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Magnetization Flop in Fe/Cr GMR Multilayers

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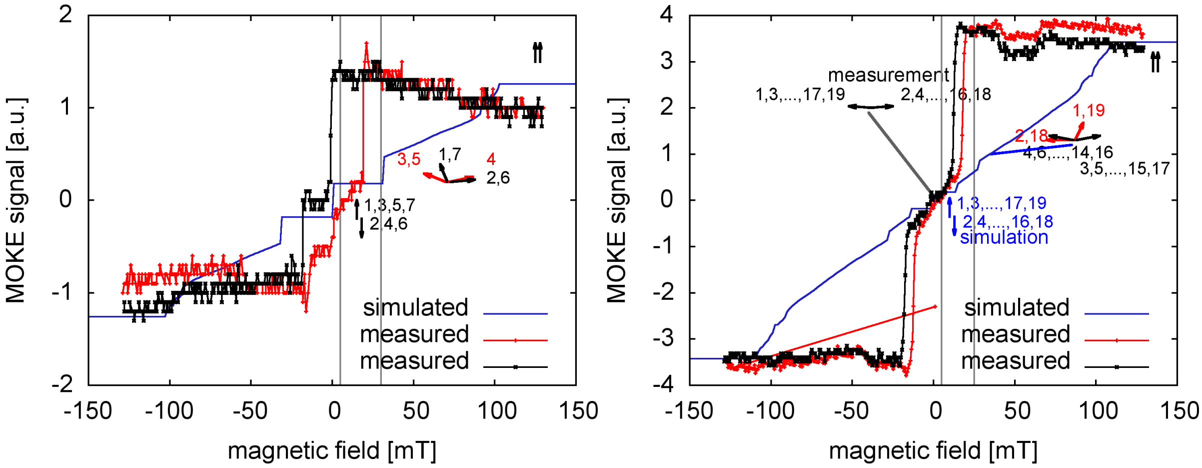
Abstract.
We study the magnetization of antiferromagnetically (AF) coupled Fe/Cr multilayers, with 7 and 19 periods respectively, under the influence of an external magnetic field. Due to the odd number of Fe layers the uncompensated magnetization of the multilayer at remanence is equal to the magnetization of a single Fe layer. Measurements have been performed using the magnetooptical Kerr effect (MOKE) for an integral overview and polarized neutron scattering under grazing incidence for a depth resolved information about the magnetization orientation of the individual Fe layers.

We find a dependence of the orientation of the remanent magnetization on the number of AF coupled Fe double layers. For a small number of periods (here: 7). The uncompensated magnetic moment is sufficient to align the magnetization of all layers parallel or antiparallel to the applied magnetic field. On the other hand, in the multilayer with 19 AF-coupled Fe layers all Fe layers are magnetized perpendicular to the field.

1. Introduction

Layered magnetic structures are main elements of today's spintronic information technology [1]. A prominent example is the applications of the giant magnetoresistance effect (GMR) [2] in hard disk drives or magnetic field sensors. The complexity of physical properties of magnetic multilayers (ML), due to the competition between interlayer (IL) exchange coupling, the different anisotropies and external influences is not yet fully understood.

In this paper we report on the remagnetization behaviour of AF-coupled multilayer structures as a function of the number of multilayer periods. To address this issue a model system is needed, which shows reproducible concurrent influences. This is given in epitaxial Fe/Cr-MLs. The coupling phenomena in Fe/Cr layered structures have been discovered in the 1980's as the first IL exchange coupled system of transition metals [3, 4, 5]. The AF coupled Fe/Cr-MLs are grown with molecular beam epitaxy (MBE), macroscopically characterized by MOKE and measured with neutron scattering with full polarization analysis under grazing incidence. This method allows one to investigate the magnetic behaviour layer by layer as a function of the applied magnetic field and provides additional lateral information on roughnesses and magnetic domains.



(a) $[Fe/Cr]_7$ (b) $[Fe/Cr]_{19}$

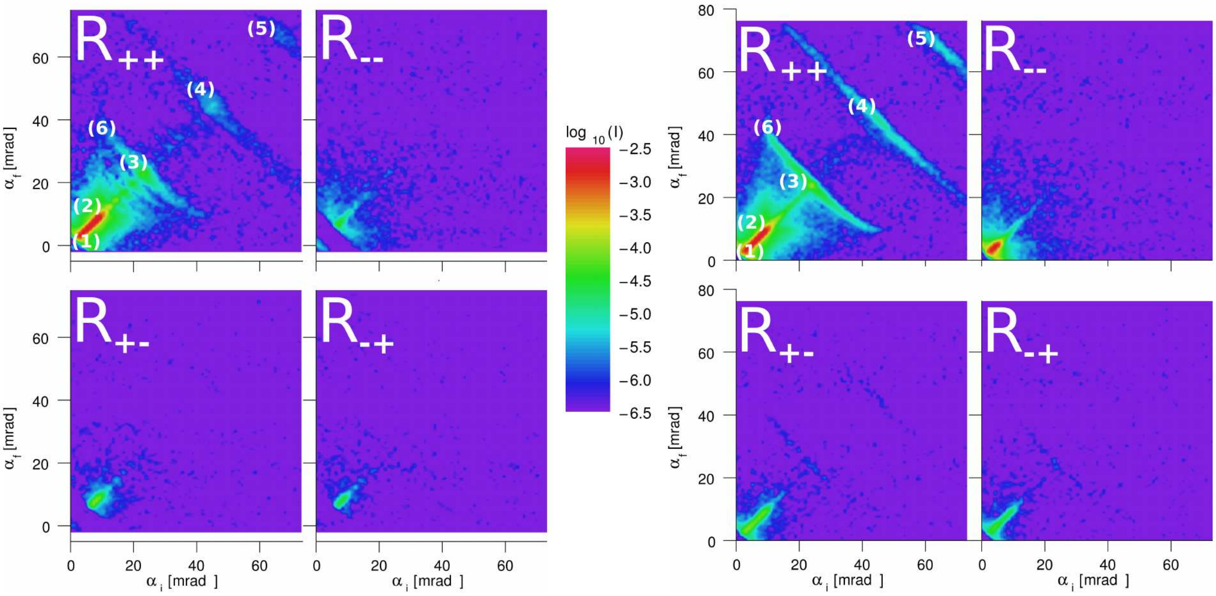
Figure 1. MOKE measurements (red: increasing, black: decreasing field) and simulations (blue) of AF coupled [Fe/Cr] MLs. The vertical pale lines indicate fields selected for neutron measurements. The numbered arrows show the in-plane orientation of the magnetization. The main difference between the two measurements is the behaviour at remanence. The $[Fe/Cr]_7$ system shows a jump at $H = 0$ while the $[Fe/Cr]_{19}$ system smoothly crosses the zero. In the intermediate field range, there appears to be a strong difference between measurement and simulation, because of the transverse Kerr effect that distorts the curve where the magnetization is oriented perpendicular to the field, and because of the limited penetration depth, which emphasizes the top layer, while the simulation uses equal weights for all layers. (color online)

2. Sample preparation and macroscopic characterization

Two samples with the layer compositions $[Fe_{10\,nm}/Cr_{1\,nm}]_{x6}/Fe_{10\,nm}$ and $[Fe_{10\,nm}/Cr_{1\,nm}]_{x18}/Fe_{10\,nm}$ on a GaAs(001) substrate with a $Ag_{150\,nm}$ buffer layer have been grown epitaxially by MBE using the standard procedure described in reference [6, 7]. In the rest of the text, we use the abbreviations $[Fe/Cr]_7$ and $[Fe/Cr]_{19}$ for the two samples, respectively. Because of the single crystalline growth the magnetic easy axes due to crystalline and shape anisotropy are known to be parallel to the four in-plane [100] directions of the substrate.

The magnetization as a function of the applied magnetic field is precharacterized by MOKE. This method enables a qualitative measurement of the magnetization as a function of the magnetic field. The magnetization signal is distorted due to the limited penetration depth of the light, due to contributions of the transversal Kerr effect during the rotational transition of the magnetization and due to thermal drift and noise. Nevertheless, it allows the determination of the type and strength of the IL coupling by fitting the transition fields to a model based on the total energy.

Figure 1 shows the MOKE measurements of both samples with the magnetic field aligned parallel to one of the easy axes. One can easily identify the AF character of the interlayer coupling from the reduced magnetization at small fields. To be able to understand the MOKE measurement of the complex multilayer, we have performed simulations based on a simple model of minimizing the total magnetic energy with respect to the angle between the magnetic moments of the individual layers and the direction of the applied field. The AF coupling, Zeeman energy and the cubic crystalline anisotropy have been taken into account. The interplay of these three contributions determine the alignment of the magnetic moments in the layers and thus the magnetization component parallel to the field. The model is based on the assumption that there is a homogeneous magnetization in every layer (single domain state) and neglects potential



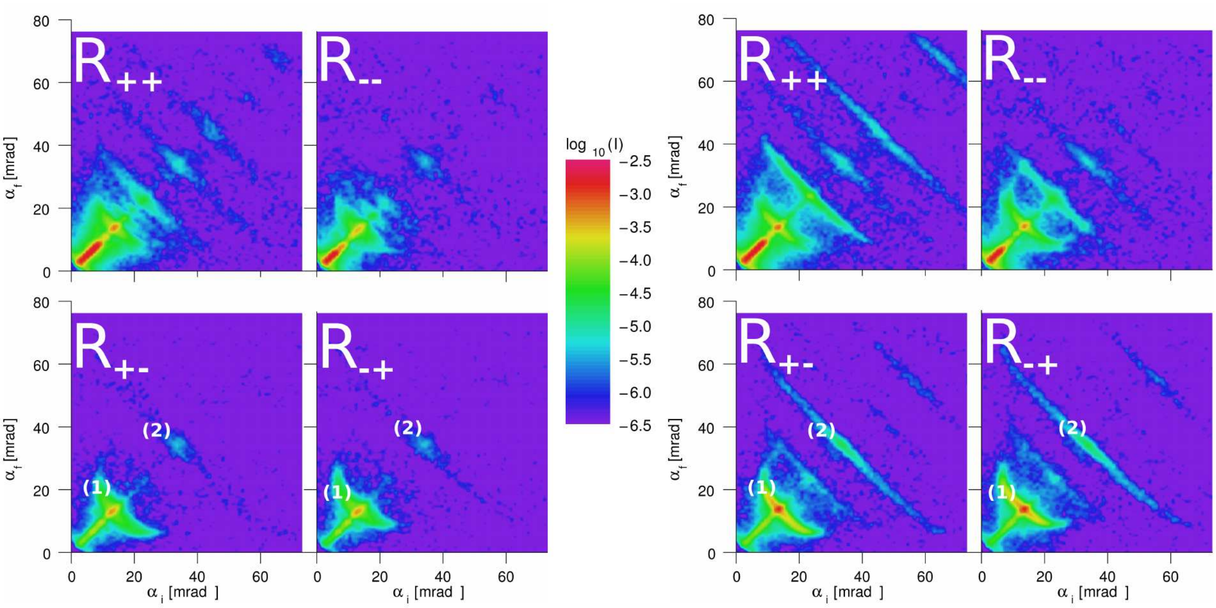
(a) [Fe/Cr]$_7$ (b) [Fe/Cr]$_{19}$

Figure 2. Neutron measurement in saturation field of 300 mT. Plotted is the logarithm of the scattering intensity vs. incident and outgoing angles α_i, α_f. The four polarization channels are the NSF channels (R_{++} and R_{--}) and the SF channels (R_{+-} und R_{-+}). Indicated are the primary beam blocked by the beamstop (1), the plateau of total reflection (2), the first (3), second (4) and third order (5) Bragg-peak (giving information about the layer structure) and the Bragg-sheets (information about correlated roughness)(6). (color online)

walls, so that the hysteresis effects cannot be reproduced. The values of the constants of bilinear coupling J_1 and biquadratic coupling J_2 have been adjusted by a reference measurement of an [Fe/Cr/Fe] sample, where extinction effects can be neglected.

For the [Fe/Cr]$_7$ sample we find a reasonable agreement of measurement and simulation. The net magnetization of the ML at remanence is the magnetization of a single layer. This is found to be sufficient for the alignment of the magnetization of all layers alternatingly parallel and antiparallel to the field. When crossing zero field, the magnetization of all layers is reversed, resulting in a jump in the MOKE curve. With increasing field the influence of the AF coupling energy is reduced compared to the Zeeman energy which tends to magnetize all layers along the field. The compromise is then a state, where all magnetizations are somewhat aligned perpendicular to the field, alternatingly left and right, with a canting towards the field direction. The canting induces a magnetization component in every layer parallel to the field in favour of the Zeeman energy, while the alternation satisfies the AF coupling. The magnetic moments cant more and more until they finally reach saturation, when they are all aligned parallel to the field.

The MOKE measurement of the [Fe/Cr]$_{19}$ sample shows a smooth transition at zero field. This is contradictory to the previously described measurement and contradictory to the simulation. The transition towards the state, where the net magnetization is aligned with the field, is not observed experimentally. Together with the neutron data, it became clear that the coercivity effects, which are not included in the model calculation, inhibit this transition, as the energy gain is not sufficient to cross the anisotropy barrier.



(a) $[Fe/Cr]_7$ (30 mT) (b) $[Fe/Cr]_{19}$ (25 mT)

Figure 3. Neutron measurement in intermediate field. Indicated are the AF superstructure Bragg peaks of the order $\frac{1}{2}$ (1) and $1\frac{1}{2}$ (2). (color online)

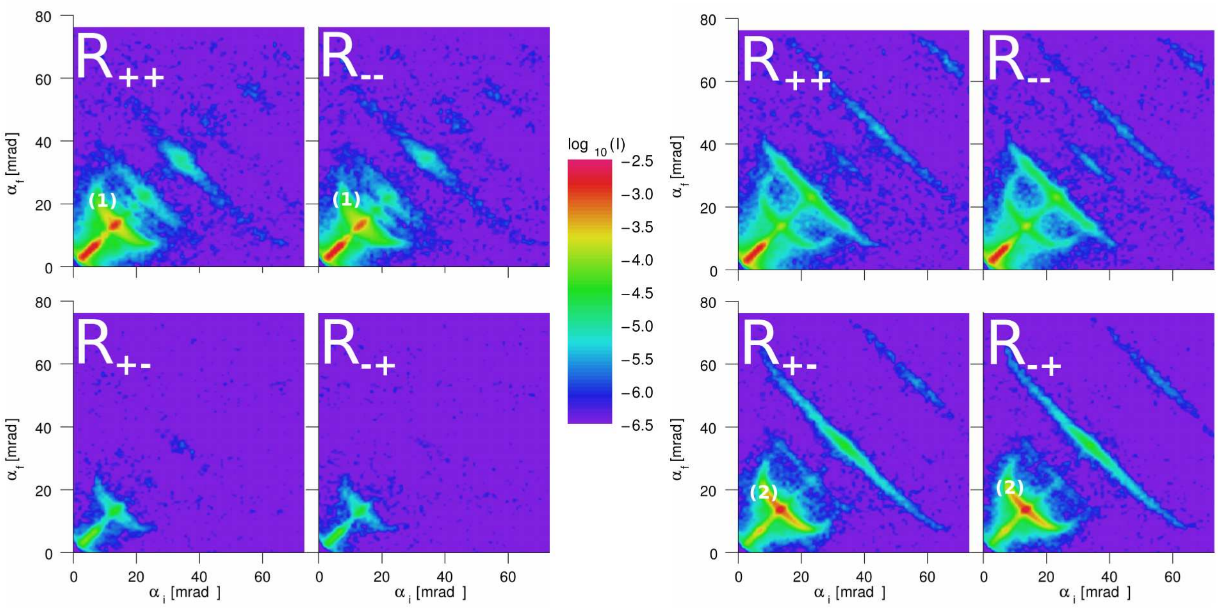
3. Polarized neutron reflectometry and off-specular scattering

Polarized neutron reflectometry (PNR) and off-specular scattering reveal information about the in-plane magnetization vector of individual layers and their domain structure. The experiments have been performed at the reflectometer TREFF of the JCNS at the FRM II research reactor in Garching. The setup allows to simultaneously measure specular and off-specular scattering with full polarization analysis. The neutron wavelength was fixed at 4.73 Å. The efficiencies of the polarizer, analyzer and both spin flippers are above 98%.

An external magnetic field has been applied in-plane parallel to one of the easy axes. Based on the MOKE measurements, we have defined the magnetic fields suitable for the neutron measurements. We have decided to perform three measurements on one branch of the hysteresis curve, from saturation at 300 mT down to remanence.

The figures 2 - 4 show the scattered intensity in a logarithmic colour plot as a function of the angle of incidence α_i and the outgoing angle α_f. The four graphs R_{++}, R_{--},R_{+-}, and R_{-+} show the different combinations of incoming and outgoing polarization of the neutron beam. The incident and outgoing angles α_i and α_f are defined as the angles between the incoming and outgoing wave vectors $\vec{k_i}$ and $\vec{k_f}$ and the sample surface, respectively. If $\alpha_i = \alpha_f$, we observe specular reflectivity. This part contains only information on the out-of-plane structure because the scattering vector $\vec{Q} = \vec{k_f} - \vec{k_i}$ is perpendicular to the surface. In off-specular geometry $(\alpha_i \neq \alpha_f)$ the scattering vector has a component in plane which contains information on lateral correlations e.g. from roughness and magnetic domains with a size smaller than the in-plane coherence length ($\approx$ 20 μm)[8, 9]. Scattering in the non-spin-flip (NSF) channels (R_{++} and R_{--}) are due to the correlations of the structure and the magnetization components parallel to the external field. The information in the spin-flip (SF) channels (R_{+-} and R_{-+}) has its origin only in the magnetization component perpendicular to the external field.

In saturation (fig. 2) all magnetic moments are aligned with the field, so no SF scattering



(a) $[Fe/Cr]_7$ (b) $[Fe/Cr]_{19}$

Figure 4. Neutron measurement in remanence field of 5 mT. Indicated are the AF superstructure Bragg peaks of order $\frac{1}{2}$ in the NSF channel of the $[Fe/Cr]_7$ system (1) and in the SF channel of the $[Fe/Cr]_{19}$ system (2). (color online)

is observed. The intensity in the SF channels is purely parasitic due to the limited flipping ratio of the instrument. As the nuclear scattering length density of Cr is almost equal to the difference between nuclear and the magnetic scattering length density of Fe, there is no contrast for spin-down neutrons. Therefore, in R_{--} only the total reflection is observed.

At the intermediate field of 30 mT or 25 mT, resp., (fig. 3) we observe intensity in the SF-channels (Bragg peaks of half orders). This is induced by an additional magnetization component perpendicular to the external field, because of the stronger influence of the AF coupling compared to the Zeeman energy at reduced magnetic field. A magnetic contrast between adjacent Fe layers has evolved, so the magnetic unit cell is twice as large as the structural unit cell. The behavior of both systems in this field range is the same.

At remanence (fig. 4) there is obviously a big difference between both samples. In the $[Fe/Cr]_7$ system there is magnetic information (doubled unit cell because of AF alignment) only in the NSF-channel, because all moments are (anti-)parallel to the quantization axis. The remaining intensity difference between R_{++} and R_{--} is a signature of the remaining uncompensated magnetic moment in field direction. This is in agreement with the MOKE data and its simulation. The $[Fe/Cr]_{19}$ system shows the half order AF Bragg peaks only in the SF channels while only the structural integer order Bragg peaks remain in the NSF channels (the faint intensity in the other channels is a parasitic effect due to the limited flipping ratio). This shows that the moments are all aligned perpendicular to the small external field. The intense wide Bragg sheets in the SF channels indicate a magnetic domain pattern with domain sizes in the μm regime.

For a quantitative analysis we have modeled the specular part of the intensity measured (fig. 5). With a fit of the model parameters to the data, we were able to retrieve the directions of the magnetic moments with respect to the external field (tab. 1). In saturation field all moments align parallel to the external field, so that we could use it for fixing all structural parameters.

In an intermediate field of 30 mT ($[Fe/Cr]_7$) or 25 mT ($[Fe/Cr]_{19}$) we find a more complex magnetic structure. The competing influences of Zeeman-, anisotropy- and AF coupling energy lead to differently aligned outer and inner layers because the inner layers feel the coupling from both sides. The results from the PNR fit are in good agreement with the simulation results describing the MOKE measurements as can be seen in table 1.

In remanence the statements of the qualitative analysis hold. In the $[Fe/Cr]_7$ system the moments align parallel and antiparallel to the field while in the $[Fe/Cr]_{19}$ system the magnetization is aligned perpendicular to the field with a slight canting in field direction. This is consistent with the MOKE measurement, but only in the case of $[Fe/Cr]_7$ it is also consistent with the model calculation.

The difference to the result of the simulation in the case of $[Fe/Cr]_{19}$ can be explained as follows: The model only minimizes the total energy of the system without taking into account potential walls for domain wall movement or activiation energies to cross a hard anisotropy axis. Effects of coercivity, which make a system remain in a state it had previously, can not be described. The difference between the systems can be attributed to the increase of energy which is necessary to flip the magnetization of the whole ML across a hard anisotropy axis. All layers have to be flipped at once, so the activation energy is proportional to the number of Fe layers. In contrast, the magnetic field only works on the magnetic moment of the single layer, whose magnetization is not compensated by the AF coupling. In the $[Fe/Cr]_7$ system it is energetically favorable to flip all 7 Fe layers to gain the Zeeman energy of the uncompensated layer. For 19 Fe layers the Zeeman energy of the uncompensated layer is the same while flipping the whole system needs much more energy. Thus for the $[Fe/Cr]_{19}$ system the gain in Zeeman energy is not sufficient to overcome the anisotropy barrier, so that the system remains with the magnetic moments aligned perpendicular, slightly canted to the external field direction.

4. Conclusion

We carried out MOKE measurements, specular and off-specular polarized neutron scattering of AF coupled Fe/Cr MLs. The magnetic behavior of the systems shows a dependence on the number of Fe layers. In the intermediate and high field range, the systems show identical behaviour as it is governed by the competition between AF coupling and Zeeman energy. At

(a) $[Fe/Cr]_7$ system

Fe-layer	**Angle to external field**			
1 and 7	0	$8,1$	21	0
2 and 6	180	$-104,3$	-91	0
3 and 5	0	$16,5$	73	0
4	180	$-76,4$	-79	0
	PNR fit 5 mT	**PNR fit 30 mT**	**MOKE-Sim. 32 mT**	**PNR fit 300 mT**

(b) $[Fe/Cr]_{19}$ system

Fe-layer	**Angle to external field**			
1 and 19	$-83,86$	$-54,5$	-72	0
2 and 18	$86,55$	$87,9$	82	0
3,5,7,...,15,17	$-83,86$	$-76,3$	-80	0
4,6,8,...,14,16	$86,55$	$81,5$	80	0
	PNR fit 5 mT	**PNR fit 25 mT**	**MOKE-Sim. 25 mT**	**PNR fit 300 mT**

Table 1. Angles of the magnetization vectors of the individual Fe layers as retrieved from the fit of the specular neutron reflectivity or the MOKE simulation, resp.

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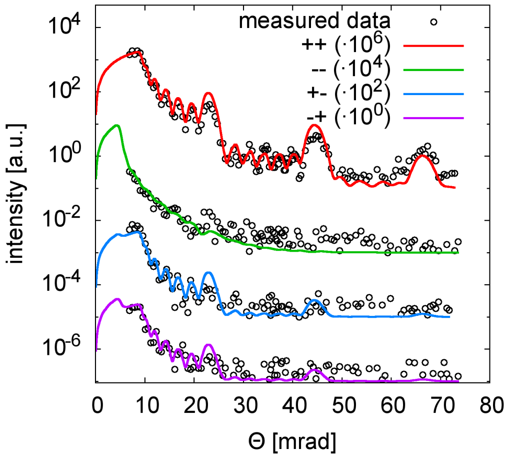
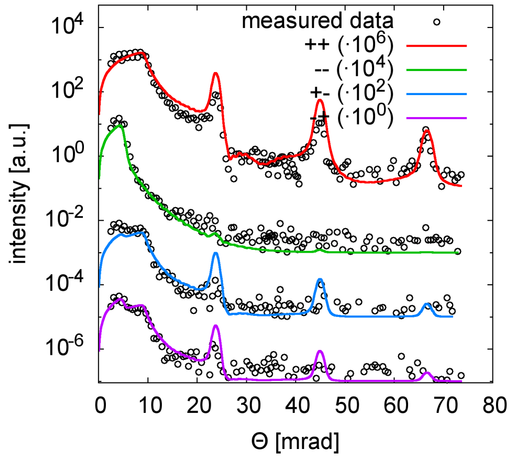
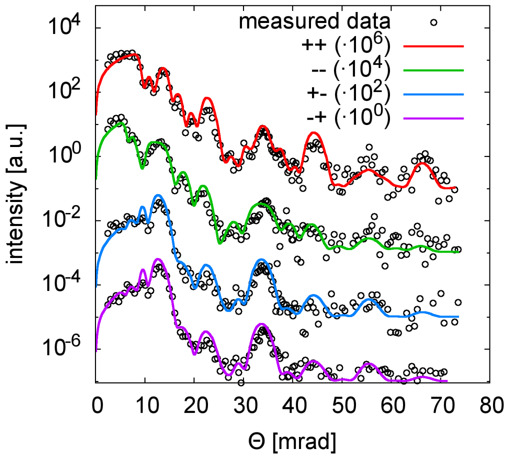


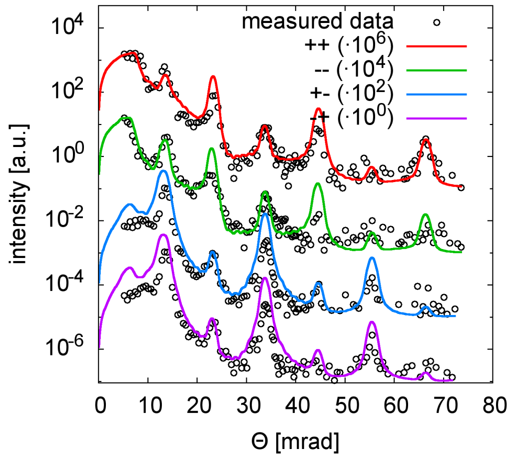
(a) $[Fe/Cr]_7$ 300 mT



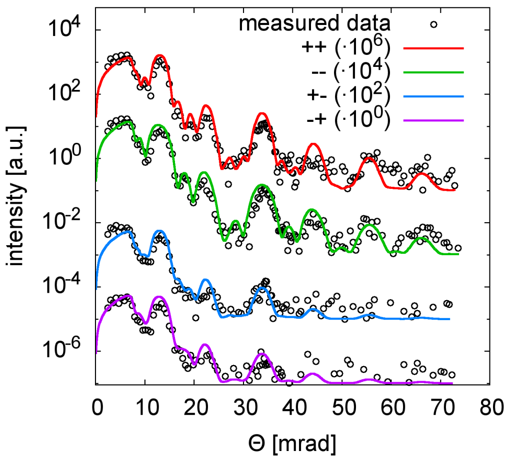
(b) $[Fe/Cr]_{19}$ 300 mT



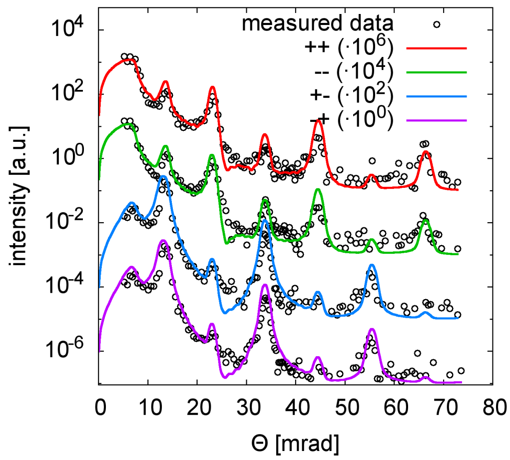
(c) $[Fe/Cr]_7$ 30 mT



(d) $[Fe/Cr]_{19}$ 25 mT



(e) $[Fe/Cr]_7$ 5 mT



(f) $[Fe/Cr]_{19}$ 5 mT

Figure 5. Fit of the specular reflectivity of both samples at all magnetic fields. The different polarization channels are scaled for better perceptibility, the symbols indicate the experimental points, the lines show the fits. (color online)

remanence, the alignment is driven by the Zeeman energy of the uncompensated magnetic moment working against the coercivity. In the $[Fe/Cr]_7$ system the Zeeman term is sufficient to align the magnetization of all layers along or opposite to the applied field. With increasing number, the situation changes. In a ML with 19 AF-coupled Fe layers, we have found the entire magnetic signal in the spin-flip channels, which means that all Fe layers remain magnetized perpendicular to the field.

We have been able to model the magnetic behavior of AF-coupled systems with a simple approach. The simulations of the magnetic behavior of these MLs are consistent with our MOKE and neutron measurements within the limitations of the model.

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