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Measurement and simulation of polarized neutron reflectivity and off-specular scattering from evolving magnetic domain structure in Co/Cu multilayers

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Abstract

We report on the measurement and simulation of the field-dependent polarized neutron reflectivity (specular) and scattering (off-specular) for an antiferromagnetically coupled Co/Cu multilayer (ML) with number of bilayers $N = 40$. The first-order Bragg peak is visible in the non-spin flip (NSF) channels representing the bilayer periodicity. We observe off-specular intensity around the AF Bragg peak at the half-order position in both SF and NSF channels. These Bragg sheets are most intense at lower fields and gradually disappearing at higher fields as the system attains saturation. We attribute the Bragg sheets to vertically correlated AF domains along the ML stack which get bigger in size with field strength. Those interpretations are confirmed by simulation of the data within the distorted wave born approximation (DWBA).

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Keywords: Polarized neutron reflectometry; Magnetization reversal mechanisms; Off-specular scattering

Ferromagnetic layers separated by non-magnetic spacers have been extensively investigated in the last decade mainly due to the giant magnetoresistance (GMR) properties and the oscillatory interlayer exchange coupling between two adjacent magnetic films [1–3].

The physical properties as interlayer coupling and GMR are closely related to the morphological structure of the multilayers (ML) [4] and also on the details of the magnetic domain structure [5]. In the present work, we report on the polarized neutron scattering measurements for antiferromagnetically coupled Co/Cu multilayers with morphological vertical correlation [4].

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PNR measurements are performed at the polarized neutron reflectometer with polarization analysis HADAS [6] at the Jülich research reactor FRJ-2 (DIDO). The neutron wavelength is fixed at $\lambda = 4.52$ Å. The instrument is equipped with a 2D detector with a special spin analyzer that covers the whole detector area and thus allows simultaneously measuring specular and off-specular intensities with polarization analysis. The polarization efficiencies of the polarizer and analyzer are both equal to 95%. The specimens are kept at RT and a guiding field H_a of up to 4 kOe has been applied.

The ML studied in the present work are structures of Co/Cu prepared by DC magnetron sputtering. Samples are prepared by alternate deposition of Co and Cu layers on SiO_2 substrates kept at RT. The sputtering pressure of 3.4×10^{-3} mbar is controlled by the flow of Ar in the chamber. The Cu thickness in the ML corresponds to the first AF coupling maximum of the oscillatory interlayer coupling across Cu with structures $SiO_2/Co(1.45\,nm)/[Cu(1.02\,nm)/Co(1.45\,nm)]_{\times 40}$.

The microstructure and the layer quality are investigated by low-angle X-ray reflectivity (XRR) and X-ray diffuse scattering (XDS) measurements [4]. Hysteresis loops are recorded by the magneto-optic Kerr effect (MOKE) and giant magnetoresistance (GMR) is measured by the conventional four-probe DC technique at RT.

XRR patterns show the sharp Bragg peaks up to second-order confirming the good quality of the ML and the XDS intensity at the position of the first Bragg peak indicates the high degree of vertical correlation in the ML [4]. The MOKE hysteresis loop and the GMR is shown in Fig. 1.

We perform PNR measurements at seven different fields H_a on one side of the hysteresis loop. Fig. 2 shows the intensities in the non-spin flip (NSF) (I_{++}, I_{--}) and the spin flip (SF) (I_{+-}, I_{-+}) maps as a function of the incident angle α_i and the exit angle α_f at applied fields of $H_a =$ 20, 100 Oe (close to the remanent state) and at saturation field of 500 Oe (see in Fig. 1). The data are simulated within the distorted weave born approximation (DWBA) approximation [7,8], confirming the interpretations given below. Those

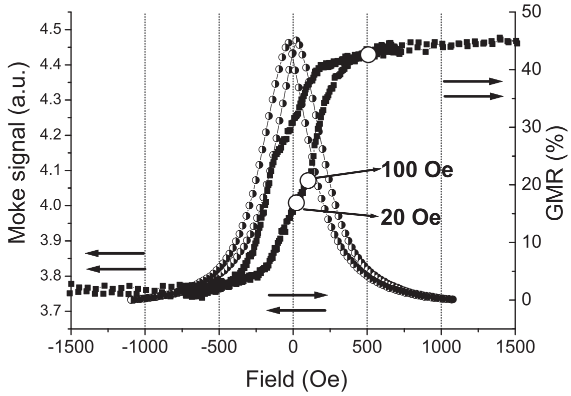

Fig. 1. MOKE hysteresis loop and the GMR curve for the ML $SiO_2/Co(1.45\,nm)/[Cu(1.02\,nm)/Co(1.45\,nm)]_{\times N=40}$. Circled numbers are the fields of Neutron measurements which are shown.

simulations properly take into account the limited efficiencies of the polarizer and the analyzer.

Intensity along the specular line $\alpha_i = \alpha_f$ is visible along the plateau of total reflection in the four channels and at the first-order Bragg position due to the bilayer periodicity (around $\alpha_i = \alpha_f = 92$ mrad) in the two NSF channels. SF reflectivities along the reflectivity plateau are due to the limited efficiencies of the polarizing and analyzing elements and are thus NSF in nature. The NSF intensity at the first-order Bragg position are equal at the remanent state ($H_a = 20$ Oe) and increase (resp., decrease) in the I_{--} (resp., I_{++}) channel as H_a is increased. In the saturated state, this intensity is maximum in the I_{--} channel and equal to zero in the I_{++}. This is due to the relative values of the nuclear and magnetic scattering length densities of Co and Cu. At $H_a = 100$ Oe a small difference in the two intensities is observed, revealing a small net magnetization along the applied field which is not the case at $H_a = 20$ Oe.

Intensities are also present around the half-order Bragg peak position (around 46 mrad) both in the SF and in the NSF channels due to the antiferromagnetic coupling in the ML. Those intensities in the SF are more intense than in the NSF. The half-order peaks are broader in the $(\alpha_i - \alpha_f)$ plane than the intensities observed around the first-order Bragg position. Moreover,

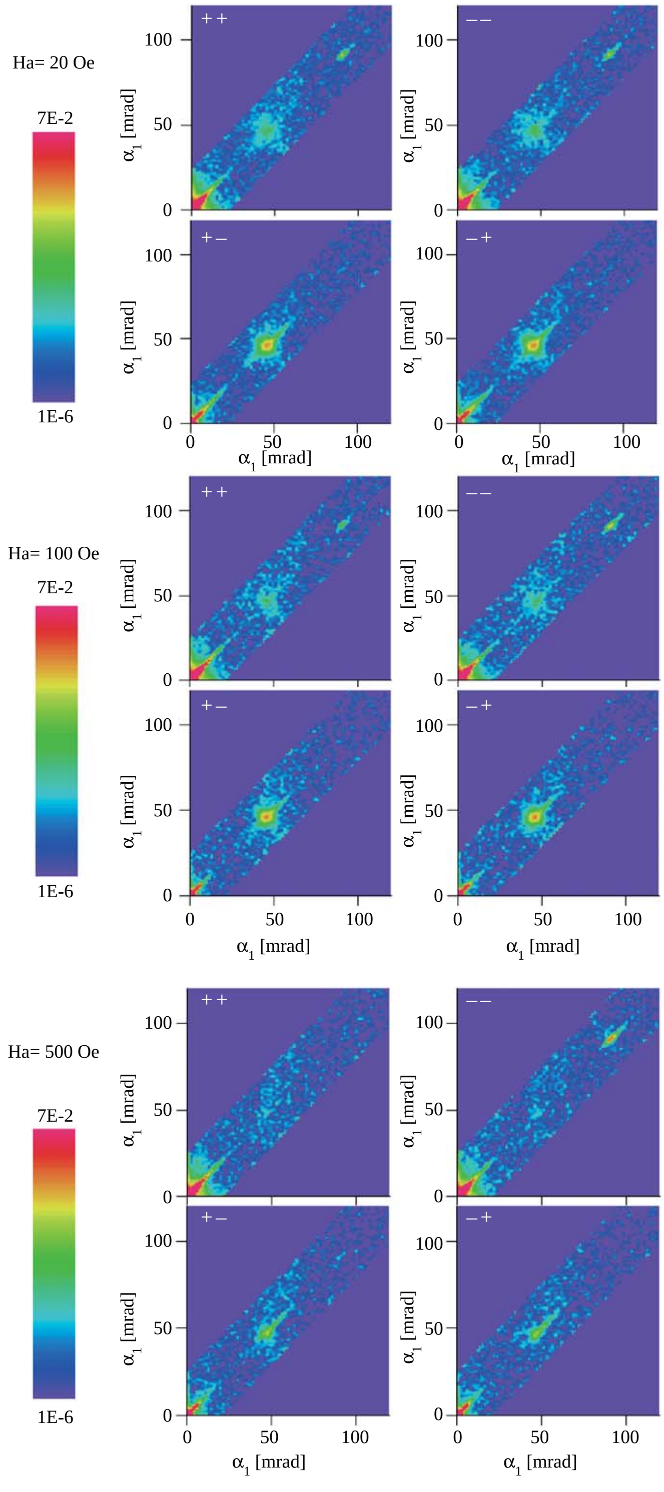

Fig. 2. Experimental NSF and SF intensity maps of a $SiO_2/Co(1.45\,nm)/[Cu(1.02\,nm)/Co(1.45\,nm)]_{\times N=40}$ ML at 20, 100 and 500 Oe (circled in Fig. 1). Off-specular intensity appears around the AF Bragg peak (≈ 46 mrad) in SF and NSF channel for lower fields but is gradually disappearing at higher fields.

these intensities shrink perpendicular to the specular line and decrease in intensity when the applied field is increased, to disappear at saturation [9]. This disappearance shows that they are of magnetic origin. Off-specular intensity arises when the in-plane translational symmetry is broken by interfacial roughness or magnetic domains on a length scale shorter than the in-plane projection of the neutron coherence length. The broadening of the half-order Bragg peaks or the Bragg sheets indicate magnetic correlation along the sample plane due to vertically correlated domains which are columnar for antiferromagnetically coupled layers. The SF intensities come from the fluctuations of the magnetizations perpendicular to the applied field, introduced by the domains. The NSF intensities are not solely due to limited instrumental polarizing efficiencies, but arise also from fluctuations along the applied field.

We show the simulated intensity map for the NSF and SF channels in Fig. 3 for $H_a = 100$ Oe, where the polarization of the neutron beam is better than at 20 Oe. The model for the presently observed correlations has been presented earlier [8]. The correlation length and the amplitude of the fluctuations are described by three parameters: the domain size (ξ), the mean deviation angle (Φ) from perpendicular alignment with respect to the applied field direction of the magnetizations inside the domains, and the rms width (σ) of the Gaussian fluctuations of the angles around Φ. σ describes the fact that the angle of the magnetization with respect to the field is not the same for all domains, but fluctuates from domain-to-domain.

ξ is determined from the spread perpendicular to the specular line of the diffuse intensity. Φ is not equal to zero when a net magnetization appears along the guiding field and is therefore determined from fitting the NSF specular reflectivities. At small Φ values, the SF diffuse intensities are mainly governed by Φ itself, and the NSF diffuse intensities are governed by both Φ and σ. Adjusting those values to the data lead to $\xi = 0.7\,\mu m$, $\Phi = 15^\circ$ and $\sigma = 12.8^\circ$.

We observe vertically correlated domains in AF-coupled Co/Cu ML, where the component of magnetization with respect to the applied field fluctuates from domain-to-domain. Combination of diffuse scattering of polarized neutron with polarization analysis and simulations within the DWBA, can precisely and quantitatively inform about the domain structure.

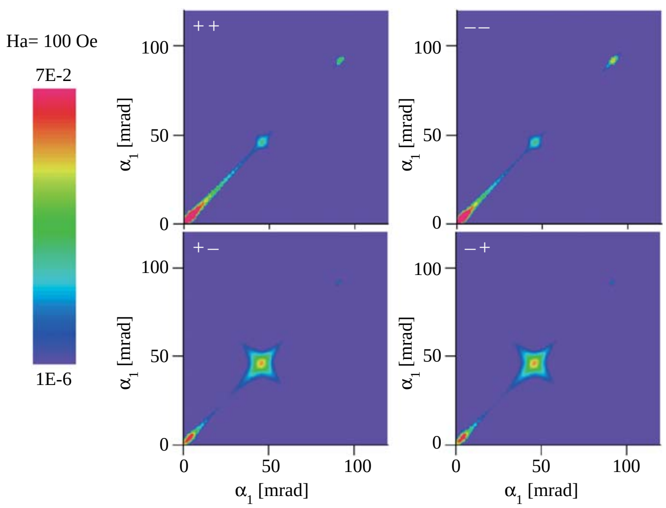

Fig. 3. Simulated NSF and SF intensity maps of a SiO_2/Co(1.45 nm)/[Cu(1.02 nm)/Co(1.45 nm)]$_{\times N=40}$ ML at 100 Oe. The data is simulated within the DWBA.

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