Magnetisation reversal mechanism in Co–Cr media for perpendicular magnetic recording

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Abstract

In this study Co–Cr thin films with perpendicular anisotropy are investigated. Three films with values for $H_a$ of 11, 90 and 170 kA/m have been selected for this paper. Besides the coercivity several other parameters such as the $H_e/H_k$, Cr-segregation, domain structure, column sizes, etc. were studied by VSM, SEM, NMR, MFM, AFM and selective etching. The anomalous Hall effect (AHE) has been used to record the hysteresis curves of submicron Hall crosses. This very sensitive technique in combination with e-beam lithography and ion-beam etching resulted in the recording of AHE hysteresis loops with dimensions of the Hall crosses as small as $0.3 \times 0.3 \mu \text{m}^2$. The AHE loops of three samples, with less than 60 columns, show different micromagnetic properties. Only the sample with $H_{el} = 90$ kA/m shows clear steps in the curves above the noise level. The largest steps correspond with the reversal of one column and the total number of steps was five times the number of columns for this sample. The different reversal mechanisms observed by the AHE are related to the differences in structure, coercivity and domain size.

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Keywords: Co–Cr; Reversal mechanism; Thin film; Hall effect; Micromagnetism

1. Introduction

The interest in ultra-high density magnetic recording is still growing. In the last few years, two important reasons are its enormous potential for data storage and the fact that the principal limits for recording will not be reached within the next 20 years. The ultimate state for a Co–Cr medium for example is predicted to be 400 Mbyte/mm$^2$ and will be reached around the year 2020 [1]. This corresponds to bit sizes of $50 \times 50 \text{ nm}^2$. To achieve this density the knowledge of the micromagnetic behaviour in relation to its macroscopical and its structural parameters becomes more and more important.

The micromagnetic approach to this problem is severely limited by the number of Co–Cr columns which can be simulated. Due to the complexity of the problem only a few hundred columns can

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be simulated even with the most advanced supercomputers.

In 1987 Lodder et al. [2] studied the reversal mechanism by calculating the $H_{c1}/H_k$ and observing the domain pattern of the samples with Kerr microscopy. From this study it has been shown that Co–Cr samples with $H_{c1}/H_k = 0.02$ have long stripe domains. Short stripes occur for values around 0.05 and short stripes or a dot-like domain pattern are present in samples with $H_{c1}/H_k \geq 0.1$.

In the present study three samples with different values for $H_{c1}/H_k$ were studied with a number of techniques such as VSM, torque, NMR, AFM and SEM.

The 'meso'-magnetic behaviour of the samples is studied by using a very sensitive technique: the anomalous Hall effect (AHE) applied on submicron Hall crosses. This technique offers us the possibility to bridge the gap between the macromagnetic and the micromagnetic behaviours responsible for the reversal mechanism. Finally, the results are compared with simulated hysteresis curves obtained with an array of $5 \times 5$ columns.

### 2. Experimental procedure

To study the relation between the reversal mechanism, the film structure and the micromagnetic and macromagnetic behaviours, three Co–Cr samples with different deposition parameters were prepared. The major difference was the substrate temperature ($T_s$) during deposition, as it is known that this parameter influences the film growth in such a way that large differences in structure and magnetic properties occur. This resulted in three samples with a low, a medium and a high coercivity, hereafter expressed as S1, S2 and S3, respectively.

The low and high coercive films were prepared by RF magnetron sputtering at a substrate temperature of 40 and 150°C, respectively. The medium $H_c$ film was RF-sputtered at RT.

All samples were deposited on Si substrates which had been covered first with an oxide layer of about 70 nm (SiO$_2$). After deposition (and etching for the submicron samples) the wafers were cut into $1 \times 1 \text{ cm}^2$ samples for measurement.

### 3. Macroscopic magnetic parameters

We consider the macroscopical parameters of the samples first. Fig. 1 shows the VSM hysteresis curves for the three films, both perpendicular and

![Graphs showing hysteresis curves for Sample S1, S2, and S3.](image)

Fig. 1. The perpendicular and in-plane hysteresis curves of the three samples measured with a VSM.
in-plane. An Oxford VSM with a maximum field of 3 T was used for the measurements. The differences in coercivity ($H_{c,\perp}$) can immediately be observed in the ‘perpendicular’ curves. The in-plane curves also show differences, especially near the crossing of the x-axis (at $H = H_c$) where, for the S2 sample, a large contribution from an initial layer (IL) can be observed (in-plane component of the magnetisation). The volume of the IL can be estimated by comparing the height of the jump with the height of the total loop. The IL of S1 and S3 is about 10% and for sample S2 about 16% of the total loop. The $H_{c,\perp}$ can be determined both from the perpendicular VSM and the AHE loops and, as expected, the results show similar values. The calculated $H_{c,\perp}/H_k$ predicts according to the theory [2] for the low-coercivity sample S1 a stripe domain pattern and for the other two samples a dot-like domain pattern. The macroscopical parameters obtained by several techniques are listed in Table 1.

4. Microscopic parameters (microstructure)

The column diameter ($D$) of the Co–Cr samples was measured by SEM observations of the surface and the film thickness $t$ is estimated from the sputtering time. The results are shown in Table 2. Differences in the surface roughness were found by the use of an AFM. S1 has a smooth surface, but sample S3, prepared at the high substrate temperature, a rather rough surface.

The chemical inhomogeneities were studied by the $^{57}$Co spin-echo NMR technique [3] and by selective chemical etching of the Cr and successive SEM observations [4]. The NMR measures the hyperfine field interactions or the resonance frequencies of the material and is used here to study the compositional inhomogeneities. A spin-echo spectrum of Co–Cr consists of a main line frequency ($M$) and of satellites. The main line frequency arises from Co nuclei which have only Co atoms as nearest neighbours (NN), for example, the hyperfine field of a Co nucleus in pure FCC Co has a main line frequency of 217 MHz and for pure HCP Co of 225.5 MHz. The exact frequency depends on the crystal structure, morphology and chemical inhomogeneities. If the Co is diluted by Cr ($< 1–2$ at% Cr), beside the main line frequency the first satellite peak (Sat1) appears in the spectrum at 177 MHz and is caused by Co nuclei which have one Cr atom at the NN site. A second satellite line

<table>
<thead>
<tr>
<th>Sample</th>
<th>$t$ (nm)</th>
<th>%Cr (target)</th>
<th>$M_s$ (kA/m)</th>
<th>$H_{c,\perp}$ (VSM) (kA/m)</th>
<th>$H_{c,\perp}$ (AHE) (kA/m)</th>
<th>$H_k$ (kA/m)</th>
<th>IL (vol%)</th>
<th>$H_{c,\perp}/H_k$</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>320</td>
<td>22</td>
<td>236</td>
<td>13</td>
<td>11</td>
<td>244</td>
<td>11</td>
<td>0.04</td>
</tr>
<tr>
<td>S2</td>
<td>200</td>
<td>23</td>
<td>329</td>
<td>89</td>
<td>91</td>
<td>306</td>
<td>16</td>
<td>0.29</td>
</tr>
<tr>
<td>S3</td>
<td>320</td>
<td>22</td>
<td>428</td>
<td>173</td>
<td>169</td>
<td>501</td>
<td>10</td>
<td>0.34</td>
</tr>
</tbody>
</table>

Table 1
Macroscopical parameters measured by VSM, AHE and torque, the thickness $t$ and the %Cr are determined from sputter time and target composition

<table>
<thead>
<tr>
<th>Sample</th>
<th>$t$ (nm)</th>
<th>$D$ (SEM)</th>
<th>$M$ (NMR)</th>
<th>%Co enriched (NMR)</th>
<th>Stripes visible after etching?</th>
<th>Domain size (MFM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>320</td>
<td>60</td>
<td>&lt; 150</td>
<td>Bulk</td>
<td>No</td>
<td>147</td>
</tr>
<tr>
<td>S2</td>
<td>200</td>
<td>75</td>
<td>207</td>
<td>90</td>
<td>Faint</td>
<td>147</td>
</tr>
<tr>
<td>S3</td>
<td>320</td>
<td>70</td>
<td>312</td>
<td>97</td>
<td>Faint</td>
<td>258</td>
</tr>
</tbody>
</table>

Table 2
Summary of the microscopical parameters with $t$ the film thickness, $D$ the column size and $M$ the main line frequency
areas. S2 has components with 90% Co and S3 with 97% Co. On the other hand, sample S1 has no M peak above the 150 MHz which indicates that there are no Co-enriched areas and that there is a homogeneous distribution of the Cr through the sample.

Another technique to study the segregation is the selective chemical etching of the Cr from the surface of the samples and by the observation of the surface afterwards in a SEM. The results are shown in Fig. 3a–Fig. 3f with the samples before etching at the left-hand side and those after etching at the right-hand side.

In Fig. 3d and Fig. 3f there are faint stripes visible in S2 and S3 after 7 h of chemical etching of the samples. This is also an indication for compositional separation and the presence of a chrysanthemum pattern (CP) structure [4]. On the other hand, sample S1 shows no chemical inhomogeneities inside the columns, even after 14 h of etching. This confirms the NMR results for this sample with a homogeneous Cr distribution.

A magnetic force microscope was used, in the dynamic mode, for observing the ‘magnetic surface’ of the samples. A commercially available tungsten tip covered with a Co/Ni layer was applied for scanning a $2 \times 2 \mu m^2$ area of each sample. The images were recorded in the remanent state after a field of 64 kA/m was applied perpendicular to the sample. The domain size determined by the MFM of S2 and S3 are, respectively, 147 and 258 nm. Together with the column size it can be estimated that the number of columns for one domain in the remanent state is about 5 and 14 for these two samples. Unfortunately, it was not possible to measure the domain size of the low coercive sample S1. The magnetic tip influenced the magnetisation beneath the tip too much, even when the tip was replaced by a magnetic tip with a soft magnetic layer of Ni/Fe. From this sample a Kerr image was recorded which showed long stripe domains.

5. Anomalous Hall measurements on submicron samples

With conventional techniques, such as VSM or Kerr it is not possible to observe the micromagnetic
Fig. 3. SEM images of sample S1 (a, b), S2 (c, d) and S3 (e, f): as-deposited (left) and after chemical etching (right).

switching of individual columns in a hysteresis loop. The maximum sensitivity of a commercial VSM is typically in the order of $10^{-7}$ kA/m, whereas the magnetic moment involved in the switching of one Co–Cr column is of the order of $10^{-12}$ kA/m. With the AHE technique a sensitivity of $10^{-14}$ kA/m can be reached. The principle of AHE measurements on submicron Hall samples in
Co–Cr was first used in 1987 by Webb and Schultz [5]. Their samples had thickness of 1–1.4 μm and a smallest Hall cross size of 0.7 μm. Our samples were prepared by e-beam lithography and ion-beam etching. Using this process samples with a smallest Hall cross dimensions of 0.3 × 0.3 μm² could be prepared. A description of the anomalous Hall measurement set-up is given in Ref. [6].

Fig. 4 shows a drawing of the Hall cross with a limited number of columns inside the Hall cross. The SEM photograph (Fig. 5) shows the smallest Hall cross which could be made and from which a hysteresis curve was recorded.

5.1. Demagnetisation

We will discuss first some aspects of the recorded hysteresis loops which are the results of the smaller dimensions of the Hall cross. As can be seen from the SEM image (Fig. 5) large areas of the Co–Cr near the cross have been removed by etching. This reduces the perpendicular component of the demagnetising factor $(N_z)$ inside the Hall cross and therefore the recorded hysteresis loops will become less sheared.

In Fig. 6 two AHE curves are drawn for an unetched $10 \times 10$ mm² sample (dashed line) and for an etched sample with a Hall cross of $0.3 \times 0.3$ μm² (solid line). The curves are normalised to the maximum and minimum value of the Hall voltage in the loop in order to compare the shape and especially the slopes of the two curves.

Fig. 7 shows the upper part of several Hall hysteresis curves of Hall crosses of different size (active area: $w = 10.0$ mm, 0.8 μm, 0.7 μm, 0.5 μm and 0.3 μm). In a uniformly magnetised sheet, cylinder or sphere there will be ‘charges’ at the surface. These ‘magnetic charges’ produce an internal demagnetising field $H_d (= - N_d M)$ which is proportional and opposite to the magnetisation $(M)$ and which is responsible for the shearing of the hysteresis loop. The internal magnetic field $H_1$ is therefore equal to the sum of the applied magnetic field $(H_d)$ and the demagnetising field $(H_d)$. The sample
geometry of a submicron sample is different from a uniformly magnetised thin film, which results in a lower demagnetising field in the z-direction and therefore $N_z < 1$, $N_x > 0$ and $N_y > 0$.

From Fig. 7 it is clear that the drop in $N_z$ with $w$ is considerable for $w < 1 \mu m$. To calculate the change in $N_z$, the tangent of the curve at $V_{Hall} = 0 \text{ V}$ was determined. The $N_z$ for the $10 \times 10 \text{ mm}^2$ sample is assumed to be equal to 1, the $N_z$ for the $0.3 \times 0.3 \text{ \mu m}^2$ then becomes $N_z = 0.65$.

In Fig. 8 the $N_z$ is plotted as a function of the width ($w$) of the Hall cross for sample S2, represented by the squares. It shows that the drop in $N_z$ is less than 10% for structures larger than $1 \mu m$ but decreases rapidly for the submicron structures with decreasing $w$. The 'central' volume in the Hall cross approaches a cube with decreasing $w$ for which $N_z$ equals 0.33. The higher value of $w = 0.3 \mu m$ can therefore mainly be attributed to the influence of the contact paths.
Fig. 8. Values for \( N_z \) as a function of Hall cross width (\( w \)) of the samples in Fig. 7 and for a sample with \( w = 2.0 \mu m \) (squares). The dashed line represents the theoretical values for a block with dimension \((w \times w \times 200 \text{ nm}^3)\) and the solid line for a strip with width \( w \) (all with the same film thickness).

The theoretical values of a block and a long strip with the same thickness have been obtained by computer calculations [7]. From the difference in \( N_z \), between the theoretical curves of the blocks and the strips it can be concluded that the contact paths have a significant influence on the demagnetisation in the cross. The measured values of the real Hall crosses are in agreement with these curves as the same trend with \( w \) can be seen and all values of \( N_z \) are higher than those of the strips.

5.2. Coercivity

Another significant difference in the curves is a change in coercivity for the S2 sample due to a change in Hall cross dimensions. Fig. 9 is an enlargement of Fig. 6 near the coercive field and demonstrates the increase in coercivity for the small Hall cross (\( \times \)), compared to the unetched sample (\(-\bigcirc\)). The increase is from 90 to 104 kA/m, an increase of 16%. This cannot be explained by a change in internal field due to demagnetisation as the magnetisation in the sample is zero at the coercive field and therefore zero at the demagnetising field also.

The larger coercivity can be caused by the edges of the Hall cross which can act as pinning point if the reversal takes place by domain wall motion (d.w.m.). This explanation is confirmed by the fact that the coercivity for these Co–Cr films increases with reduced dimensions of the cross. The precise shape of the cross and the etch angle can also have an effect on the pinning.

This increase in coercivity is, however, not observed in the other two samples where the coercivity is independent of the Hall cross size. A possible explanation is that for sample (S1) the coercivity is so low that the reversal is not hindered by the edges and for the high coercive sample that there is a more particulate-like reversal mechanism without d.w.m.

5.3. AHE curves and measurement noise

To reveal more of the details of the reversal mechanism hidden in the hysteresis curves, the AHE curves were recorded with very small field steps. The samples which will be discussed here are two submicron S2 samples with dimensions of the Hall cross of, respectively, 0.3 and 0.6 \( \mu m \), two S3 samples (\( w = 0.4 \) and 0.5 \( \mu m \)) and one S1 sample (\( w = 0.4 \mu m \)).

To achieve a good signal-to-noise ratio for the AHE measurements, the time constant was set to \( \tau = 300 \text{ ms} \) and the measured Hall voltage was averaged over three readings of the lock-in amplifier at each field. The size of the field steps was chosen to be small enough to minimise the chance that two successive independent steps (above noise level) in the Hall voltage would be detected as one
single step (a step in the Hall signal is defined as the change in Hall signal for two successive field values). After each field step the program waited until the field was stable (~5 s). The size of the field steps was also adjusted to the shape of the hysteresis curve (small field steps if the Hall signal changes fast). The total number of measuring points was 4000 for each AHE loop, resulting in a 9 h recording time for each loop.

In all samples the thermal noise was much smaller than the noise from other sources. A lot of noise is probably caused by the contacts in the sample holder which can rotate through two axes. These contacts and the unshielded wires near the sample will give the major contribution to the noise.

In Fig. 10 the AHE loops are shown for the three samples with an enlargement of a typical area in the steep part of the loop. These graphs show that there are only steps in the AHE hysteresis curve for the S2 sample. The largest jumps correspond to the switching of one average-sized column. Both the jumps there is an area in which the Hall voltage is almost constant (‘plateau’). A closer look at this area (Fig. 11) reveals that there is also an increase in the signal in this part of the curve. From an enlargement of this ‘plateau’ it can be calculated that the slope is 30 times the slope of the Hall curve in saturation. This means that this effect is not caused by the normal Hall effect but by a very small increase in the AHE voltage for these very small field steps.

The noise in the curves was measured by determining $4 \times$ the rms noise at saturation which contains about 95% of all data points and is about 0.033% of the total signal ($100\% = 2 \times M_s$).

As the number of columns in the centre of the Hall cross in this sample is about 25, and most of the AHE signal is derived from the Hall cross we expect that the number of jumps would be about 25 if the reversal would take place by the switching of the individual columns independently of each other. To study the behaviour of the switching units in more detail several statistical analyses were carried out. The hysteresis curves were recorded many times and the field values of the large steps were studied as a function of the applied field.

This distribution of the step sizes as a function of the applied field shows that there are significant differences in successive measurements with the same sample. For these results Fig. 12 is a typical example (the small steps below the noise level have not been plotted). It shows that even for the two branches in the same loop, the distribution is different for the ascending and the descending branch and that most of the large steps occur around the coercive field $(H_c \approx 90 \text{ kA/m})$. The largest steps around 2–3% correspond to one column.

In another sample of S2, with a Hall cross size of $0.6 \times 0.6 \mu\text{m}^2$, steps in the curve can be also seen. Again the largest steps correspond to the switching of one column. As the number of columns is much larger for the second sample, the individual jumps are more difficult to measure. This is also due to the fact that for AHE measurements the absolute value of the Hall voltage, corresponding to one column, is inversely proportional with the Hall cross dimensions.

As can be seen from the AHE curves in Fig. 10a, Fig. 10b, Fig. 10e and Fig. 10f there are no steps observed in the low and the high coercive samples. We think that the reason is that sample S1 has such a low coercivity that the domain wall motion takes place very gradually with a change in the field that no step occurs above the noise level. For the high-coercivity film S3 we propose that the reversal takes place by the rotation of very small units inside the Co–Cr columns and that those units are exchange decoupled and switch independently from each other.

Table 3 gives a summary of the relevant parameters. The number of columns in the central area of the Hall cross (fourth column) has been estimated as the number of columns that fits in the active area. The numbers in column 2 correspond to different cross sizes and ‘bulk’ with a sample of size $10 \times 10 \text{ mm}^2$.

5.4. Analysis of AHE loops

To study the AHE-hysteresis curves in more detail, each AHE curve was divided into five separate curves. Each curve contains only the steps with a certain step size and each of these step size-distinguished partial hysteresis loops (SPH-loops) can be considered as the hysteresis loop of all the magnetic ‘volumes’ within a certain range. Each
Fig. 10. Anomalous Hall effect hysteresis loops (left) and details of these loops (right) of the samples S1 (a, b), S2 (c, d) and S3 (e, f), respectively.
range of jump sizes is denoted by a class, and those classes are defined in Table 4, where \( \Delta M \) is the change in magnetic moment of each step.

In Fig. 13 the division of an AHE curve of sample S2 in five SPH loops is shown for the loop in Fig. 10c, with the division in classes as given in Table 4. According to this table the loops of Class 1 contain the large steps, Class 2 the small steps, Classes 3 and 4 the small positive and negative steps and also noise, and Class 5 the small negative steps.

Class 1 contains the 'large' (irreversible) steps of volumes > 30 nm\(^3\). Table 5 gives the results of one classification of a typical hysteresis loop. From this table it can be seen that Class 5 has about 5%, which corresponds to steps in the 'reverse' direction, but Class 1 has the largest component with almost 60% (59.6% and 58%). As Class 4 has only 24%, we can assume that the noise is a minor component in the hysteresis curve as Class 4 contains both the noise and a reversible component of the magnetisation.

Fig. 12. Distribution of the steps in the hysteresis curve of sample S2 as a function of the applied field, derived from the loop in Fig. 10c, with \( \square \) for the ascending branch and \( \times \) for the descending branch (the very small steps below the noise level have been omitted).

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### Table 3

Survey of the submicron and the 10 \( \times \) 10 mm\(^2\) ('bulk') Hall samples measured with the AHE

<table>
<thead>
<tr>
<th>Sample</th>
<th>Hall-cross size (w) (( \mu m ))</th>
<th>Column diameter (SEM) (nm)</th>
<th>Number of columns in Hall cross</th>
<th>Domain size (MFM) (nm)</th>
<th>( H_c ) (AHE) (kA/m)</th>
<th>Steps in curve?</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>~ 0.4</td>
<td>~ 60</td>
<td>~ 60</td>
<td>–</td>
<td>13</td>
<td>No</td>
</tr>
<tr>
<td>S1</td>
<td>~ 0.5</td>
<td>~ 60</td>
<td>~ 100</td>
<td>–</td>
<td>14</td>
<td>No</td>
</tr>
<tr>
<td>S1</td>
<td>~ 1.1</td>
<td>~ 60</td>
<td>~ 400</td>
<td>–</td>
<td>–</td>
<td>No</td>
</tr>
<tr>
<td>S1 (bulk)</td>
<td>–</td>
<td>~ 60</td>
<td>–</td>
<td>–</td>
<td>13</td>
<td>–</td>
</tr>
<tr>
<td>S2</td>
<td>~ 0.3</td>
<td>~ 75</td>
<td>~ 25</td>
<td>–</td>
<td>108</td>
<td>Yes</td>
</tr>
<tr>
<td>S2</td>
<td>~ 0.6</td>
<td>~ 75</td>
<td>~ 100</td>
<td>–</td>
<td>103</td>
<td>Yes</td>
</tr>
<tr>
<td>S2 (bulk)</td>
<td>–</td>
<td>~ 75</td>
<td>–</td>
<td>~ 147</td>
<td>88</td>
<td>–</td>
</tr>
<tr>
<td>S3</td>
<td>~ 0.4</td>
<td>~ 70</td>
<td>~ 40</td>
<td>–</td>
<td>168</td>
<td>No</td>
</tr>
<tr>
<td>S3</td>
<td>~ 0.6</td>
<td>~ 70</td>
<td>~ 100</td>
<td>–</td>
<td>163</td>
<td>No</td>
</tr>
<tr>
<td>S3 (bulk)</td>
<td>–</td>
<td>~ 70</td>
<td>–</td>
<td>~ 258</td>
<td>173</td>
<td>–</td>
</tr>
</tbody>
</table>
The loop of Class 1 has the largest coercivity and the $H_c$ decreases for the loops which contain the smaller volumes but does not become zero, not even for Classes 4 and 5 (see last row of Table 5). This indicates that these loops have also a significant magnetic origin, as mere noise would not result in a coercivity for these loops.

### 5.5. Computer simulations

The reversal of a small number of columns which can be measured by the anomalous Hall effect gives us the opportunity to compare and evaluate these results with computer simulations.

The computer model has been described in Ref. [8]. This model takes into account the external field, the anisotropy energy, the demagnetising energy and the exchange coupling. The Landau-Lifschitz equation is solved to obtain the dynamic magnetisation process. The Hall cross was simulated by an array of 5 × 5 exchange decoupled particles (columns). Each column was divided into $6 \times 6 \times 18$ cubic cells with cell dimensions of 8.5 nm$^3$. The particles are magnetostatically coupled and in this case no exchange coupling between the columns was considered. The field step between two successive points is 1.6 kA/m.

In these computer simulations we studied the influence of an IL of 0, 2 and 8% of the total sample volume on the hysteresis loop. In the remaining of this paper we will call these samples A, B and C, respectively. The initial layer was simulated by assigning a random in-plane magnetisation to a certain number of cubic cells in the lower two rows of the particles near the substrate. In real samples this component can be part of an initial layer and/or distributed throughout the sample.
As macroscopical input parameters for our simulation model we used realistic parameters obtained by VSM and torque \(M_s = 400 \text{ kA/m} \) and \(K_1 = 1.6 \times 10^5 \text{ J/m}^3\). Except for the IL the sample has a perpendicular anisotropy with a spread in easy axis of 1.8° from the film normal.

In Fig. 14 the three simulated hysteresis curves are presented. Several changes can be observed with the increase in IL volume. Starting from the saturated state, the drop in magnetisation with decreasing field takes place much earlier with the presence of the IL. The value of the reverse field at which the first large step occurs (corresponding to the switching of one or more columns) is also much lower for the samples with an IL. The total contribution of the small (reversible) parts of the magnetisation, before the first large step takes place is 2.5, 3.9 and 10.6%, respectively, for samples A, B and C. Also can be seen from the size of the large steps that the number of columns which switch independently is 14 and 10 for samples B and C and only 3 for sample A. The largest number of columns switching together in one field step is 5 for sample A and both 3 for samples B and C.

Remarkable changes for the coercivity (410, 403 and 310 kA/m) and the saturation field (760, 750 and 620 kA/m) only occur for sample C with the large IL component of 8%. From these data we conclude that the presence of a large IL or in-plane component of the magnetisation facilitates the reversal, lowers the coercivity and results in the switching of smaller units (less switching of more than one column at a time). The results of all the simulations are summarised in Table 6.

The 'plateaux' in Fig. 15 which is an enlargement of a part of the curve of Fig. 14c shows significant similarities with the 'plateau' in Fig. 11 of sample S2. The gradual decrease (or increase) of the magnetisation can be seen, only there are no 'reverse' steps and there is of course no measurement noise. For a larger IL component the increase of the magnetisation per unit of the applied field of the 'plateau' is larger.

![Graph showing simulated hysteresis loops for an array of 5x5 Co-Cr columns with an IL volume of 0% (a), 2% (b) and 8% (c).](image)

**Fig. 14.** Simulated hysteresis loops for an array of 5x5 Co-Cr columns with an IL volume of 0% (a), 2% (b) and 8% (c).

**Table 6**

Summary of the results obtained by computer simulation of an array of 5x5 Co-Cr columns with a different thickness of the initial layer (IL)

<table>
<thead>
<tr>
<th>Sample</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>IL volume put in model (%)</td>
<td>0</td>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td>Contribution of the IL (%) (ΔM/M_s &lt; 0.3%)</td>
<td>2.48</td>
<td>3.94</td>
<td>10.56</td>
</tr>
<tr>
<td>Number of columns switching individually</td>
<td>3</td>
<td>14</td>
<td>10</td>
</tr>
<tr>
<td>Switching of first column at field (kA/m)</td>
<td>-221</td>
<td>-58</td>
<td>-16</td>
</tr>
<tr>
<td>Total reversed volume before first column (%)</td>
<td>0.23</td>
<td>0.784</td>
<td>6.87</td>
</tr>
<tr>
<td>Largest number of columns switching together</td>
<td>5</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Saturation field (kA/m)</td>
<td>750</td>
<td>760</td>
<td>620</td>
</tr>
<tr>
<td>Coercivity (kA/m)</td>
<td>410</td>
<td>403</td>
<td>310</td>
</tr>
<tr>
<td>(H_c) of Class 1</td>
<td>-408</td>
<td>-338</td>
<td>-309</td>
</tr>
<tr>
<td>(H_c) of Class 2</td>
<td>-626</td>
<td>-424</td>
<td>-451</td>
</tr>
<tr>
<td>(H_c) of Class 3</td>
<td>-395</td>
<td>-253</td>
<td>-112</td>
</tr>
</tbody>
</table>
We also divided the curves into separate curves with different step sizes in the same way as has been done in Fig. 13 for a real Co–Cr sample. A typical example is shown in Fig. 16 for sample C. The loops of Class 1 correspond to the steps of multiple column switching ($\Delta M > 5.0\%$), Class 2 with the switching one column at a time ($3.0\% < \Delta M < 5.0\%$), and Class 3 with very small changes ($0.0\% < \Delta M < 3.0\%$). The curves with reverse steps (Classes 4 and 5) as shown for the real AHE measurement are not present, resulting in only three SPH loops.

For all the three samples the coercivity of the Class 3 loops is much lower than for the Class 1 and Class 2 loops. This is in agreement with measurement results and an indication that the small and in-plane components are responsible for the Class 3 contribution to the total hysteresis loop. Unfortunately, the model is not sophisticated enough to simulate the more complicated CP structure of sample S2 and S3.

6. Discussion and conclusions

The reversal mechanism of Co–Cr has been studied intensively during the last decades but a clear answer whether the reversal takes place by d.w.m. or by a rotation mechanism has not been obtained for all samples with different coercivities and composition. We started with three films of different coercivities and different microstructures.

The measurements on ‘bulk’ samples and the AHE measurements on submicron samples of the three samples reveal that the reversal mechanism in the three samples with $H_e$ values of 11, 90 and 170 kA/m is different both on a macroscopic and on a ‘meso’-scopic scale.
The low-coercivity sample S1 has a low $H_{c1}/H_k$ value corresponding to a stripe domain in the remanent state. The AHE measurements show no jumps as the reversal takes place by a continuous d.w.m. in very small steps.

Sample S2 shows small jumps in the AHE curve, the largest comparable to the reversal of one column, and also a very gradual increase in Hall signal which can be attributed to a combination of domain wall motion and rotation of (parts of) a column.

The high coercivity film S3 has probably a reversal mechanism by rotation of the magnetisation of very small volumes. This is in agreement with the microstructure as has been shown by NMR and SEM imaging after selective chemical etching (CP structure and high compositional separation (CS)). More evidence was found recently by Takei et al. [9]. They found by SANS (small-angle neutron scattering) that the magnetic unit for Co–Cr films with a high CS was smaller than that of a grain. Furthermore, Hono et al. [10] showed by APFIM (atom probe field ion microscopy) studies that compositional fluctuations are present inside the grains of Co–Cr sputtered films which correspond to the CP structure.

The dependence of the $H_c$ on the size of the Hall cross for the S2 sample is attributed to pinning of the domain walls at the edges of the Hall cross which becomes relatively more important for smaller Hall crosses. This dependence is not present in the other two samples as there is no d.w.m. in the S3 sample and in the S1 sample the pinning at the edges is no obstruction for stripping out of the domains in the other directions.

From the results of the computer simulations we have seen that an initial layer (or in-plane) component lowers the coercivity and the saturation field and facilitates the reversal of smaller units. If the real Co–Cr sample has a CP structure the in-plane components (magnetic and non-magnetic) are also distributed inside the columns making the reversal of parts of the column more probable. This makes it more likely that in the case of a CP structure the reversal can take place by the switching of small units, smaller than one column as we have seen for the AHE measurements. A more sophisticated computer model is necessary to simulate the CP structure.

We have also seen that the 'plateau' in the real AHE measurement has much resemblance with the simulation and that the slope can be attributed to the reversal of very small magnetic volumes. Good agreement was also found for the hysteresis loops which were divided into loops with large medium and small steps (SPH loops). The most significant result here was that the coercivity of the Class 3 loops was much smaller than that for the Class 1 and Class 2 loops for both the measurement and the simulations.

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References