a versus film thickness (see text).
Magneton sputtered CoCr films.

Results for the Magneton films are similar. In Fig. 3a, Kerr and VSM slopes are plotted as a function of film thickness. Again the symbols without error bars refer to single samples published earlier [1] and the symbols with error bars represent the average values plus standard deviations for group 1 and group 2 samples. The VSM slope of the two groups are comparable and are both represented by a ‘k’.

The Kerr hysteresis curve becomes significantly steeper (say 10%) than the VSM curve for films thicker than about 800 ± 100 nm for group 1 and 2 type samples respectively, as can be deduced more clearly from Fig. 3b. In this figure the ratio between the Kerr and the VSM slopes calculated from the data in Fig. 3a is plotted as a function of film thickness.

DISCUSSION AND CONCLUSIONS

In Table 1 experimental values for the critical film thickness based on the coercivity ratio $t_{c1}$ (C.R.) and on the slope ratio $t_{c2}$ (S.R.) of Kerr and VSM hysteresis loops are summarized together with the film thickness $t_{max}$ at which a maximum coercivity is reached. This $t_{max}$ is approximately the same for $H_{K}$ and $H_{c}$. After the maximum is reached $H_{c}$ decreases more rapidly than $H_{K}$. For RF-films this decrease is very abrupt. From $t=100$ to 150 nm $H_{c}$ decreases from 12 to 8 kOe. These results indicate that the decrease in $H_{c}$ after the maximum is reached probably originates from the top surface.

At a film thickness near the maximum coercivity the slope of the Kerr hysteresis loop becomes larger than the VSM slope. These results hold as well for the RF-films as for the group 1 and 2 type Magneton samples. So a relation between the three phenomena could exist.

<table>
<thead>
<tr>
<th>Film thickness</th>
<th>CoCr 81/19 at%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RF</td>
</tr>
<tr>
<td>$(in \text{nm})$</td>
<td></td>
</tr>
<tr>
<td>$t_{c1}$ (C.R.)</td>
<td>125</td>
</tr>
<tr>
<td>$t_{c2}$ (S.R.)</td>
<td>150</td>
</tr>
<tr>
<td>$t_{max}$ (H)</td>
<td>90</td>
</tr>
</tbody>
</table>

The authors would like to thank J.D. Baxter and J. Yntema for their contribution to this work.

REFERENCES