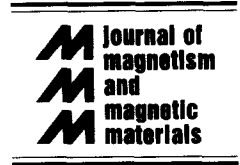




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Reversal studies on sub-micron Co–Cr thin films by AHE analysis

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Abstract

In this study three Co–Cr thin films, prepared under different deposition conditions, are investigated. They have values for the coercivity (H_c) of 11, 90 and 170 kA/m, respectively. The anomalous Hall effect (AHE) has been used to record the hysteresis curves of specially prepared sub-micron Hall crosses. With this very sensitive technique the hysteresis loops were recorded of samples with Hall cross dimensions as small as $0.3 \times 0.3 \mu\text{m}^2$. The AHE loops of the samples, with less than 60 columns, show different ‘meso-magnetic’ properties. Only the sample with $H_{c\perp} = 90$ kA/m shows large steps in the curves above the noise level. The largest steps correspond with the reversal of one column. In this case the number of steps was 5 times the number of columns. From these measurements we conclude that the basic switching unit is smaller than one column. Furthermore the AHE results confirm that the low and the high coercive films reverse by domain wall motion and rotation respectively. The sample with $H_c = 90$ kA/m switches with a combination of these two reversal mechanisms.

1. Introduction

With conventional techniques, such as VSM or Kerr magnetometry, it is not possible to observe the switching of individual columns in a hysteresis loop. The maximum sensitivity of a commercial VSM is typical in the order of 10^{-7} kA/m, whereas the magnetic moment involved in the switching of one Co–Cr column is in the order of 10^{-12} kA/m. With the AHE technique a sensitivity better than 10^{-14} kA/m can be reached. The principle of AHE measurements on sub-micron Hall samples in Co–Cr was first used in 1987 by Webb [1].

2. Experimental results

Details about the sample preparation can be found in [2] and the measurement set-up is described in [3]. The samples which will be discussed here are given in Table 1. In Fig. 1 typical areas in the steep part of the AHE loops are shown for the three samples with in the inset the total (major) loop. These graphs show that there are only steps in the AHE hysteresis curve for the S2 sample. The largest jumps correspond with the switching of one average sized column. In all samples the thermal noise was much smaller than the noise from other sources. The noise in the curves was measured by determining $4 \times$ the rms noise at satura-

tion 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 of sample S2 (with $w = 0.3 \mu\text{m}$) is about 30, and most of the AHE signal is derived from the Hall cross we expect that the number of jumps would be about 30 if the reversal would take place by the switching of the individual columns independent from each other. To study the behaviour of the switching units in more detail several statistical analysis were carried out. The hysteresis curves were recorded many times and the stepsizes in the curves were plotted as a function of the field. For these results Fig. 2 is a typical example of sample S2, with $w = 0.3 \mu\text{m}$ (the small steps below the noise level have not been plotted). It shows that the even for two branches of one curve there are significant differences in the distribution of the stepsizes as a function of the field. Most of the large steps however occur around the coercive field. The total

Table 1

Macroscopical parameters of the samples. The thickness t is determined from sputter time, the saturation magnetisation by VSM and the coercivity by AHE. w is the Hall cross size.

Sample	t [nm]	M_s [kA/m]	$H_{c\perp}$ (AHE) [kA/m]	w [μm]
S1	320	236	11	0.4
S2	200	329	91	0.3, 0.6
S3	320	428	169	0.4, 0.5

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number of steps above the noise level in this sample is about 150, 5 times the number of columns. In another sample of S2 (cross size: $0.6 \times 0.6 \mu\text{m}^2$) steps in the curve can also be seen. Again the largest steps correspond with a switching volume of one column. As the number of columns is much larger than for the first sample the individual jumps are more difficult to measure.

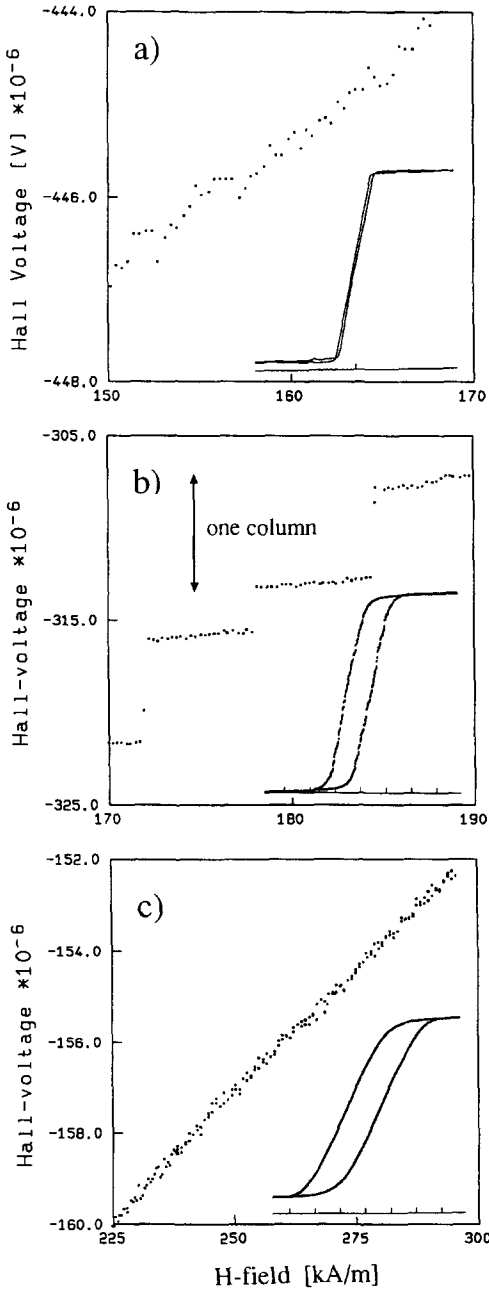


Fig. 1. Parts of AHE hysteresis curves of sample S1 (a), S2 (b) and S3 (c), with in the inset the total hysteresis loop recorded from -1000 kA/m to $+1000 \text{ kA/m}$.

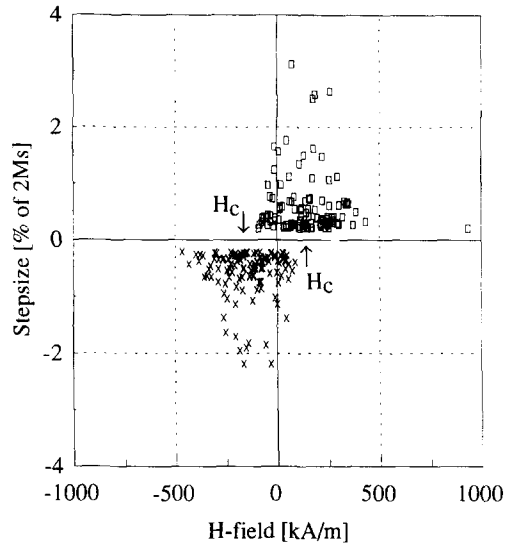


Fig. 2. Stepsizes in the hysteresis curve of sample S2 (Fig. 1b) as a function of the field for the ascending (\square) and the descending branch (\times).

As can be seen in Fig. 1a and c there are no steps in the low and the high coercive samples. An explanation is that sample S1 has such a low coercivity that domain wall motion takes place and no steps occur above the noise level. For the high coercive 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 independent from each other. From this high coercive sample it is known that the microstructure has a chrysanthemum pattern (cp) structure [2,4].

3. Stepsize-distinguished partial hysteresis loops (SPH loop)

To study the AHE hysteresis curves in more detail each loop was divided into 5 separate curves [5]. Each curve contains only the steps with a certain stepsize. These so called Stepsize distinguished Partial Hysteresis loops (SPH loops) can be considered as the hysteresis loop of all magnetic ‘volumes’ within a certain range. Each range of

Table 2
Stepsizes for the classes used to classify the 5 SPH loops

SPH class	Stepsize [% of $2M_s$]	Step specification
1	$\Delta M > 0.3$	large positive
2	$0.1 < \Delta M < 0.3$	small positive
3	$0 < \Delta M < 0.1$	very small positive
4	$-0.1 < \Delta M < 0$	very small negative
5	$\Delta M < -0.1$	small negative

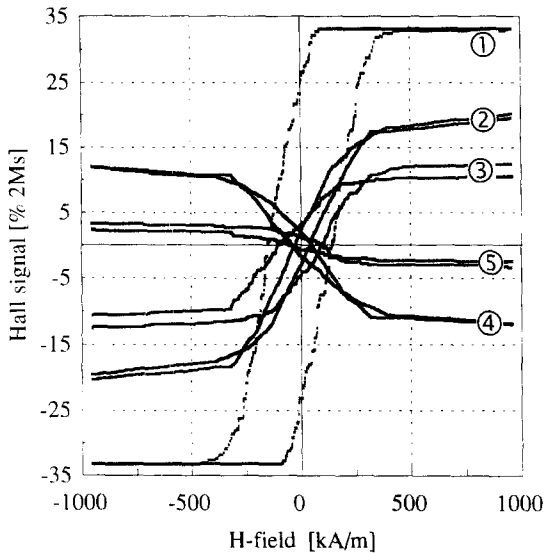


Fig. 3. SPH loop of sample S2 with the classification according to Table 2.

jump sizes is denoted by a Class, and those classes are defined in Table 2, where ΔM is the change in magnetic moment of each step. So we try to analyze the hysteresis loops as a function of particle size and the 'sum' of all SPH loops results again in the original hysteresis loop.

In Fig. 3 the division of an AHE curve of sample S2 in 5 SPH loops is shown for the major loop in Fig. 1b, with the division in classes as given in Table 2. Class 1 contains the 'large' (irreversible) steps of volumes $> 30 \text{ nm}^3$ and has the largest contribution with almost 70% of $2M_s$ (amplitude of the original loop). This loop has also the largest coercivity and the H_c decreases for the loops with smaller volumes but does not become zero, not even for Class 4 and 5. Class 5 has about 5% of $2M_s$, this corresponds with steps in the 'reverse' direction. As Class 4 has only 24% of $2M_s$, we 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.

4. 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 domain wall motion or by a rotation mechanism has not been obtained for all samples with different coercivities and composition. We started with three films with different microstructure and consequently different coercivities.

The measurements on as-prepared samples ($1 \times 1 \text{ cm}^2$) and the AHE measurements on sub-micron samples of the three specimens with H_c values of 11, 90 and 170 kA/m reveal that the reversal mechanism is different on both macroscopical and mesoscopical scale.

The AHE measurements on the low coercive sample S1 show no jumps as the reversal takes place by a continuous domain wall movement 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 (between two steps) in Hall signal which can be attributed to a combination of d.w.m. and the rotation of (parts of) a column. The number of steps in the AHE curve above the noise level is about 5 times the number of columns inside the Hall cross, therefore it can be concluded that the reversal of most of the columns takes place in several steps. The high coercive 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 by selective chemical etching and SEM imaging (cp structure and high compositional separation (CS)), these data will be published in a separate paper [2]. Recently, Takei et al. [6] found by SANS (Small Angle Neutron Scattering) that the magnetic units for Co–Cr films with a high CS was smaller than that of a grain.

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