DOMAINS AND MAGNETIC REVERSALS IN CoCr

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ABSTRACT

Magnetron sputtered CoCr layers with various thicknesses, coercivities and other magnetic properties have been studied by a digital enhanced magneto-optical Kerr microscope. The slope (T) at $[dM/dH]_{M=0}$ is determined from the perpendicular hysteresis loop. Together with K_1 these values have been used for calculation of the characteristic stripe domain properties. The observed domain densities have been compared with the calculated densities based on a continuous or particular behaviour of CoCr. The relation between typical fields (like the nucleation field and surface coercivity), the observed domain configuration and the shoulder of the hysteresis loop are given.

On the basis of the domain structure (from stripe to cluster-like) we conclude that the samples can be classified in low, medium and high coercive layers.

INTRODUCTION

The last few years an enormous avalanche of data about the structural properties and magnetic behaviour of deposited CoCr layers has been presented in literature. All these layers exhibit a more or less columnar morphology with the hcp c-axis perpendicular to the surface. A very important question to be answered is the nature of the magnetization reversal process and the domains. Based on microstructural properties two basic types of magnetic behaviour are proposed namely the domain wall motion model (in the so-called continuous layer) and the rotation model of the particle structure. In the first model that is often found in several ferromagnetic layers, there will be an exchange interaction across the column boundaries. Domain wall motion can then occur at every crystal (column) size or layer thickness.

The particle model is, in principle, based on the absence of exchange forces between the columns. This leads, as a function of the crystal size, to single domain particles which can reverse their magnetization by one of the rotation mechanisms or by domain wall motion as a multidomain particle does. In the case of the particle model the reversal behaviour could be influenced by the magneto-static interaction.

Both models are discussed in literature and supported by direct and indirect measurement methods. The latter are carried out by measuring the shearing of the perpendicular (easy-) hysteresis loop [1], determining H_c and H_r as a function of the applied field [2-5], calculating Rh from torque curves [3,6] and domain studies by neutron depolarisation [7]. These references support the different modes of rotation [2-6] and domain wall motion [1,7].

Two direct observational methods which are extensively used at the moment are photon and electron techniques. The magneto optic method equipped with a digital image-processing system [8], having a resolution of about 200 nm, provides information about the surface magnetic properties by recording the domain structure. A much higher spatial resolution can be obtained with Lorentz microscopy. Using this method a direct relation between microstructural and chemical aspects and the magnetic structure can be obtained. A disadvantage of this method is that in general relatively thick CoCr layers have to be thinned to an acceptable thickness and this could change the magnetic structure. At the moment there is little experimental information available on the relation between domains and microstructure in CoCr. Preliminary experiments [9] obtained from layers with a thickness of 110 nm have shown a continuous transition between wall movements and magnetization reversals that only take place inside the columns. Nevertheless this thickness is normally not used for recording media (about 500 nm). Also by Lorentz microscopy it is reported that the domain width is assumed to correlate with the columnar size [10].

The present paper describes some experiments on the relation between observing domains with the digital enhanced Kerr microscope [11] and the perpendicular hysteresis loop.

RELATION BETWEEN HYSTERESIS LOOP AND DOMAINS

In general, the easy axis loop of ferromagnetic thin layers having a uniaxial anisotropy shows a rectangular shape (excluding demagnetizing fields) and exhibits irreversible changes. If the magnetization is uniform and the switching mechanism takes place by coherent rotation, then $H_c = H_k$. In most materials domain walls are nucleated (at a field H_n) and M can be reversed by wall motion ($H_n < H_k$). Domain wall coercivity (H_{cw}) is caused by the interaction of the wall with imperfections. In polycrystalline materials (like CoCr) the boundaries are the most important centre for this. The experimental perpendicular hysteresis loop for CoCr has an anomalous shearing which is different from that expected in the first place from the demagnetizing field. The sheared loop shows that the average magnetization can have every value between positive and negative M_s. This is impossible for a single domain film with pure coherent rotation.

A multidomain structure, for instance, can explain this slope by variation of the domain width. The domain walls have a great influence on the magnetization process and consequently the shearing of the easy loop can be described by [12].

If the medium has a particulate behaviour then the average magnetization is the sum of all particle magnetizations. Such particles can be switched by rotation (single domain) or by domain wall motion in a particle without stable domains. Again the loop shearing (and the H_c) will be changed by the type of particle character.

The relation between the film thickness and the slope (T) of the easy loop was first measured by Wielinga et al.[1] for RF sputtered CoCr layers. Comparison of measured and calculated data of this initial perpendicular susceptibility led to the conclusion that there is a good agreement with the domain wall model [1]. This result is supported by Schmidt [14] who also concludes the characteristic behaviour of a continuous medium on basis of Kerr microscope observation.

Another important feature of the perpendicular loop of CoCr is the presence of the typical "shoulder" which directly corresponds with bubbles and/or stripe domains. The explicit existence of such a shoulder depends on the magnetic properties and consequently the preparation conditions. Starting from saturation one of the characteristic fields is the nucleation field (H_n) where reversed domains (bubbles?) are nucleated and another typical parameter is the field where the reversed domain starts to grow (H_{cw}). H_n depends on the amount and nature of the nucleation centres and consequently on the microstructural aspects. Again the loop shearing will also be influenced by the wall coercivity which strongly depends on the pinning centre density. If, for instance, the domains and crystals both have the same order of magnitude then the domain growth is hindered by crystal boundaries and the domain structure will be poor. This is mostly the case in layers with a high H_c.

Films where domains vary in shape and size will have a different demagnetizing energy to those with pure stripe domains. This results in a different shearing of the easy loop. Beside the layer thickness the initial susceptability also depends also on the material parameter ($= \sigma_w / \mu_0 M_s^2$).

For pure stripe domain structures the domain period (Po) and other typical parameters can be calculated by minimizing the total energy per unit volume of the domain media, given by the sum of the demagnetizing energy and the wall energy and can be calculated from [12]. The domain wall energy and coercivity will be influenced by the layer thickness, surface roughness, stress and inhomogeneities. For RF sputtered CoCr films (15 and 19 at% Cr) the relation between T and Po is given in

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[1] by applying [12,13].

EXPERIMENTAL PROCEDURE

The CoCr layers used are RF magnetron sputtered (3" target) on Si substrates with a background pressure of $1.5*10^{-7}$ mbar and Par = $6*10^{-3}$ mbar. The sputter power (and consequently the rate) is varied from 250-550 watt by varying the sputter voltage from 150-250 volt. The film composition (21 at% Cr) and thickness were determined by XRF. The magnetic parameters (M_s, H_{cv}, T) are measured by VSM, torque magnetometer (K_1), M.O. Kerr hysteresis loop tracer [17] (surface coercivity H_{cs}) and the digitally enhanced Kerr microscope (domain structure).

DIGITALLY ENHANCED KERR MICROSCOPE

The specimens are observed with the microscope described in [8]. The maximum applied field during observation depends on the substrate thickness and can reach 800 kA/m. This perpendicular field is generated by a tipped pole which is located under the specimen. Domain observation in CoCr- layers, using the polar Kerr effect, is very difficult because the surface is microscopically rough. Image processing is therefore an indispensable technique to suppress the non-magnetic background structure. Moreover, all samples are covered with a 1/4 λ evaporated ZnS layer in order to intensify the optical properties. In general the procedure was as follows: First the film is completely saturated and a reference image is stored. Then, by lowering the field, the image on the monitor is a subtraction of the actual from the reference image. Further, the quality of the resulting images can be optimized, before taking a photograph, by varying several parameters, i.e. the mean number of images used to form the reference image.

EXPERIMENTAL RESULTS

The most relevant properties obtained from VSM and torque measurements are given in Table 1.

Sample	M_s [kA/m]	h [nm]	Hcv [kA/m]	Pmr [nm]	D [nm]	Domain densities $[1/cm^2]x10^6$				
						Nm	Nb	Nh	Nr	Nn
1	402	520	8	660	76	70	90	6664	1720	3082
2	384	700	28	?	92	-	-	4547	1044	1875
3	423	700	18	730	92	46	95	4547	1100	1975
4	410	1230	8	910	136	23	51	2081	543	966
5	426	1436	40	?	132	-	-	2209	467	839
6	415	1300	24	960	136	30	44	2081	492	875
7	441	760	10	790	100	54	95	3849	974	1742
8	441	790	20	-	102	-	-	3700	882	1578
9	437	788	60	-	102	-	-	3700	665	1190
10	425	1311	52	-	136	-	-	2081	396	705
11	426	650	32	700	88	51	180	4970	1090	1964
12	413	1220	46	850	136	137	83	2081	427	760
13	434	700	60	-	92	-	-	4547	791	1420

Table 1

The slope (T) of the perpendicular hysteresis loop varies from 1.10-1.50 and the first order anisotropy constant K_1 has an average value of $15*10^4$ J/m^3 for the present samples. With these data the characteristic stripe domain parameters have been calculated from [13,14]. For each sample we have determined Po, material length (λ), Bloch wall energy (σ_w), exchange constant (A) and Bloch wall thickness (l).

We found that the measured T has a great influence on these calculated values. The exchange constant and consequently the domain wall thickness, calculated with this method, show a wide range of values. Acceptable values for these parameters were only found for a few samples showing stripe domains.

All specimens were observed with the Kerr microscope and it was only from samples 8-10 and 13 that no domain structure could be registered. Based on our experience this is mainly due to the surface roughness.

Typical examples of the observed domain structures are given in figures 1 and 2 together with the perpendicular hysteresis loops for samples 4 and 12 respectively. Both have different magnetic properties (see table 1). Sample 4 having a very low H_{cv} shows a typical bubble loop (shoulder). If the field is decreased, starting from saturation, the round domains (about 50 nm) will grow into "stripe" domains. In remanence the field is reversed and increasing it causes the stripes to finally break up into round domains.

This type of hysteresis loop is also found for samples with higher coercivities (samples 1-4, 6,7 and 11).

Also in table 1 different properties obtained from domain observation are given together with some other characteristic values like the domain period (Pmr) and domain densities per cm^2 (N) both in remanent state.

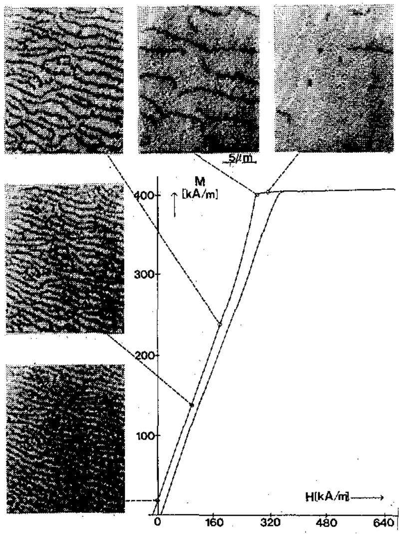

Fig.1. Domain configuration in relation to the perpendicular hysteresis loop for low H_c (sample 4).

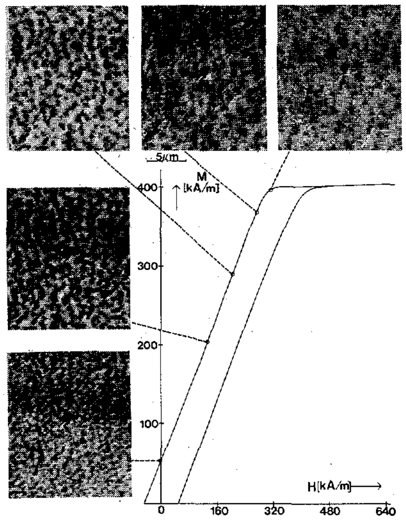

Fig.2. Domain configuration in relation to the perpendicular hysteresis loop for high H_c (sample 12).

Using TEM surface replicas we measured the crystal (column) diameter (D) for another series of magnetron sputtered samples. Applying these values to the present samples, it can be calculated that the domain width at remanence (dmr) is about 4D. For comparison of the theoretical and observed domain densities we utilize the continuous and particle behaviour. First we determine the measured density (Nm) from the photographs by counting the number of domains and dividing by the area. Secondly we use a simple bubble lattice geometry and calculate $Nb = (2.5\ dmr)^{-2}$. Finally three different column distribution functions are used to translate the "physical structure" into a "domain structure" with the particle behaviour as starting point. Two are based on the crystal distribution function which was determined from a TEM-replica (surface) micrograph of a 950 nm thick layer [15].

The random distribution function (Nr) is determined after randomly adjusting an up or down magnetization to the columns. The intersection length of the domain structure can be measured from this. Maximization of the number of pairs of neighbouring columns with opposite signs gives the so-called natural distribution (Nn). Both distribution functions have been used for all thicknesses of our samples and are given per cm^2. Finally a simple hexagonal model of uniform grain size (honeycomb shaped) was introduced by Schmidt [14] by using $Nh = 2/3\sqrt{3}\,D^2$.

We calculated (for the particulate model) the domain densities for the three models which are also given in table 1. It can be clearly seen that the experimental densities are much smaller than these values.

In table 2 some characteristic fields are listed together with a qualitative judgement of the hysteresis loop and the domain behaviour. From a series of photographs as a function of the applied field the H_n (determined by extrapolation) and H_{cw} are derived. The H_{cs} is measured with the M.O Kerr hysteresis tracer and $H_k = 2K_1/\mu_0 M_s$.

We have classified our samples in 3 groups on the basis of the observed domain structures (see table 2). First the long stripe domain material (samples 1,3,4) having a very pronounced shoulder at low coercivity (8-16 kA/m), of which an example is shown in Fig. 1. The second group having a medium coercivity (24-32 kA/m), short-stripe domains and a small shoulder (samples 6 and 11). Finally the high coercivity ($\geq$ 40 kA/m) group without the typical shoulder showing a more cluster-like domain structure (see Fig. 2). At least in the latter case the definition of H_{cw} is questionable. To explain the different domain behaviours the ratios of characteristic fields are given.

Sample	Hn [kA/m]	Hcw [kA/m]	$\frac{Hcw}{Hk}$	$\frac{Hcs}{Hcw}$	$\frac{Hcs}{Hn}$	$\frac{Hcv}{Hcw}$	shoulder	stripe domains
1	320	260	.53	.02	.02	.03	++	++
3	352	272	.53	.04	.03	.07	+	++
4	352	312	.58	.02	.02	.03	++	+++
7	364	236	.44	.03	.02	.04	++	+
6	432	256	.43	.13	.09	.10	+	-+
11	368	212	.39	.15	.12	.04	+	-+
5	408	320	.54	.13	.10	.13	-	-
12	395	200	.33	.23	.15	.23	-	-

Table 2

DISCUSSION AND CONCLUSIONS

It is not possible to fully understand the domain behaviour and reversal mechanism of the CoCr layers on the basis of our prelimary experiment. The parameter dependency and the complicated relation with the theory allow only understanding of particular samples. A general explanation is not possible at present. When relating the measured results with the known theory [13] we have to realize that the following assumptions have been made. The influence of the coercivity and the wall volume is neglected and the wall energy is taken independent of the film thickness. This is not the case for our samples. Nevertheless after comparing the measured and calculated data for the domain densities (using both models) we conclude that the wall motion model can explain our results. The domain wall theory and the measured results are only in agreement for some of the samples namely 4 and 7 which both show the typical shoulder and stripe domain configuration.

On the basis of our observations we divided our samples into 3 groups of low, medium and high coercivities which correlate with the appearance of the typical shoulder and the stripe domain behaviour. This is supported by the ratios of the characteristic fields. For instance small values for H_{cs}/H_n show a more pronounced stripe domain character. If this factor more increases a more cluster-like structure appears. Our observations are in agreement with the results of Schmidt [14] who measured samples which were made by various deposition methods having different magnetizations.

We have also found a relation between the coercivity and the nucleation density. For the 3 classified groups this relation is roughly 2:5:10.

High coercivity films ($\geq$ 40 kA/m) are more suitable for perpendicular recording and the cluster-like domains resemble more the "chain of columns" type proposed on the basis of neutron depolarization [7].

Magnetic reversal in the columns has to be studied with advanced electron microscopical observation methods. Together with neutron depolarization [16], surface coercivity studies [17] and more detailed observations with Kerr microscopy this problem may be tackled in the near future.

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REFERENCES

[1] T. Wielinga, J.C. Lodder and J. Worst, IEEE Trans. Magn., MAG. 18, 6, pp. 1107-1109 , (1982)
[2] H.N. Betram and S. Shtrikman, J. Magn. Mag. Mat. 45, pp. 88, (1984)
[3] S. Iwasaki, K. Ouchi and N. Honda, IEEE Trans. Magn. MAG. 16,5, pp. 1111-1113, (1980)
[4] C. Barbero et al., IEEE Trans. Magn. MAG. 18, 6, pp. 1104-1106, (1982)
[5] E.R. Wuori and J.H. Judy, IEEE Trans. Magn. MAG. 20, pp. 1867, (1984)
[6] E.R. Wuori and J.H. Judy, IEEE Trans. Magn. MAG. 20, pp. 774, (1984)
[7] K. Hemmes, J.C. Lodder, M.Th. Rekveldt and W.H. Kraan, J. Phys. D. 17, L157, (1984)
[8] F. Schmidt, W. Rave and A. Hubert, IEEE Trans. Magn. MAG. 21, pp. 1596, (1985)
[9] H. Hoffman private communication
[10] P.J. Grundy and M. Ali, J. Magn. Mag. Mat. 40, 1-2, pp. 154-162, (1983)
[11] At the University of Erlangen, Erlangen, Germany
[12] C. Kooy and U. Enz, Philips Res. Repts. 15, 7, (1960)
[13] P. Dekker, "Magnetization reversal processes in thin MnBi films", Thesis, Delft University of Technology, Delft, The Netherlands, (1974)
[14] F. Schmidt and A. Hubert, Submitted to J. Magn. Mag. Mat.
[15] W.H. Kraan, M.Th. Rekveldt, K. Hemmes and J.C. Lodder, Physica 13B, 440, (1986)
[16] W.H. Kraan, M.Th. Rekveldt, K. Hemmes and J.C. Lodder, Presented at MRM '86, Parma, Italy (1986)
[17] K. Hemmes, J.C. Lodder and Th.J.A. Popma Presented at MRM '86, Parma, Italy (1986)