Domain wall effects in neutron depolarisation in Co–Cr films

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The height and stripe width of the domains in Co–Cr films of 300 nm thickness is determined from angle-dependent 3-D neutron depolarisation. The effect on the data due to Bloch walls and due to domain walls identical with column boundaries is discussed. The maximum wall thickness derived is ~ 2 and ~ 30 nm, respectively.

1. Introduction

A long-standing question connected with the magnetisation reversal mechanism in Co–Cr film is whether the film is to be considered as a continuous magnetic medium or as a medium composed of crystallites with parallel *c*-axes behaving magnetically as a collection of particles.

A possibility to shed light on this question is to investigate the thickness of the domain walls (DWs). In a continuous medium the DWs would be Bloch walls of thickness of the order $\pi\sqrt{A/K_u}$ (*A* being the exchange constant and K_u the constant of uniaxial anisotropy). In a particulate medium the DWs could (partly) coincide with crystallite boundaries. Exchange would play a minor role in determination of the thickness of the boundary, and hence it should be much thinner than a Bloch wall. On the other hand, by Cr segregation the boundary could be degenerated into a non-magnetic region of any thickness. In this paper the consequences of both views for static neutron depolarisation are discussed and compared with observations.

2. Depolarisation technique

A neutron beam with its polarisation vector successively parallel to the axes of the coordinate system is transmitted through a sample. After transmission, the components of the polarisation along the axes are analysed. Figure 1 shows the experiment with the coordinate system used. Inside the domains Larmor precession occurs:

$$\phi = 5.72 \times 10^8 (M_s l) \lambda, \quad (1)$$

where M_s is the saturation magnetisation, *l* is the path

length and λ is the neutron wavelength in meters. For a domain model as shown in the cross section through the film in fig. 1, the depolarisation as a function of θ is given by [1]:

$$\begin{aligned} D_{xx} &= 1 - \sin^2 \theta (1 - \langle \cos \phi \rangle) \\ D_{yy} &= 1 - \cos^2 \theta (1 - \langle \cos \phi \rangle) \\ D_{zz} &= \langle \cos \phi \rangle, \end{aligned} \quad (2)$$

where $\langle \dots \rangle$ represents an averaging over all neutron paths.

The domain height is found from D_{zz} at $\theta = 0$:

$$h_{\text{dom}} \approx \frac{1}{5.72 \times 10^8 \lambda M_s} \cos^{-1} [D_{zz}(\theta = 0)]. \quad (3)$$

Assuming that the domains are stripes running isotropically in the plane of the film, the stripe width *D* is found from the θ dependence of D_{yy} and D_{zz} according to:

$$D \approx \frac{2}{3} \beta h_{\text{dom}} \theta_0, \quad (4)$$

Fig. 1. Neutron depolarisation experiment in Co–Cr film; cross section through the domain structure.

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Fig. 2. Diagonal elements measured as functions of θ (see fig. 1) in a stack of 80 films.

where the angle θ_0 is shown in fig. 2 and β is a factor that depends on the 'curliness' of the stripes and is between 0.5 and 1. It is taken to be equal to 0.75.

3. Samples and results

The samples used were magnetron-sputtered films with a product $M_s h_{\text{film}}$ (VSM measurement) equal to 0.187(3) A and K_u (torque measurement) ≈ 100 kJ/m³. Hence the angle ϕ in eq. (1) for 0.4 nm neutrons is 0.042 rad and D_{zz} according to eq. (2) will differ from 1 by only 9×10^{-4} . To enhance the depolarisation effect, a stack of 80 films was used instead of a single film, so D_{zz} will drop to 0.932.

Figure 2 shows the observed D_{xx} , D_{yy} and D_{zz} as functions of θ , in the remanent state after in-plane magnetisation $\parallel y$. From the fact that D_{xx} equals 1, the uniaxial anisotropy perpendicular to the film plane is confirmed.

The composition of the films was not determined, so the exact value of M_s itself is not known. For the analysis of the data according to eqs. (3) and (4) we take $M_s = 460$ kA/m, corresponding to a composition Co₈₁Cr₁₉. This value is correct to within 10%, so the value obtained for h_{dom} and D may have a systematic error not exceeding 10%. Table 1 gives the relevant quantities for the discussion below.

Table 1
Characterisation of Co-Cr films

$M_s h_{\text{film}}$ [A]	K_u [kJ/m ³]	h_{dom} (eq. 3) [nm]	D (eq. 4) [nm]
0.187 (3)	100	302 (8)	75 (7)

4. Discussion

The value of h_{dom} determined according to eq. (3) is only 75% of h_{film} . The lack of depolarisation ΔD_{yy} and ΔD_{zz} in D_{yy} and D_{zz} , as compared with their values expected for a domain height equal to the film thickness, may be accounted for in three ways:

4.1. Domain walls

The presence of DW implies that a fraction $\eta = t/D$ of the sample area consists of DWs. The fact that η is not to zero will have consequences for the values of D_{xx} , D_{yy} and D_{zz} .

(i) D_{xx} : If the DWs are Bloch walls, the wall thickness t according to $t = \pi \sqrt{A/K_u}$ will be ~ 8 nm for $A = 6 \times 10^{-13} \dots 1 \times 10^{-11}$ J/m [2] (it is assumed that the value for A of the Co-Cr under study falls within this range). Hence η will be between 4 and 15%. Due to the in-plane component of the magnetisation inside the DWs, D_{xx} will be smaller than 1 for $\theta \approx 0$. Assuming that no Bloch lines parallel to the film plane occur over the area fraction η , the element D_{xx} will differ from 1 by 0.04, i.e. as much as D_{yy} and D_{zz} do for $\theta \approx 0$. However, the observed difference, if present, falls within the statistical error of 0.002, so η cannot exceed 0.002/0.04, i.e. $\sim 5\%$. This yields a maximum Bloch wall thickness equal to 5% of D , i.e. $t_{\text{max}} = 4$ nm. Using the statistically more precise data from the complete thermal neutron spectrum (100 times more intense than the monochromatic beam used for the measurement of fig. 2), t_{max} can be reduced to 2 nm. On the other hand, if the DWs coincide with grain boundaries, no effect in D_{xx} (nor in D_{yy} and D_{zz}) will occur, so upper limits for η and t cannot be given in this case.

(ii) D_{yy} and D_{zz} : When the DWs are Bloch walls, the area fraction η will give only half the depolarisation in D_{yy} and D_{zz} as if the same area fraction were occupied by domains. However, because of D_{xx} , η is at maximum 5%, the corresponding ΔD_{yy} and ΔD_{zz} will be negligible. In the case of thick grain boundaries, a 'rounding' in D_{yy} and D_{zz} will occur over an angular interval $\approx t/h_{\text{film}}$ around $\theta \approx 0$. According to the observations this interval may amount to 5° , so the maximum thickness of the non-magnetic region between adjacent domains is ~ 30 nm, i.e. 40% of the stripe domain width D .

4.2. Initial layer

If inside such a layer with in-plane magnetisation the domain dimensions are very small, no measurable

depolarisation in any diagonal element will occur. Hence, the absence of depolarisation in D_{xx} , together with the presence of ΔD_{yy} and ΔD_{zz} , is consistent with an initial layer amounting to 25% of h_{film} . This layer is one of the points of interest in current neutron reflectometry studies.

4.3. Imperfect orientation

The spread in orientation of M_s around the normal may account for ΔD_{yy} and ΔD_{zz} , together with a 'rounding' of these elements as a function of θ around 0. The observed 'rounding' may account for a maximum spread in orientation of 5°; this results in ΔD_{yy} and ΔD_{zz} smaller than 0.005.

5. Conclusions

The precision of the current depolarisation data of Co-Cr films of 300 nm gives upper limits regarding

domain walls, orientation and initial layer. The maximum thickness of domain walls in case of Bloch walls is ≈ 2 nm; in the case of grain boundaries ≈ 30 nm. The initial layer makes up a fraction of maximum 25% of the film thickness. The maximum misorientation of M_s from perpendicular is around 5°.

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