Physica B 404 (2009) 2553–2556

Contents lists available at ScienceDirect

Physica B

journal homepage: www.elsevier.com/locate/physb

Magnetization distribution in magnetic films studied with Larmor-encoding

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ARTICLE INFO

Keywords:
Polarized neutron reflectometry
Larmor-precession
Magnetic films
Off-specular scattering

ABSTRACT

Additional information about the magnetization distribution in magnetic films is obtained with a 3D-polarimetry set-up. A pilot experiment was performed with the neutron polarization aligned perpendicular to the surface of a Fe-film in a magnetic field parallel to its surface. The Larmor-precession in the magnetic field between two current sheets was used to adjust the neutron polarization perpendicular to the sample surface. This new polarization-magnetization configuration was probed with a Fe-film in specular and off-specular scattering. The off-specular scattering is created by the magnetic domain structure of the Fe-film in remanence. The results of specular and off-specular scattering are reproduced by calculations for the configuration of the incoming neutron polarization parallel to the sample surface and the magnetic field and for the configuration of the incoming neutron polarization perpendicular to the sample surface and the magnetic field.

Three-dimensional (3D) vector polarimetry with neutrons is a very powerful method of investigation of bulk materials revealing its magnetization structure [1–6]. The application of 3D-polarimetry to neutron reflectometry including off-specular scattering was proposed in our earlier publication [7]. A new effect was demonstrated in a model-calculation with the neutron polarization perpendicular to the sample surface in extension to the conventionally used configuration with neutron polarization parallel to the sample surface. This new effect concerned the off-specular spin-flip Bragg-sheet scattering in a Fe/Cr multilayer [8]. The off-specular magnetic Bragg-sheet scattering was for the first time measured and simulated by model calculations based on a magnetic domain model. Here we verified the model of magnetic domain in a thick Fe-film with two configurations of 3D-vector polarimetry in reflectometry. The usually obtained effects in specular and off-specular scattering are enriched by intensity oscillation of Larmor-pseudo-precession (LPP) [9], which give additional data analysis possibilities to determine the magnetization structure in magnetic films with 3D-vector polarimetry.

In reflectometry the processes of the interaction of the neutron with the sample are split into two groups, the specular reflection and the off-specular scattering. This separation of the two effects is unique for reflectometry. The first one is caused by the interaction with the mean optical potential averaged over the scale greater than the lateral projection of the coherence length, while the second effect is due to local deviations of the interaction potential from its mean value, e.g. due to domains within the coherence length. This situation is shown in Fig. 1 on the example a 250 nm thick Fe-film on MgO-substrate, which will be studied here. On the MgO-substrate the Fe-film shows an easy axis for its magnetization, which was oriented parallel to the external magnetic field H so into the y-direction in Fig. 1. First the magnetic field was raised to saturation of the magnetization and then reduced to remanence. Thus it can be assumed that the film has a magnetic domain structure, for which the magnetization components perpendicular to the external field add up to zero. This situation is schematically shown in Fig. 1. The size of the domains (smaller than the coherence length) is modelled to follow an exponential-type distribution function. The mean value for the domain size was taken as 10 μm. In the example shown in Fig. 1 the nuclear optical potential, as well as the component of the mean magnetic induction parallel to the external magnetic field cause only specular reflection. The components of the domain magnetization perpendicular to the mean parallel magnetic induction compensate at averaging over the coherence range and solely contribute to the off-specular scattering. Spin-flip (SF) scattering manifests in off-specular directions in view of that the polarization vector, which is parallel to the mean magnetization, interacts with the

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0921-4526/$ - see front matter © 2009 Published by Elsevier B.V.
doi:10.1016/j.physb.2009.06.131

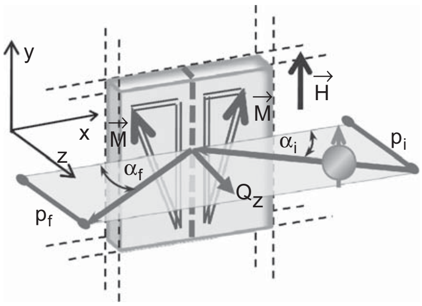

Fig. 1. Scattering geometry of polarized neutron reflectometry of a Fe-film with domains. A model of two domains with magnetization M is shown, which are highlighted out of the 250 nm thick Fe-film. The domain size is of the order of 10's of μm. The scattering scheme shows the perpendicular to the sample surface components of the incoming and outgoing wave vector k_i and k_f named p_i and p_f, respectively. The corresponding scattering angles are α_i and α_f, respectively.

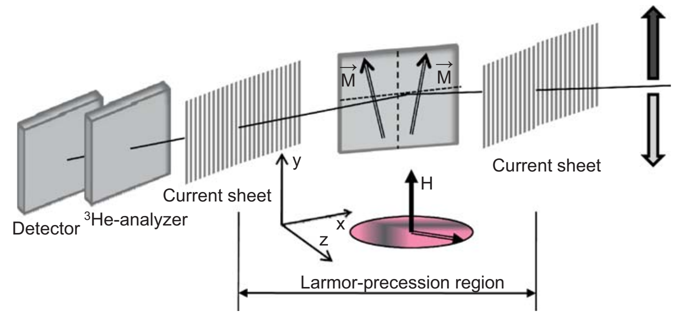

Fig. 2. Schematic outline of the Larmor-precession set-up. The polarized neutrons are Larmor-precessing after the first current sheet and its polarization can be directed perpendicular to the sample surface. The second current sheet together with the following ^{3}He analyzer allows detecting the neutron polarization in the x–z plane [11].

perpendicular domain magnetisation component [7,10]. The same scattering scheme applies to the beforehand mentioned study of a Fe/Cr multilayer [8].

In general, the complete determination of the direction of the magnetization vector in e.g. a magnetic film requires the knowledge of its three components. Thus the set-up in Fig. 1 with one polarization direction of the neutron cannot be used as only tool for the determination of the magnetization if e.g. also an out-plane magnetization component exists. In the following we show that with Larmor-precessing neutrons the missing polarization directions can be obtained in a weak magnetic field.

A rather new effect should be introduced first, when the sample with its magnetization is turned by 90° around its surface normal keeping the same scattering geometry in Fig. 1, then the mean sample magnetization, which is rotated perpendicular to the polarization vector, induces a SF at the first sample interface. The following rotating progression of the polarization vector inside the sample is recorded in particular below the apparent total reflection threshold by intensity oscillations as a function of Q_z seen with the same sample of Fig. 1 and ascribed to Larmor-pseudo-precession (LPP) [9]. The amplitude of the LPP modulation generally depends on the one hand on the absolute value of the mean magnetization and its orientations with respect to the direction of the incoming polarization vector and on the other hand on the direction of the polarization analysis. Therefore, the length and in-plane direction of a mean magnetization vector can be determined totally only in a set of experiments with various mutual orientations between the incident polarization vector and directions of the polarization analysis.

The perpendicular orientation between the neutron polarization and the sample magnetization thus constitutes a basic tool for investigating the magnetic state of films, e.g. with domain structure. In the presented study the symmetry effect seen in the off-specular scattering in this set-up is shown proving the perpendicular orientation of neutron polarization. Further effects of non-specular scattering are deduced from model calculation for the used Fe-film on MgO.

The method to use Larmor-precession in order to adjust the polarization direction has the advantage that the polarization can be adjusted to any angle with respect to the sample surface within the x–z-plane (see Fig. 2). This means to perform 3D-polarimetry. Here we apply this technique to adjust the neutron polarization perpendicular to the external field and perpendicular to the sample surface (see Fig. 2).

The schematic experimental set-up on the instrument EVA at ILL is presented in Fig. 2. The set-up follows the one in Ref. [11]. The Larmor-precession starts when the monochromatic beam with a wavelength of 5.4 Å crosses the first current sheet. As the Larmor-precession field of 56 Gauss is low, the Larmor-precession is slow and the polarization can be adjusted with a low angular divergence at the sample surface. The second current sheet together with the analyzer is used to analyse the neutron polarisation in the x–z-plane. The adjustment of the Larmor-precession was performed by varying the distance between the current sheets according to the appearing oscillations in beam without sample [11].

The current sheets were deactivated in the first part of the experiment and a "conventional" reflectivity experiment was performed, in which the four transitions $\pm y$ to $\pm y$ were measured. {+,−} denotes the two spin-states, here along the y-polarization direction. The experimental data are presented in Fig. 3 including the model fits. The specular ridge runs along $p_i = p_f$. The momentum transfer Q_z is the sum p_i+p_f (see Fig. 1). The influence of the magnetic scattering length density manifests in the different extension of the total reflecting region, so in the two critical edges, for {+y,+y} and {−y,−y}. The intensity distribution along the specular line is reproduced in the model calculation. In the model calculation the incomplete analyzing efficiency of the ^{3}He filter is neglected and the polarization was taken to 1. So, in the calculation intensities from spin-flip and non spin-flip scattering do not mix. The off-specular scattering appears on the one or the other side of the specular scattering line in spin-flip scattering {+y,−y} or {−y,+y} and its apparent intensity origin in Q-space is regulated by the two critical edges of the Fe for its two spin-states. This effect is analogue to the asymmetric behaviour of the off-specular scattering of the Fe/Cr multilayer [8]. It should be noted here that the width of the intensity along the calculated specular scattering is due to the inclusion of the instrumental resolution. In the off-specular scattering calculation this broadening is not included. The measured off-specular scattering for {+y,−y} or {−y,+y} is the same as the calculated one in the frame of a qualitative comparison. The calculated detailed intensity structure does not show up in the experimental patch-like intensity due to not high enough instrumental resolution. The detailed calculated off-specular intensity shows that the experimental intensity patches consist of bands of LPP-intensity oscillations mentioned before (see Ref. [9]). The intensity origin of these oscillating intensity bands has the coordinates of the critical edges. Valuable information is contained in the structure of these oscillations for the determination of the magnetization components of the magnetic film. There is also additional specular spin-flip scattering visible along the specular line for {+y,−y} or {−y,+y} in the model calculation, which is also marked by the LLP-intensity oscillations. This scattering shows maximal intensity between the critical edges, an effect which is found reproduced in