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Domains and interface roughness in Fe/Cr multilayers: influence on the GMR effect

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Abstract

Different types of roughness in magnetic multilayers can be distinguished with off-specular neutron scattering. We report on roughness originating from magnetic domains in Fe/Cr multilayers and on structural roughness being created at the Fe–Cr interfaces. The influence of these types of roughness on the GMR-effect is outlined.

Keywords: Polarised neutron reflection; Non-collinear exchange coupling; GMR effect; Interface roughness; Magnetic domains

Exchange coupled Fe/Cr multilayers show giant magneto resistance (GMR) [1] and from the same samples off-specular neutron scattering also is detected [2,3]. The relation between the two effects is that in both cases spin-flip scattering occurs in the multilayer, once performed by electrons [4] and in the other case by neutrons [2,5]. We focus here on the source of neutron spin-flip (sf) and non-spin flip (nsf) scattering and then relate it qualitatively to electron sf scattering.

$[^{57}\mathrm{Fe/Cr}]_n$ superlattices were grown by molecular beam epitaxy on (1 1 0) Al_2O_3 substrates covered with a Cr buffer layer. The samples were characterised with reflection high-energy electron diffraction and X-ray diffraction. The in-plane magnetisation measurements were performed at room temperature using vibrating sample magnetometry and show extremely strong in-plane anisotropy (with respect to the out-of-plane direction). The magnetisation measurements show the in-plane four-fold anisotropy [2].

The polarised neutron reflectometry experiments were carried out at FLNP [6] and ILL [7] on the reflectometers SPN and ADAM, respectively. SPN is working in time-of-flight mode and ADAM in monochromatic mode. The reflected and scattered intensities were recorded without spin analysis with position-sensitive detectors. An external magnetic field was applied parallel to the sample surface. The scattering scheme for specular and off-specular scattering is shown in Fig. 1 together with the sketch of the sample composition and a model of its layer magnetic moments distributed into the domains. In the top figure only the perpendicular to the external field components of layer l magnetic moments M_x^l are sketched. The top view shows the distribution of the layer magnetic moment of the domains. In one domain the coupling angle φ is depicted between the direction of the magnetic moment M^l and the direction $M^{l'}$ of the magnetic moment of the underneath (l') Fe-layer. The spin state of the incoming neutrons is parallel ("+" state) or antiparallel ("−" state) with respect to the external magnetic field.

The data obtained from the sample $[^{57}\mathrm{Fe}(67\,\text{Å})/\mathrm{Cr}(12\,\text{Å})]_{12}$ (sample 1) in the "−" state are depicted in Fig. 2a as a 2-D intensity map in the co-ordinates p_i–p_f

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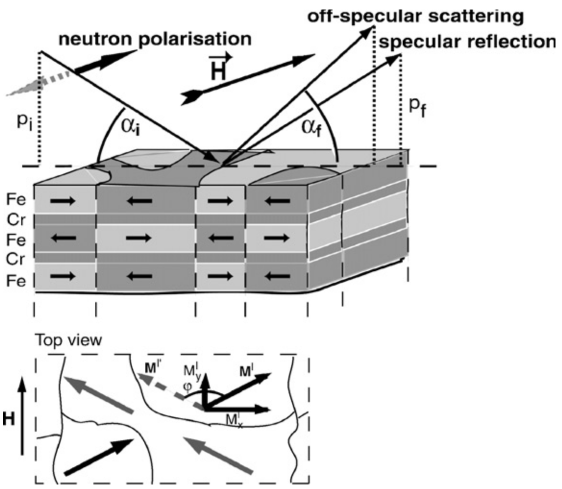

Fig. 1. Scattering geometry for polarised neutrons from a Fe/Cr multilayer. Schematically, the sample composition is presented. The top figure shows only the magnetic moment components in the Fe-layers perpendicular to the external magnetic field H. The top view shows the magnetic moment in the domains of the top layer. The coupling angle φ relates the magnetic moment of one magnetic layer (within a domain) with the magnetic moment of the adjacent Fe-layer(s).

and p_i+p_f (p_i and p_f are shown in Fig. 1 and are the components of the neutron wavevectors being perpendicular to the sample surface). p_i+p_f is the momentum transfer perpendicular to the surface, so that the structure of the multilayer along this direction is probed. The intensity of the specular line as a function of p_i+p_f at $p_i-p_f=0$ reflects the following features. The total reflecting region at low momentum transfer p_i+p_f is followed by Bragg peaks originating from the layer structure of the sample. Full-order Bragg peaks due to the bilayer thickness of 79 Å appear at $p_i+p_f=0.08$ and 0.16 Å^{-1}, respectively. In addition, half-order Bragg peaks are measured at $p_i+p_f=0.04$ and 0.12 Å^{-1} which arise due to the alternating magnetic components in the sample, an effect which doubles the unit cell [2]. The result of the fit to the data (shown in Fig. 2b) concerning the reflectivity line yields the before-hand mentioned composition of the sample and the layer magnetic moments in the direction parallel to the external field.

The off-specular scattering in Fig. 2a appears as intensity bands perpendicular to the reflectivity line crossing it at the half-order positions and no off-specular scattering is seen crossing the full-order peaks. This means that no measurable structural roughness is present at the Fe–Cr interfaces.

In Ref. [2] it was proven by polarisation analysis that the off-specular scattering through the half-order Bragg peaks is sf scattering. The sf off-specular scattering is created at the components of the layer magnetic moments oriented perpendicular to the external field. The range of intensity of the off-specular scattering perpendicular to the direction of the specular scattering is a measure of the objects giving rise to off-specular scattering, which are the magnetic domains sketched in Fig. 1. The average domain size was determined to be around 4500 Å. This value is obtained from the 2-D fit to the data seen in Fig. 2b. In particular, the cuts through the 2-D intensity map along the off-specular Bragg sheets at $p_i+p_f=0.04$ and 0.12 Å^{-1} in Fig. 2c reflect the average domain size diameter. It should be noted that the sf scattering does not only show up in the off-specular Bragg sheet, but also in an sf-component on the specular line measured with spin analysis. This is visible in the rather strong intensity at the $\frac{1}{2}$ order Bragg peak position in Figs. 2a and b. As the coherence length of the neutrons at this momentum transfer is about

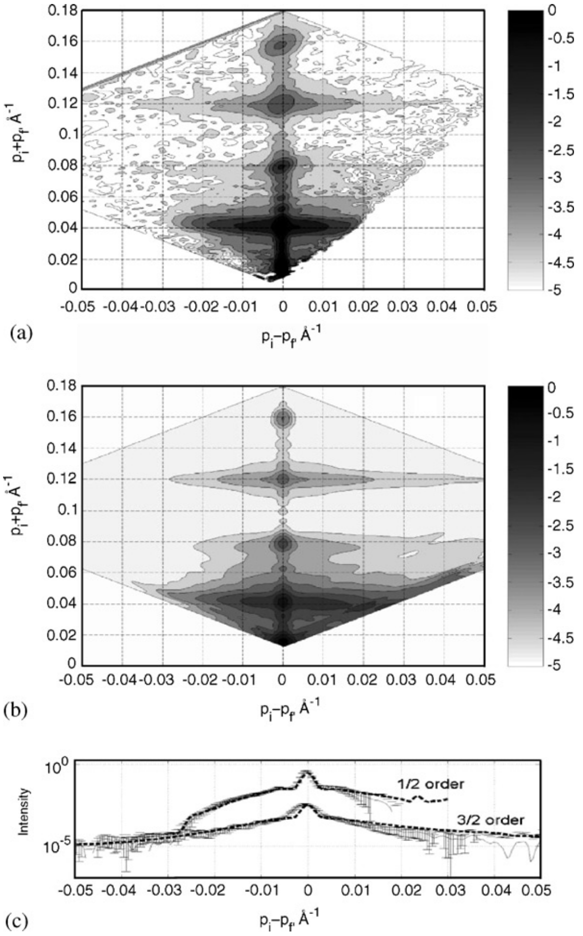

Fig. 2. (a) 2-D intensity map of an Fe/Cr multilayer (sample 1) in an external field H of 405 G. (b) 2-D calculated intensity map for the sample in Fig. 2a. (c) Horizontal cuts taken from Figs. 2a and b and fits (- - -) through the half-order Bragg positions at $p_i+p_f=0.04$ and 0.12 Å^{-1}, respectively.

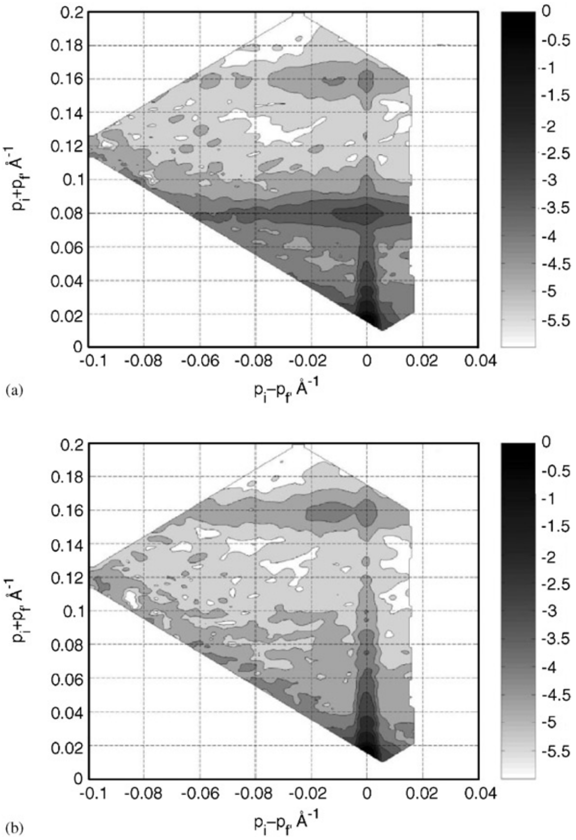

Fig. 3. (a) 2-D intensity map of an Fe/Cr multilayer (sample 2) in an external field of 300 G. (b) 2-D intensity map of the Fe/Cr multilayer (sample 2) in an external field of 4.5 kG.

60 μm, it means that domains bigger than the coherence length are also present. The fact that the off-specular scattering is concentrated into Bragg-sheet scattering across the (half-order) Bragg peaks means that the "roughness" is correlated through the multilayer stack; thus the domains can be visualised as being column-like as depicted in Fig. 1. The complete 2-D model calculation in Fig. 2b proves this conclusion. With the determination of the two components of the layer magnetisation, the coupling angle φ between the layer magnetisation of two successive layers is also determined (see Fig. 1) [8]. In this example here with an external field of 405 G, this angle is in average 80°.

The data obtained from the sample $[^{57}\mathrm{Fe}(28\,\text{Å})/\mathrm{Cr}(15\,\text{Å})]_{12}$ (sample 2) is depicted in Fig. 3a. The data look similar with respect to the data in Fig. 2a. Again off-specular Bragg-sheet scattering through the $\frac{1}{2}$ order Bragg peak (at $p_\mathrm{i}+p_\mathrm{f}=0.08\,\text{Å}^{-1}$) is present. However, in addition, strong off-specular scattering through the full-order Bragg peak at $p_\mathrm{i}+p_\mathrm{f}=0.16\,\text{Å}^{-1}$ appeared. So, we are not only concerned with magnetic domains correlated through the multilayer, but also with correlated interfacial roughness. The fit to 2-D data and in particular to the sf off-specular scattering yields a lateral domain size of about 1200 Å. The correlated interfacial roughness can be modelled by steps through the multilayer stack of a height of about a monolayer and an average diameter of about 100 Å. These values correspond to growth-induced steps previously seen by electron transmission microscopy [9]. An important feature is that the off-specular scattering through the full-order Bragg peak is not disappearing when the sample is exposed to a saturating field, whereas the magnetic off-specular scattering through the $\frac{1}{2}$ order peak disappears as seen in Fig. 3b. It should be noted that the off-specular scattering intensity through the full-order Bragg peak becomes stronger in a saturating field. This is however only a "technical" effect, because due to the enhanced magnetic scattering potential for the neutrons, the scattering becomes stronger, but the roughness stays effectively the same.

The magnetic domains being present in the sample of Fig. 2 have a not too big influence on the GMR because the average domain size is big compared to the mean free path of the electrons of a few hundreds of Ångströms. Only the small domains within the distribution will give an influence. This means that the domain size being relevant for the spin-flip of the neutrons is not relevant for the spin-flip of the electrons. Only the small domains within the distribution would give an influence. The same argument holds for the magnetic domains of the second sample. The interfacial roughness of the second sample did not show any magnetic component.

The quantitative two-dimensional data analysis and model calculation in Fig. 2b (not presented for the sample in Fig. 3) was performed simultaneously for both, specular reflection and off-specular scattering. This analysis is based on the distorted wave Born approximation combined with the supermatrix formalism and allows for a detailed comparison to the data [10,11].

In conclusion, we have shown how neutrons see "roughness", in a general sense, and how conclusions can be drawn with respect to the GMR. The magnetic domains play only a role with respect to GMR if their size is of the order of the electron mean free path.

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