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**LETTER TO THE EDITOR**

# The magnetic domain structure of CoCr layers studied by neutron depolarisation

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**Abstract.** The domain structure of relatively thick RF-sputtered CoCr (81 : 19 at %) layers with a columnar morphology in the range of thickness 1–5 $\mu$m was investigated using a polarised neutron beam. On the basis of the results a model of straight domains running through the entire film thickness has to be rejected. Arguments are given for a serpentine-like domain structure with a domain width about the same as the column diameter (0.1–0.3 $\mu$m), resulting in a 'chain of columns' model.

Sputtered CoCr layers have already been applied as a perpendicular recording medium with extremely high density (Iwasaki 1980). The morphology and crystal structure and therefore the magnetic properties of the film depend strongly on the deposition and growth conditions.

Our films consist of conically shaped crystals or columns with c-axis textured hcp-structure (Lodder *et al* 1983). The crystal or column diameter increases almost as the square root of the film thickness. In order to understand the magnetisation process, domain studies are of great importance. If the exchange force is restricted to the columns the domain size coincides with the crystal diameter. The columns will act as single domain particles and a rotational switching mechanism is to be expected for the magnetisation process. In this case the domain structure is determined by a minimum of the magnetostatic energy and will appear as a kind of checkerboard pattern formed by the individual columns. In the case of a continuous model, where the exchange forces extend over the crystal boundaries, the magnetisation process is due to domain wall motion which is more or less hindered by the column boundaries.

The domain dimensions of both particle and continuous models are too small to be observed by Kerr microscopy or the Bitter technique. The most suitable method for observing small domains is Lorentz transmission electron microscopy. A 1 MeV microscope has to be used for observing CoCr layers thicker than 0.1 $\mu$m, up to a maximum of 0.3 $\mu$m (Ouchi and Iwasaki 1982, Grundy and Ali 1983). A specially designed sample stage to exclude an external perpendicular field from the specimen during domain observations is essential (Ouchi and Iwasaki 1982, Ohkoshi and Kusuda 1983).

Different domain configurations with in-plane magnetisation are observed in thin (<60 nm) CoCr layers (Grundy and Ali 1983, Ohkoshi and Kusuda 1983, Wielinga 1983). This can be explained by variations in the preparation methods. None of these films have a well oriented hcp c-axis. For a good textured layer ($Co_{77}Cr_{23}$), with a

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thickness of 50 nm, stripe domains with a width of 0.1 $\mu$m were observed by Grundy and Ali (1983). Different domain forms were observed for films with much better orientation and a thickness of 0.1 $\mu$m (Grundy and Ali 1983, Ohkoshi and Kusuda 1983, Wielinga 1983). A magnetic black-and-white dot structure with a distance between the dots in the same order as the columnar diameter has been shown by Ohkoshi and Kusuda (1983). In this case the film morphology (one column consists of several crystallites) is totally different from the equiaxed crystal structure present in the layers of Grundy and Ali (1983) which show a stripe domain width in the order of the crystal size.

Ouchi and Iwasaki (1982) showed a stripe–maze domain configuration having a stripe width less than 0.1 $\mu$m which again is the same as the column diameter. A relatively thick film (0.3 $\mu$m) made by Grundy and Ali (1983) has a similar domain configuration as the 0.1 $\mu$m film of Ouchi and Iwasaki (1982).

We can conclude from these Lorentz microscopy results that the domain width is of the same order as the crystal (column) size. Grundy and Ali (1983) concluded that the stripe domain structure consists of a chain of crystals.

Andra *et al* (1984) have investigated theoretical models for columnar film structures where the magnetisation reversal is explained by the rotational mode. They have shown by numerical calculations that successive magnetisation reversal of rows of columns is likely to occur. On measuring the angular dependence of the coercive field in a 1 $\mu$m film, Iwasaki *et al* (1980) concluded that the magnetisation reversal in CoCr films takes place by a rotational mechanism of the individual columns. After analysing the hysteresis loop over a range of films (thicknesses 50–2000 nm), studying the coercivity and stand-still recording experiments Wielinga *et al* (1982) proposed that a domain-wall motion model is a better alternative.

It is clear that from theoretical and experimental data the magnetisation reversal mechanism in polycrystalline columnar CoCr films is not yet completely understood. For a better understanding we introduce preliminary results of neutron depolarisation measurements.

When a polarised neutron beam passes through a ferromagnetic specimen, Larmor precession of the polarisation vector occurs around the spontaneous magnetisation inside the magnetic domains. This rotation of the polarisation of the neutron beam when passing a magnetic material offers, in principle, the possibility of measuring the dimensions of magnetic domains if the magnetic induction inside the material is known. The polarisation vector can be directed in one of the $(x, y, z)$ directions of the laboratory system and after transmission through the sample its component along any one of these directions can be analysed. Thus, a $(3 \times 3)$ depolarisation matrix can be measured (Kraan and Rekveldt 1977, Rekveldt *et al* 1979). Here only the diagonal elements will be considered.

If the domains extend through the thickness of the film as shown in figure 1, the rotation angle of the polarisation for a neutron beam passing perpendicularly through the film and with its polarisation vector perpendicular to the beam is given by:

$$\varphi = 5.72 \times 10^8 (M_s \cdot h) \cdot \lambda \tag{1}$$

where $M_s$ is the saturation magnetisation in $\mathrm{Am}^{-1}$, $h$ the film thickness and $\lambda$ the neutron wavelength, both in metres. It can be shown, that in this case the matrix elements $D_{yy}$ and $D_{zz}$ are equal to the cos $\varphi$ and $D_{xx} = 1$ (Rekveldt 1976).

For CoCr films, with a practical thickness for perpendicular recording of 0.5 $\mu$m and $M_s = 460\ \mathrm{kAm}^{-1}$, cos $\varphi$ is found to be 0.9982 using a neutron wavelength of 0.47 nm. This value cannot be distinguished from the unaffected value of cos $\varphi = 1$. Regarding

equation (1) and the limitations on $M_s$ and $\lambda$ there is a need for thicker films and/or more films in a row. Consequency four series of fourteen films were RF-sputtered on Si substrates of 1 × 1 cm in the range of 1–5 $\mu$m using a CoCr (81 : 19 at %) target. Optimised preparation conditions have been described by Lodder and Wielinga (1984). Film thicknesses were measured using both SEM and x-ray fluorescence, which agreed within 5%. From the data a sputtering rate of 0.256 nm $s^{-1}$ can be determined.

The product $(M_s \cdot h)$ of all films was accurately measured with a vibrating sample magnetometer calibrated with a pure Ni sample, and found to be constant within 4% standard deviation for all series. This product together with the film thickness leads to a saturation magnetisation of 460 $kAm^{-1}$.

In passing a polarised neutron beam through $n$ samples the total precession angle $\varphi$ is not simply obtained by multiplying the angle of one film by $n$, since in one film the polarisation rotation might be opposite to that in the next. Statistical considerations lead to a matrix element determined by $<\cos \varphi>^n$, where the brackets stand for an averaging over all possible neutron paths. Calculated values at $\theta = 0$ (using a neutron wavelength of 0.472 nm) for packages of 14 films used in the experiment are given in table 1.

**Table 1.** Calculated values of the depolarisation according to equation (1) compared with experiment. The film thickness $h$ is determined from a least squares fit to the x-ray fluorescence and SEM measurements.

| $h$ ($\mu$m) | $M_s \cdot h$ (A) | $\cos \varphi$ | $\cos^{14} \varphi$ | exp | $h_{eff}/h$ |
|---|---|---|---|---|---|
| 0.95 | 0.421 | 0.994 | 0.913 | 0.965 ± 0.005 | 0.63 ± 0.07 |
| 1.90 | 0.855 | 0.973 | 0.686 | 0.88 ± 0.005 | 0.58 ± 0.03 |
| 3.81 | 1.737 | 0.892 | 0.202 | 0.67 ± 0.01 | 0.51 ± 0.02 |
| 4.76 | 2.185 | 0.831 | 0.075 | 0.57 ± 0.01 | 0.48 ± 0.02 |

Assuming a simple one-dimensional domain structure (figure 1) the domaon period can be determined by measuring the depolarisation as a function of the angle $\theta$ between the film normal and the neutron beam. If $\theta = \tan^{-1}(2d/h)$ and the polarisation rotation in two adjacent domains will cancel each other out leading to $\cos \varphi = 1$. The same holds for a package of $n$ films. The result of such a measurement for the 4.76 $\mu$m thick CoCr films is shown in figure 2. In the same figure the one-dimensional model is fitted to the

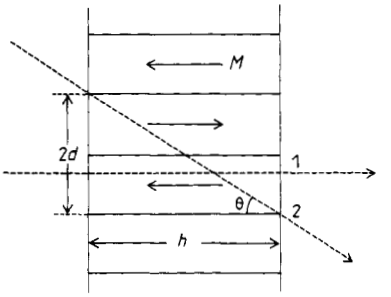


**Figure 1.** One-dimensional model of straight domains through the entire film thickness in which the beam directions of maximum (1) and zero depolarisation (2) are indicated.

results at small angles by varying the domain width and an effective film thickness discussed below. The minimum of $D_{yy}$ (or $D_{zz}$) at $\theta = 0$ is not as large as expected based on a model of straight domains running through the entire film thickness. This discrepancy can be expressed in an effective film thickness, which for all films is about one half of the real thickness. The discrepancy is larger for the thicker films (see table 1). This may be due to the existence of closure domains or due to 'spike domains' on the substrate side with opposite magnetisation, which effectively diminish the depolarisation.

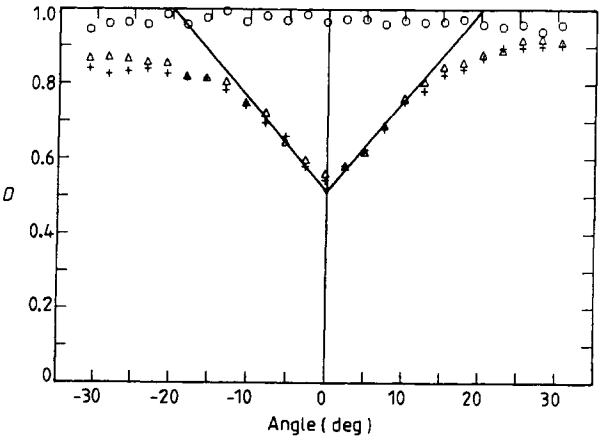


**Figure 2.** The diagonal elements $D_{xx}$ (○), $D_{yy}$ (△) and $D_{zz}$ (+) of the depolarisation matrix as a function of the angle between the neutron beam and the film normal, for a package of fourteen 4.76 μm thick CoCr films. The solid curve is a fit of the one-dimensional model to the results at small angles.

Closure domains may occur since for these films the uniaxial anisotropy constant $K$ is slightly smaller than $\frac{1}{2}\mu_0 M_s^2$. The accuracy of $D_{xx}$ (which should reveal an in-plane component of the magnetisation) is not large enough to confirm the existence of closure domains. However, even if these do exist they cannot fully account for the low effective thickness. Hence the reason may be found in spike domains which could be formed in the smaller cyrstallites of the initial layer.

From the fit of the simple one-dimensional model the order of magnitude of the domain width can be calculated according to:

$$\langle d \rangle = \tfrac{1}{2} h_{\text{eff}} \cdot \tan(20°). \tag{2}$$

The effective thickness has been provisionally used here instead of the real film thickness. But depending on the cause of the discrepancy between these two thicknesses perhaps a higher value should be used.

Care should be taken in the interpretation of the measured domain width $\langle d \rangle$ indicated in figure 3, since it depends on the domain structure assumed. In a serpentine-like domain structure, which is quite common for films with perpendicular anisotropy, the measured domain width is the average intersection length of random lines across the domains in the plane of the film. This will be larger by about a factor 1.5 to 2 than the perpendicular cross-over usually referred to as the domain width. In this case the corrected measured domain width is lower than the theoretical value predicted by the Kooy and Enz model (1960) for straight domains in a continuous film.

In the approximation that the interaction between the poles on the top and bottom of the film is neglected, this model results in a domain width which is proportional to the square root of the film thickness:

$$d = 0.19(h)^{\frac{1}{2}} \qquad (d \text{ and } h \text{ both in } \mu\text{m}).$$

This approximation (Kittel 1949) is justified if $d \ll h$. The exact model shows a minimum in the domain width for $h = 15.4$ nm and small deviations from the Kittel approximation for $h > 30$ nm in the case of our films.

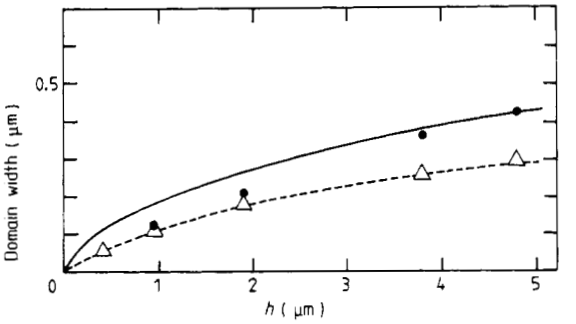


**Figure 3.** Domain width according to the Kooy and Enz model (———), column diameter (—△—) and the measured domain width (●) according to equation (2) as a function of the film thickness $h$.

This relationship is given in figure 3 together with the average column diameter at the top of the film measured by scanning electron microscopy. The same functional dependence of both the column diameter and domain width on the film thickness is striking, and an interaction of the domain structure with the columns may be expected for all film thicknesses, which will lower the Kooy and Enz domain width.

However, in a domain structure consisting of columns or clusters of columns in a checkerboard pattern, the measured intersection length is smaller than the diameter of the clusters or columns. Hence, this diameter can be found by multiplying the measured domain width $\langle d \rangle$ by a factor of about 1.3 resulting in a domain diameter which is significantly larger than the column diameter. Then only clusters of columns with the same magnetisation direction are possible. Observation of such large domains ($>0.54$ $\mu$m for the thickest film) should be possible with magneto-optical Kerr rotation. However, no magnetic contrast has been observed. This could be due to the small Kerr rotation-angle of CoCr of about 6′ in the visible region.

In a domain structure consisting of individual column domains arranged in a honeycomb pattern the domains have, on an average, two neighbouring columns with the same direction of magnetisation, resulting in a serpentine-like domain structure. The real films have an irregular columnar structure and will show the same feature, in that it is impossible for each column to have only antiparallel neighbours.

It may be tentatively concluded that in relatively thick CoCr films (1–5 $\mu$m) the domain structure is serpentine-like with a domain width of about the column diameter resulting in a configuration of a chain of columns. Further studies will deal with computer simulations based on more sophisticated models of the domain structure, in order to find a better agreement with the experimental depolarisation and to determine the domain width and structure more accurately.

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