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Polarization analysis of off-specular neutron scattering from domains and rough interfaces in a FeCoV/TiZr multilayer

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Abstract. Specular neutron reflectivity is commonly used as a powerful tool in determining the scattering length density (SLD) profile perpendicular to the surface of thin films. Information about the lateral fluctuations in the SLD, such as the presence of magnetic domains and rough interfaces between layers, can be obtained by studying the pattern of off-specular scattering. Advancements in neutron-source brilliance, beamline optics and detector efficiency, as well as advances in the theoretical description of off-specular scattering, have contributed to the increasing importance of off-specular neutron-reflectometry studies. We present specular and off-specular polarized neutron reflectometry experiments on FeCoV/TiZr multilayers, with a detailed description of the orientations of the magnetic moments inside the FeCoV layers and at the FeCoV/TiZr interfaces.

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Recent polarized neutron investigations of FeCoV/TiZr multilayers have shown high amounts of off-specular scattering [1]. The character of the off-specular scattering changes from predominantly diffuse scattering for applied fields close to the coercive field, to distinct lines of enhanced scattering when the sample is saturated. These two scattering processes can respectively be attributed to scattering from magnetic domains and scattering from rough correlated interfaces. The goal of the current experiments is to obtain more detailed information on the domain orientations and on the magnetic contributions to the interface roughness by performing a polarization analysis of the off-specular scattering.

1 Experiments and discussion

Polarized neutron reflectometry (PNR) experiments on FeCoV/TiZr multilayers were carried out at the CRISP beam line of the ISIS spallation source [2]. The available wavelengths for PNR studies at CRISP are $\lambda = 0.12–0.62$ nm. A one-dimensional position-sensitive detector is used to simultaneously collect specular and off-specular scattering. To enable the polarization analysis of the off-specular scattering, the CRISP beam line was modified by installing a polarization-analyzer device. This device, consisting of a stack of curved polarizing mirrors, has an angular acceptance of 30 mrad for the off-specular scattering. The incident beam ('in') polarization and the direction of polarization analysis for the scattered beam ('out') can be selected either parallel (↑) or anti-parallel (↓) to the applied field. All experiments were carried out with the grazing angle of incidence, θ_S, set to 4 mrad, resulting in an accessible wave-vector-transfer range for the specular reflectivity studies that is given by $Q = (4\pi/\lambda)\sin(\theta_S) = 0.1–0.45\,\text{nm}^{-1}$. This range includes the substrate total reflection region and the first- and second-order Bragg-reflection peaks.

In this article, we present PNR experiments on a 60× [10 nm FeCoV/30 nm TiZr] multilayer that was magnetron-sputtered on a float-glass substrate. Figure 1 shows the hysteresis curve of the multilayer. After saturating the sample at an applied field of $H = -135$ kA/m, PNR experiments were

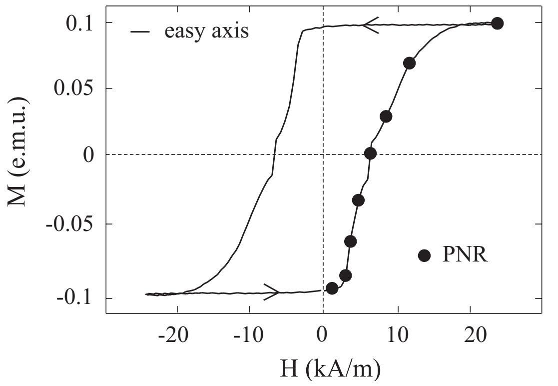

Fig. 1. Hysteresis loop of the multilayer with applied field along the easy axis of magnetization. *Markers* indicate the fields selected for PNR experiments

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performed at the marked field settings along the hysteresis curve. This report focusses on spectra taken close to the coercive field ($H_C \approx 7\,\text{kA/m}$) and on spectra taken at saturation ($H = +135\,\text{kA/m}$). A detailed 3D neutron-depolarization study of the magnetic domain structure at remanence can be found in [3].

Figure 2 shows the non-spin-flipped specular reflectivity curves, ↑↑ and ↓↓, at an applied field $H = 7.2\,\text{kA/m}$. A large similarity is observed between both reflectivity curves, including the independence of Bragg reflection peak positions on the incident-beam polarization. These observations, together with the complete absence of any spin-flipped reflectivities, are indications that the specularly reflected neutrons

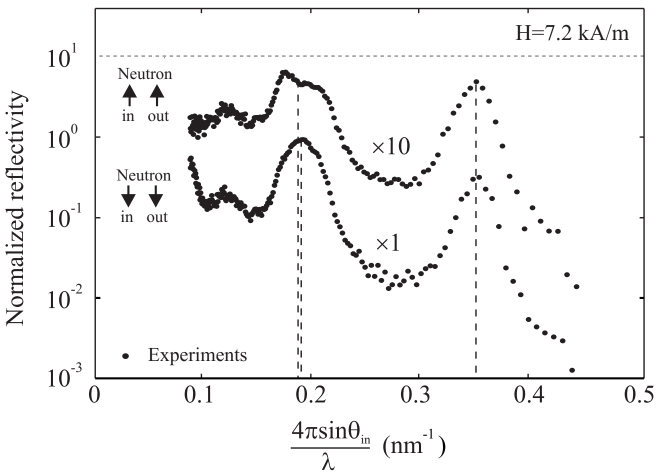

Fig. 2. Specular reflectivity curves of the multilayer with applied field close to the coercive field. The polarization direction of the incident beam ('in') and the direction of polarization analysis after scattering ('out') are marked by *arrows* indicating parallel (↑) and anti-parallel (↓) alignment with the applied field direction

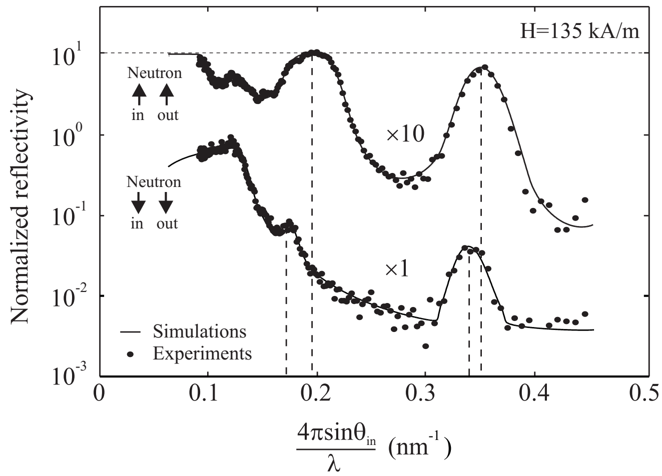

Fig. 4. Experimental and simulated specular reflectivity curves at saturation. Relevant model parameters are discussed in the text

effectively probe a non-magnetic transversal scattering length density (SLD) profile. The presence of magnetic domains inside the FeCoV layers would explain an effective magnetization that is close to zero.

More detailed information on the domains can be obtained from the off-specular scattering spectra shown in Fig. 3. These spectra predominantly consist of diffuse scattering, ruling out the presence of strong transversal correlations in the domain orientations. The experimental data can be readily transformed to momentum space: $I(\lambda, \theta) \rightarrow I(Q_X, Q_Z)$, with Q_X and Q_Z the respective parallel and perpendicular components of the neutron wave-vector transfer. The average domain size is then inversely related to the FWHM of the spectrum at constant Q_Z and can be estimated to be $5-10\,\mu\text{m}$. The complete depolarization of the diffuse scatter-

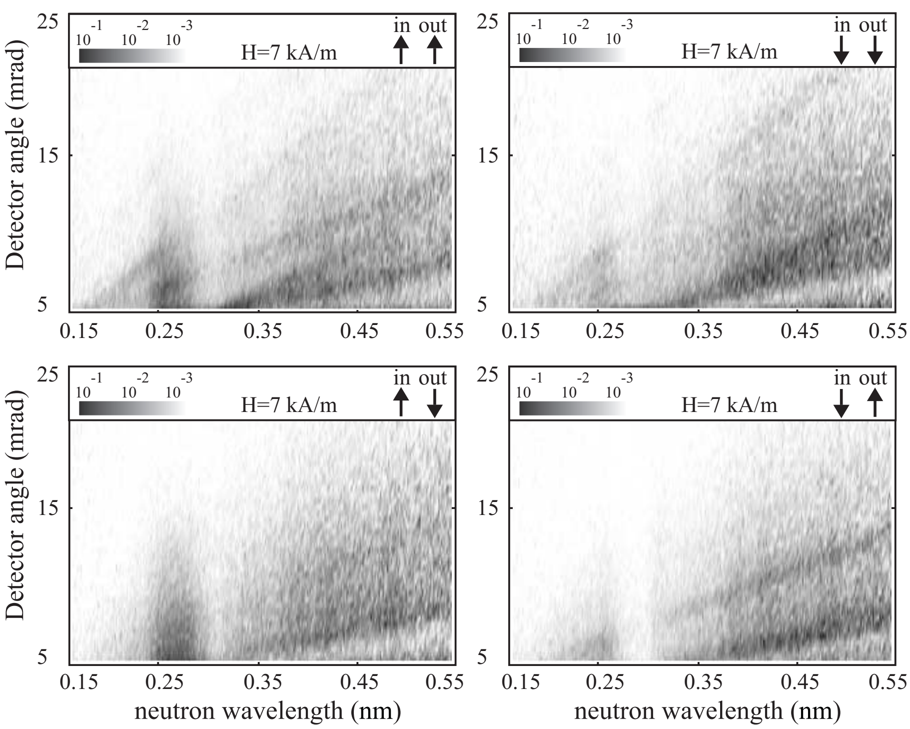

Fig. 3. Off-specular reflectivity spectra taken close to the coercive field

ing indicates a multidomain sample with an isotropic distribution of domain orientations. Preferred domain orientations can be identified by rotating the sample and repeating the experiments.

After increasing the field to $H = +135\,\mathrm{kA/m}$, large changes are observed in the specular and off-specular scattering. Figure 4 shows the $\uparrow\uparrow$ and $\downarrow\downarrow$ specular reflectivity curves. No spin-flipped specular reflectivities could be detected and the diffuse scattering that was attributed to domains was also absent (see Fig. 5). From these observations it can be concluded that all layer magnetizations are aligned parallel to the applied field direction. The specular reflectivity data are analyzed by fitting model calculations, obtained by a standard matrix formalism [4], to the experimental data. No good-quality fit could be obtained for equal shapes of the two FeCoV/TiZr and TiZr/FeCoV intermixing

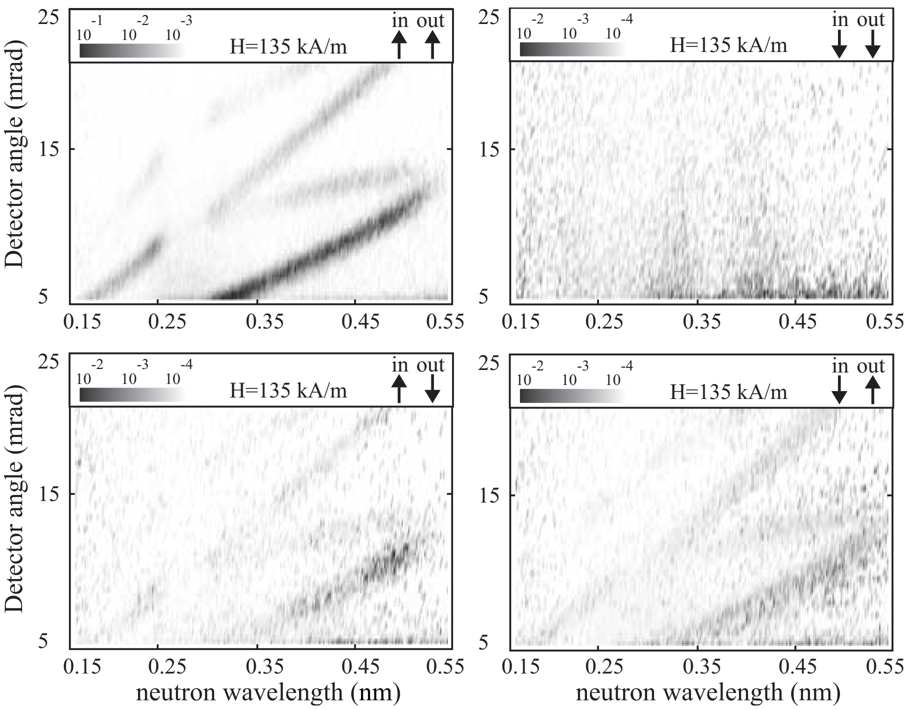

Fig. 5. Off-specular neutron-reflectivity spectra for the saturated multilayer

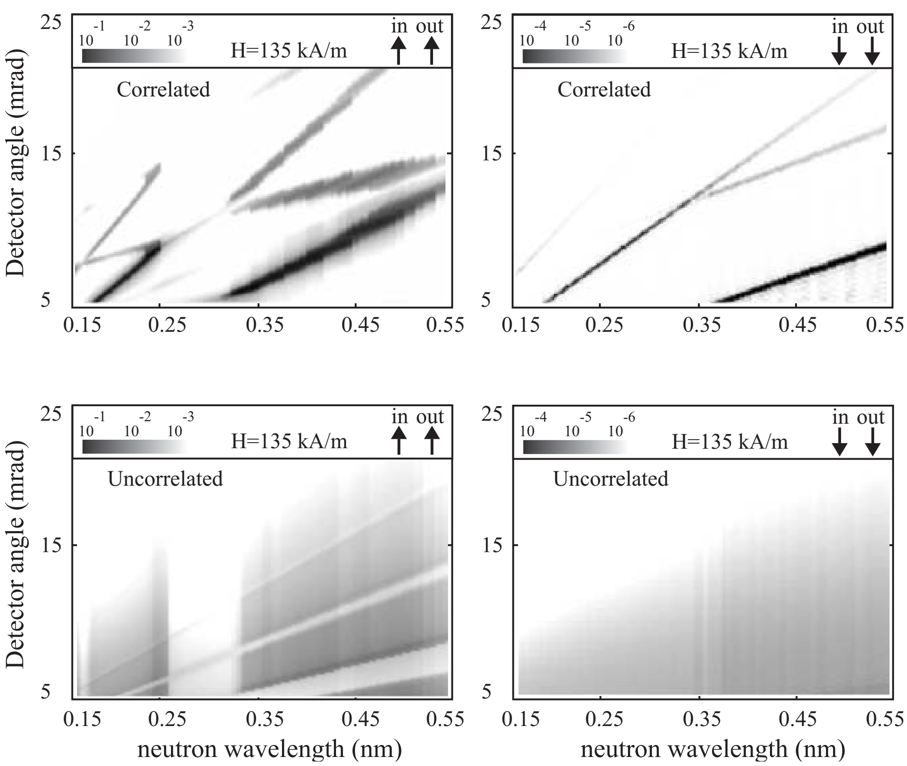

Fig. 6a,b. Model calculations of off-specular neutron reflectometry from correlated (**a**) and uncorrelated (**b**) rough interfaces. The calculated intensities for $\downarrow\downarrow$ scattering lie below the limit of detection in the current experiments regions. The calculations shown in Fig. 4 (solid lines) were obtained by using a more detailed description of the intermixing regions in the model calculations, including a non-magnetic interfacial layer of approximately 1.0 nm and unequal intermixing region widths: σ(FeCoV/TiZr) = 3.0 nm, σ(TiZr/FeCoV) = 2.0 nm.

Although the widths of the intermixing regions in the transversal direction are readily obtained by fitting the specular reflectivity data, no information is obtained about the lateral properties of the interfaces. By studying the off-specular scattering of neutrons, additional information about lateral and transversal correlations of the interface roughness becomes available. Distinct lines of enhanced scattering can be observed in the off-specular scattering shown in Fig. 5. The $\uparrow\uparrow$ and $\downarrow\downarrow$ spectra can be reproduced by model calculations using a distorted-wave Born approximation [5], including multiple-scattering effects [6]. Figure 6a shows simulations using a Gaussian surface roughness (fractal dimensionality = 0.5) and an in-plane correlation length of 5 μm. The thickness, roughness and SLD of the FeCoV and TiZr layers were taken from the fit of the specular data at $H = +135$ kA/m. The roughness of all layers is assumed to be correlated by a perfect vertical reproduction. Model calculations with uncorrelated roughness (Fig. 6b) do not show the lines of enhanced scattering that were observed in the experiments.

From the polarization analysis of the off-specular spectra at saturation it was found that, at fields sufficiently high to align the FeCoV layers, spin-flip scattering could still be observed ($\uparrow\downarrow$ and $\downarrow\uparrow$ spectra in Fig. 5). The non-zero spin-flip scattering indicates the presence of magnetic moments that are not fully aligned with the applied field. The fact that the spin-flip scattering is enhanced along the lines identified with interfacial scattering suggests that the unaligned moments are situated at the chemically rough interfaces and that their orientations are correlated throughout the multilayer stacking. From the shape of the lines, we conclude that the in-plane correlation length of the magnetic roughness is comparable in size to that of the chemical roughness.

2 Conclusions

In summary, we have performed a full polarization analysis of the off-specular scattering from FeCoV/TiZr multilayers. Experiments carried out close to the coercive field show depolarized diffuse scattering spectra that are linked to the presence of magnetic domains with no preferred orientations and no correlations throughout the multilayer stacking. At saturation, the enhancement of off-specular scattering along specific lines is caused by chemically rough interfaces, correlated over large vertical distances in the multilayer. The presence of spin-flip scattering along these lines is attributed to a correlated magnetic roughness.

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