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Single domain wall chirality studies using polarised neutrons

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A single domain wall is created in a Permalloy film of macroscopic dimensions parallel to the surface by sending a current through the foil. With additional fields parallel to the film surface the position of the wall in the depth could be varied. Using 3-dimensional neutron polarization analysis the properties of this wall were studied, under which the thickness of this wall, the thickness as function of the depth of the wall in the film, the chirality and structure of left and right handed parts of the wall. By comparing simulations of the polarization matrix using different wall structures the Bloch model could be verified. The reversal of chirality was studied as function of a field parallel and anti-parallel to the magnetization in the center of the wall. A model was made about this reversal by nucleation that fits the observation.

1. Introduction

Ferromagnetic domain studies started in the first half of the 20th century and their existence was verified by optical techniques in a large number of configurations in many materials over a large temperature range. Most observational techniques including electron transmission microscopy (TEM) were confined to the surface of the samples of very thin ferromagnetic layers and as early as 1962 domain wall thicknesses in Permalloy, Fe and Ni of 180, 100 and 55 nm were reported [1] Although proposed already by Newton and Kittel [2] in 1948, in the 80s neutron studies started by Schaerpf and coworkers. [3,4], using small angle neutron scattering (SANS) and by Strothmann and coworkers [5] and Podorets and Shilstein [6] using neutron refraction. In this respect it should be mentioned that in contrast to optical techniques neutrons enable one to study magnetic properties in bulk materials.

We will report here about the precession of the neutron polarization in a well defined domain structure with a single domain wall in Permalloy. When a polarized neutron beam passes a magnetic induction vector B, the polarization starts to precess around B with the Larmor frequency $\omega = \gamma B$. Because the interaction time is proportional to the wavelength of the neutron beam times the path length of the interaction, polarization analysis gives detailed information about the positional dependence of the field.

The study of magnetized Permalloy foils with a single domain wall parallel to the surface started for the purpose to have a controllable neutron precession angle in the foil in order to use it as a white beam π-flipper in a pulsed neutron beam [7] In this study it appears that neutron polarization analysis is very suitable to study domain walls as was proposed for the first time by Newton and Kittel [2] and recently demonstrated by Thibaudeau and coworkers [8] who studied a 90° domain wall with single axis polarization analysis with in plane crossed anisotropies.

In our previous paper [7] we studied isolated Permalloy foils of 25 μm thickness pealed off a Silicon wafer, with the purpose of producing π-flipping foils. Next, we carried out similar experiments on Permalloy foils of 9 μm thickness deposited electrochemically on a Si wafer substrate [9] We showed that the wall could be positioned very accurately linearly with a small applied field and without hysteresis. However, we found some depolarization that we attributed to surface domain nuclei and to possible inhomogeneities in the small applied fields [10] From recent wavelength dependent measurements on the same wall we got strong indication of a rather thick domain wall of about one micron causing the measured depolarization.

In the present paper we reinvestigate this film with varying inclination angles smaller than 10° and small applied in-plane fields in two orthogonal directions, with more attention to possible inhomogeneities in the field. We will compare our measuring results with simulations taking into account all present fields working around the foil. We will show that our earlier interpretation of the measured depolarization is wrong: the depolarization is caused by the domain wall itself and not by domain nuclei at the surface. We will calculate the precession angle in the whole environment of the inclined foil and experimentally investigate the properties of the domain wall on a neutron set-up with three dimensional polarization analysis. We were able to adjust the chirality of the domain wall and to

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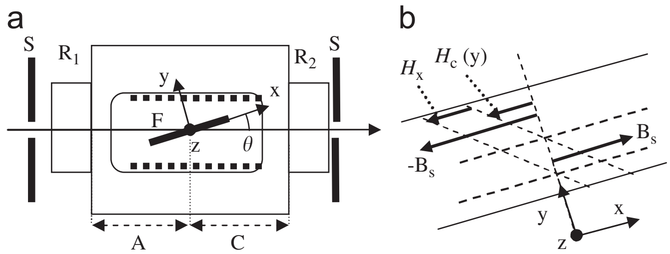

Fig. 1. (a) A monochromatic polarized neutron beam of 0.2 nm wavelength passing through the setup between two slits S, 1 m apart, that can confine the beam to 0.3 mm but routinely to 2 mm. Polarization rotators R1 and R2 around a "field free" sample box allow to measure a (3×3) depolarization matrix. In this box the foil F under study $(120\times0.009\times30)$ mm^3 is placed. Coils are provided to create fields H_x and H_z in the x- and z-direction. The assembly of foil+coils can rotated about the z-axis, allowing to vary the transmission angle θ. (b) The total field $H_t(y)=H_x+H_{cx}(y)$ inside the foil in the x-direction as a function of y. The wall position y (shown for $H_x\neq0$ and $H_x=0$, dotted lines//x) is determined by the zero transition of the total field.

study its reversal in detail. Although there are many studies of domains and domain walls in very thin films [11] we did not find papers to compare our results with.

2. Experimental and theoretical considerations

Experiments on a Permalloy foil of dimensions $(L\times t\times h)=(120\times0.009\times30)$ mm^3 in the x, y and z-directions respectively have been carried out using the 3-dimensional polarization analysis set-up PANDA at the reactor in Delft operating at 0.2 nm wavelength. Incoming and measured polarization can be aligned in both anti-parallel directions along the axes x, y and z. This gives 36 independent combinations of incoming and measured polarization. Fig. 1 gives a sketch of the set-up. We keep the coordinate system (x,y,z) fixed on the foil. An electric current I_w of maximum 20 A can be lead through the foil in the z-direction that generates a field in and outside the foil. The field component along x, denoted H_{cx} inside the foil is

$$H_{cx}(y)=\frac{I_w y}{Lt} \tag{1}$$

with y measured from the center of the foil (see Fig. 1b). The corresponding component H_y i.e. normal to the foil varies with x, but will not affect the magnetization distribution in the foil because of the strong demagnetization normal to the foil.

Coils to apply small fields H_x and H_z along x and z are fixed on the same table as the foil. The field H_z is applied to study the magnetization in the z-direction.

The transmission angle θ of the beam through the foil can be varied by rotating the table carrying the assembly around the z-axis. Notice that the axis of the coil for H_x makes a fixed angle of 10° toward the x-axis of the coordinate system defined above. This was necessary to prevent the neutron beam from passing through the x-coil at realistic angles θ.

The point along the y-axis where the sum of the external and the current field $H_x+H_{cx}(y)=0$ determines the position of a 180° domain wall in the foil. By varying H_x it can be shifted between the foil surfaces.

2.1. Calculation of precession

To calculate the polarization change along the x-axis in the region around the current carrying foil, we divide the path through the sample box (see Fig. 1a) in $2N+1$ sections x_i, $-x_{i-1}$ in which we assume an homogeneous induction B_i in a direction defined by the local direction cosines (n_{xi},n_{yi},n_{zi}). The precession of the polarization vector in a section is described by the rotation matrix

$$R(\varphi_i,n_{xi},n_{yi},n_{zi})=\begin{pmatrix}1-c_{\varphi i}(1-n_{xi}^2) & n_{xi}n_{yi}c_{\varphi i}+n_{zi}s_{\varphi i} & n_{xi}n_{zi}c_{\varphi i}-n_{yi}s_{\varphi i}\\ n_{yi}n_{xi}c_{\varphi i}-n_{zi}s_{\varphi i} & 1-c_{\varphi i}\left(1-n_{yi}^2\right) & n_{yi}n_{zi}c_{\varphi i}+n_{xi}s_{\varphi i}\\ n_{zi}n_{xi}c_{\varphi i}+n_{yi}s_{\varphi i} & n_{zi}n_{yi}c_{\varphi i}-n_{xi}s_{\varphi i} & 1-c_{\varphi i}(1-n_{zi}^2)\end{pmatrix} \tag{2}$$

where $\varphi_i=c\lambda B(x_i)(x_i-x_{i-1})$ is the precession angle $[c=\gamma h/m=4.6368\times10^{14}$ $[\mathrm{T}^{-1}\,\mathrm{m}^{-2}]$, h Planck's constant, γ the gyromagnetic ratio and m the neutron mass], $c_{\varphi I}=1-\cos\varphi_I$ and $s_\varphi=\sin\varphi_I$ For $(n_{xi},n_{yi},n_{zi})=(1,0,0)$ one recognizes the standard rotation matrix around the x-axis. The precession in the whole sample box is written as the product of three groups of rotation matrices

$$M=R_C F R_A \tag{3}$$

where R_C and R_A are the product matrices describing the precession in the regions before ($x<-t/2\sin\theta$, region A) and behind the foil ($x>t/2\sin\theta$, region C). They are given by

$$R_C=\prod_{i=0}^{N-1}R(\varphi_i,n_{xi},n_{yi},n_{zi})\quad R_A=\prod_{i=-N-1}^{0}(\varphi_i,n_{xi},n_{yi},n_{zi}) \tag{4}$$

The matrix F to describe the precession in the foil (with thickness t) itself is written as

$$F=F_C(H_x,\delta_w,\theta_w)W(\delta_w,\theta)F_A(H_x,\delta_w,\theta) \tag{5}$$

where the matrix $W(\delta_w,\theta)$ corresponds to the rotation in the domain wall of thickness δ_w (if present) and $F_A(H_x,\delta_w,\theta)$ and $F_C(H_x,\delta_w,\theta)$ to the opposite rotations in the domains in front and behind the wall, given by

$$F_A(H_x,\delta_w,\theta)=\begin{pmatrix}1 & 0 & 0\\ 0 & c_{H,\delta,\theta}(H_x) & s_{H,\delta,\theta}(H_x)\\ 0 & -s_{H,\delta,\theta}(H_x) & c_{H,\delta,\theta}(H_x)\end{pmatrix}$$

$$F_C(H_x,\delta_w,\theta)=\begin{pmatrix}1 & 0 & 0\\ 0 & c_{H,\delta,\theta}(-H_x) & -s_{H,\delta,\theta}(-H_x)\\ 0 & s_{H,\delta,\theta}(-H_x) & c_{H,\delta,\theta}(-H_x)\end{pmatrix} \tag{6}$$

with

$$c_{H,\delta,\theta}(H_x)=\cos\varphi_f(H_x,\theta,\delta_w);\, s_{H,\delta,\theta}(H_x)(H_x)=\sin\varphi_f(H_x,\theta,\delta_w)$$

and

$$\varphi_f(H_x,\theta,\delta_w)=cB_s\lambda\frac{t-\delta_w/2}{\sin\theta}\left(\frac{H_x+H_{cm}}{2H_{cm}}\right)$$

so the wall thickness appears in the argument φ_f. B_s is the spontaneous induction in the foil($\sim$1.0 T), $H_{cm}=|H_{cx}(t/2)|$ ($=$0.8A/cm at 20 A), the (maximum) current field at the foil surface. The arguments of F_A and F_C can be used to describe a wall position away from half foil thickness as a consequence of the field H_x. The rotation $\varphi_f(H)$ is maximized by $|H|\leq H_{cm}$. In the simulations below the wavelength λ will be taken as a constant 0.2 nm.

2.2. Calculation of fields in the sample box

The field in the foil and in the regions A and C are the sum of the current field components $H_{cx}(x)$ and $H_{cy}(x)$, the magnetic induction $B(x,H_x)$ in the foil and applied fields H_z and H_x in the z- and x-directions.

The current field components $H_{cx}(x)$ and $H_{cy}(x)$ outside the foil as functions of x and y are taken from earlier calculations [12] for a field stepper shaped as a foil of width L (is length in foil under study), from $z=-\infty$ to $+\infty$, placed symmetrically around