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X-ray resonant magnetic scattering on noncollinearly coupled Fe/Cr superlattices

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Abstract

We have studied in detail the structural and magnetic properties of an antiferromagnetically (AF) coupled Cr(25.6 Å)/Fe(15.2 Å) superlattice by soft X-ray resonant magnetic scattering. Using the resonance condition close to the Fe L_3 edge, magnetic peaks are observed at the half-orders Bragg peaks positions. The magnetic hysteresis loops measured at the even-order and at the half-order Bragg peaks demonstrate the biquadratic type of AF coupling for Fe/Cr multilayer. Experimental data were simulated using the matrix formalizm in order to go away from macroscopic magnetic properties of such superlattices and to understand their layer-by-layer magnetic structure.

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Keywords: Soft X-ray resonant magnetic scattering; Noncollinearly coupled superlattice

Magnetic heterostructures consisting of two or more ferromagnetic (F) layers separated by non-magnetic or antiferromagnetic (AF) spacer layers have received much attention due to their importance in fundamental science and technology. It has been shown that, depending on the thickness of the spacer layer, ferromagnetic layers may be coupled ferromagnetically or antiferromagnetically via the interlayer exchange interaction [1]. Moreover, Rühring et al. reported that in the transition regions of the coupling constants J between collinear 180°(AF) and 0°(F) spin alignment, a noncolinear 90° coupled magnetization profile exists [2].

It is well known that X-ray resonant magnetic scattering (XRMS) provides direct information on the magnetic structure of materials. During the last decade, a growing number of experiments have been carried out and it has been shown that in case of antiferromagnetically ordered multilayers, the periodicity of the magnetization amplitude leads to a magnetic contribution at the half-order low-angle Bragg peak. Furthermore, varying

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the external magnetic field during the XRMS measurements, a hysteresis loop can be measured. Up to now for most of the XRMS experimental data, especially in the soft X-ray range, a detailed analysis of magnetization and magnetization reversal is absent or has been made for collinear magnetic configuration only. For the hard X-ray range, progress in the data analysis had taken place during the last years (see, for example, Ref. [3] and refererences therein). However, for soft X-rays and in the case of antiferomagnetically coupled multilayers the situation is more complex. It has been shown earlier, that in remanence such multilayers can be in multidomain state [4,5] and/or with noncollinear coupling in adjacent magnetic layers [6,7]. For noncollinearly coupled multilayers we cannot use the asymmetry ratio $R = (I^+ - I^-)/I^+ + I^-$, where $I^\pm$ is the intensity of right/left-circular polarized radiation, because this ratio is sensitive to the magnetization in the scattering plane only ($M_\parallel$). But utilizing the direct intensity of circularly polarized or π-linearly polarized radiation, we can extract information about both in-plane magnetization components ($M_\parallel$ and $M_\perp$). In order to understand the magnetic structure a simulation of the structural factor is necessary, using possible magnetic configurations. In our previous paper [5], we presented results on Fe/Cr multilayer demonstrating the collinear coupling. In this study, we would like to focus our attention on magnetic configurations of noncollinearly coupled Fe/Cr superlattices.

We have grown Fe/Cr superlattices by molecular beam epitaxy with Cr thickness close to the second maxima (~25 Å) in the AF interlayer exchange coupling. The Fe layer thickness (~ 15 Å) and the number of repeats ($N = 10$) was chosen to not exceed the total penetration depth of the soft X-rays. The detailed procedure of the sample preparation is described in Ref. [5]. SQUID magnetometry indicated noncollinear coupling with $H_S = 2.5$ kOe. The four-fold in-plane crystal anisotropy of the magnetization has been observed by magneto-optical Kerr effect measurements.

The XRMS experiments were carried out at the undulator beamlines UE56/1 and UE56/2 of the Berlin storage ring for synchrotron radiation (BESSY). In order to study XRMS on 3d transition metals, the L absorption edges must be utilized, which are located in the soft X-ray range. Since for this energy range special vacuum conditions are required, a UHV-diffractometer ALICE containing a two-circle goniometer [8] was used for the scattering experiments to be described below. The magnetic field was applied in the scattering plane parallel to the in-plane hard axis of the sample ($\varphi = \pm 90°$). In our geometry, the magnetization vector corresponding to $\varphi = 0°$ is normal to the scattering plane and the positive direction of φ rotation is clockwise (Fig. 1a). The

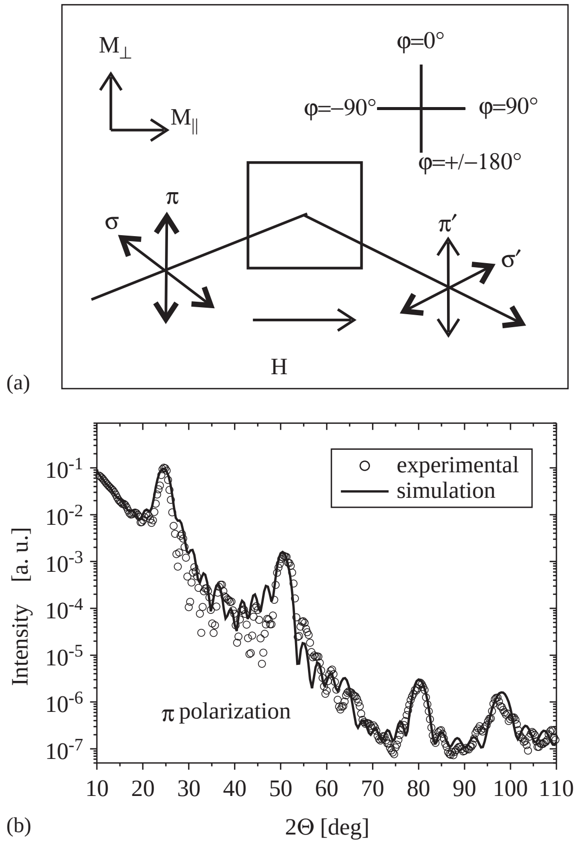

Fig. 1. (a) The scattering geometry of the experiment; (b) Reflectivity taken at the Fe L_3 edge with π-linearly polarized radiation for AF-coupled superlattice with 10 repeats of [Fe(15.2 Å)/Cr(25.6 Å)] deposited on Cr(240 Å)/MgO(0 0 1) buffer-substrate system: open circles—the experimental data, solid line—the simulation using a model, corresponding to biquadratic coupling.

Fe/Cr multilayer was characterized with both circularly and linearly polarized radiation.

By tuning the incident energy to just below the Fe L_3 edge, we observe structural Bragg peaks at the even positions and magnetic Bragg peaks at the half-order positions in units of the reciprocal lattice vector associated with the superlattice periodicity (Fig. 1b). The fact that we can observe a few orders of Bragg reflections reflects on the high structural quality of the sample. The line represents a simulation procedure based on the matrix formalism [9] with the optical constants taken from [10]. All structural parameters (layer thicknesses and interface roughnesses) were taken from the fit of the hard X-ray data using standard Parratt formalism. The magnetic interface roughnesses were introduced in the model using slicing method. More details of the simulation procedure will be published elsewhere [11]. It has been found that the magnetic roughness in the present multilayer amounts to about 65% of the value of the structural roughnesses (2.6 Å and 4 Å, respectively). The best agreement between the experimental data and the calculated values is achieved for the magnetic structure corresponding to biquadratic (90°) coupling in the multilayer with the magnetization vector in the iron layer parallel to the easy axis of the in-plane magnetic anisotropy ($\varphi_1 = -135^\circ$ and $\varphi_2 = -45^\circ$ to the scattering plane for the odd and even iron layers, respectively). This results were confirmed by the simulation of the hysteresis loops described below.

Hysteresis loops measured with linearly (π) and left-circularly ($\varepsilon^- = (\sigma - i\pi)/\sqrt{2}$) polarized radiation at the position of the structural (the 3rd order, $2\theta = 80.4^\circ$) Bragg peak and the half-order (the 7/2 order, $2\theta = 97.2^\circ$) magnetic peak are reproduced in Figs. 2 and 3, correspondingly. For a simulation of these data we calculated the dependence of the magnetization directions for the odd and even Fe layers on the external field by minimizing the energy density for each field value in a Stoner–Wohlfarth-like model [12]. Contributions of the Zeeman energy, the four-fold crystal anisotropy, the bilinear, and biquadratic exchange coupling have been taken into account. It has been established that magnetic roughnesses do not affect the shape of the hysteresis loops (there is an intensity scaling effect only). Therefore in order to simplify the simulation procedure, we used one AF domain configuration and calculated the hysteresis loops without taking into account magnetic roughness, but using some scaling of the intensity. According to this model, the

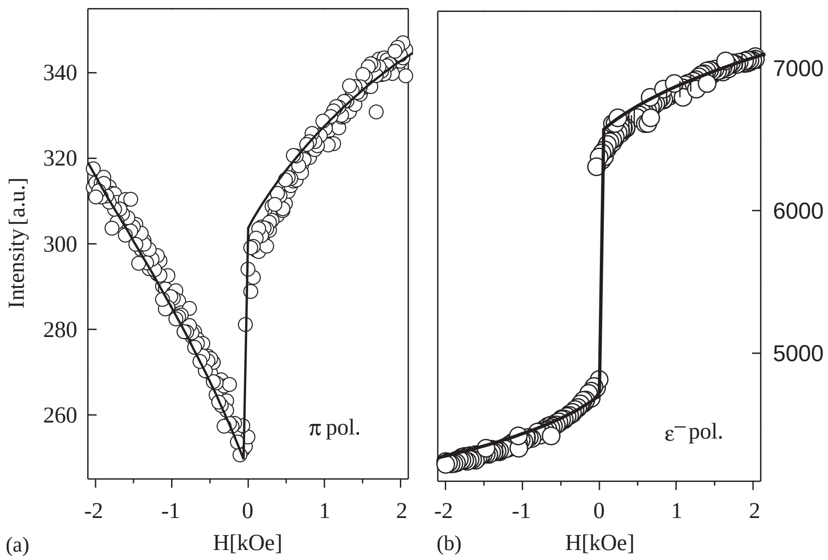

Fig. 2. Hysteresis loop measured at the position of the structural 3rd order, ($2\theta = 80.4^\circ$) Bragg peak for π linearly (a) and left-circularly polarized radiation (b). Open circles—the experimental data, solid lines—simulation with the model presented in Fig. 4.

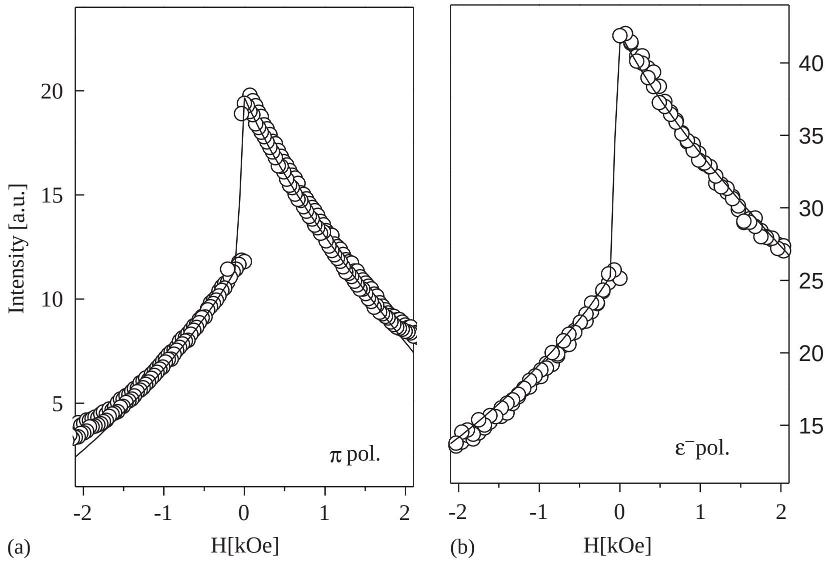

Fig. 3. Hysteresis loop measured at the position of the half-order (7/2 order, $2\theta = 97.2°$) magnetic peak for π-linearly (a) and left-circularly polarized radiation (b). Open circles—the experimental data, solid lines—simulation with the model presented in Fig. 4.

coherent rotation of the magnetization from $\varphi = -90°$ at saturation to the corresponding easy axis ($\varphi_1 = -135°$ for odd and $\varphi_2 = -45°$ for even iron layer) close to the remanent state takes place. At remanence the domain wall propagates fast through the iron layers changing, the angles of the magnetization by 180°. By increasing the magnetic field, the coherent rotation to the saturation takes place again (Fig. 4). Finally it has been found that for the best agreement between data and simulation it is necessary to add some ferromagnetic background, resulting from the presence of $\sim$ 5–10% ferromagnetically coupled domains. The results of these calculations are presented by solid lines in Figs. 2 and 3.

In conclusion, we have shown that XRMS allows to study in detail the magnetic structure of noncollinearly coupled Fe/Cr superlattices. Using the resonance condition close to the Fe L_3 edge, magnetic peaks are observed at the half-order Bragg peaks positions. The experimental data of the reflectivity and hysteresis loops and their simulation reflect biquadratic AF coupling with the in-plane easy-axis orientation of Fe magnetization in adjacent layers at remanence. With increasing magnetic field coherent rotation of the magnetization vectors takes place to the total saturation.

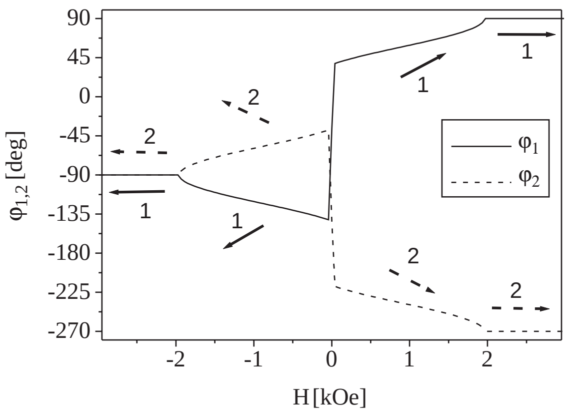

Fig. 4. The model used in the simulation of the hysteresis loops: the solid and dashed lines—the dependence of the angles $\varphi_{1,2}$ of the magnetization vector of the odd and even Fe layers, correspondingly.

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