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Magnetic depth profiling of FM/AF/FM trilayers by PNR

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Abstract

Ferromagnetic/antiferromagnetic/ferromagnetic (FM/AF/FM) trilayers are investigated by polarized neutron reflectivity (PNR) with polarization analysis to obtain the layer resolved magnetization profile at various states of magnetization. The trilayers are composed of FeCoV (FM) layers which are separated by NiO (AF) layers of varying thickness. The spin-dependent reflectivities are analyzed by modeling the magnetic states of the FeCoV layers. First, we study magnetization configurations during the magnetization reversal as a function of AF thickness. It is found that for thin AF layers the magnetization reversal of the FM layers occurs simultaneously, whereas for thick AF layers the reversal occurs in a two-step process. In a second part of the experiments we follow, by PNR, the reorientation of the top FM layer in an in-plane perpendicular field starting from a state with the magnetization in the adjacent FM layers oriented antiparallel. It is observed that the magnetization of the top FeCoV layer gradually rotates into the direction of the applied field while the bottom FeCoV layer remains pinned in its state perpendicular to the field.

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1. Introduction

In multilayers consisting of ferromagnetic layers separated by non-magnetic metallic or insulating antiferromagnetic layers, the interlayer exchange coupling (IEC) results in parallel, anti-parallel or non-collinear ordering of adjacent FM layers with respect to each other [1–3]. For metallic spacer layers, the IEC is of RKKY type mediated by itinerant electrons, and hence of long-range nature. For insulating spacer layers, an exponential decay of IEC with thickness is expected, a fact attributed to spin-polarized electron tunneling through the spacer layer [2]. If the spacer layer is an antiferromagnet, the formation of domain walls

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parallel to the interface is expected to influence the IEC [4]. Interfaces of ferromagnetic and antiferromagnetic layers may also show exchange bias (EB) with shifted hysteresis loops of the FM [5]. The EB is expected to be accompanied by a twist in the AF, which is possible only beyond a certain thickness [6]. For thin AF layers, the spin structure is expected to be rigid and the magnetization reversal in the FM layer is accompanied by an irreversible rotation in the AF. Therefore EB does not set in. Beyond a certain AF thickness, the formation of an AF domain wall parallel to the interface is possible, with the spins away from the AF/FM interface pointing along the anisotropy axis of the AF. The pinning of these spins should be important for the EB properties. In FM/AF/FM trilayers, the pinning is expected to be altered by the coupling at the second interface FM/AF and the formation of a twist in the AF spins determines the interlayer coupling.

As polarized neutron reflectivity is a powerful tool to probe the magnetization profile of FM thin films, e.g. Ref. [7], it is well suited to probe the magnetic structure of FM/AF/FM trilayers during the magnetization reversal and provide an insight into the IEC of such systems. Here we report the investigation of the magnetization profile in FeCoV/NiO/FeCoV trilayers, with varying NiO thickness.

2. Experiments

Multilayers of [Ti (5 nm)/FeCoV (20 nm)/NiO (t_{NiO})/FeCoV (20 nm)/Ti (5 nm)], with $0.9 \leqslant t_{NiO} \leqslant 100$ nm are prepared on glass on the small DC magnetron-sputtering facility at PSI. The FeCoV layers are sputtered from an alloy target with a composition of $Fe_{50}Co_{48}V_2$. The sputtering of FeCoV and Ti is performed in an Ar atmosphere, whereas the NiO layers are prepared from a Ni target by reactive sputtering in an appropriate Ar:O_2 atmosphere. Specular X-ray reflectivity (XRR) is measured and the layer structure as well as interface roughness is obtained from the refinement of the experimental results. DC magnetization loops are measured at room temperature by the extraction technique using a quantum design physical property measurement system. PNR are measured at the time-of-flight (TOF) reflectometer AMOR at the Swiss spallation neutron source SINQ. The polarization of the reflected beam is analyzed in order to distinguish non-spin flip (NSF) and spin flip (SF) contributions. Polarizing supermirrors serve as polarizing and analyzing devices. Their efficiency is determined from additional experiments where the direct polarized beam from the polarizer mirror is analyzed by the analyzer mirror, assuming the mirrors to be identical. The wavelength-dependent flipping ratio obtained by these experiments is used to correct the experimental data for the finite efficiency of the polarizing and analyzing supermirrors [8]. A Q_z-range from 0.1 to $1\,\mathrm{nm}^{-1}$ is covered by measuring the reflected TOF spectrum at two angles of incidence (0.5° and 1.4°). A magnetic field is applied in the plane of the samples in order to magnetize the samples to the desired magnetic state.

3. Results and discussion

For structural characterization specular XRR measurements are performed. Fig. 1 shows a selection of experimental results together with

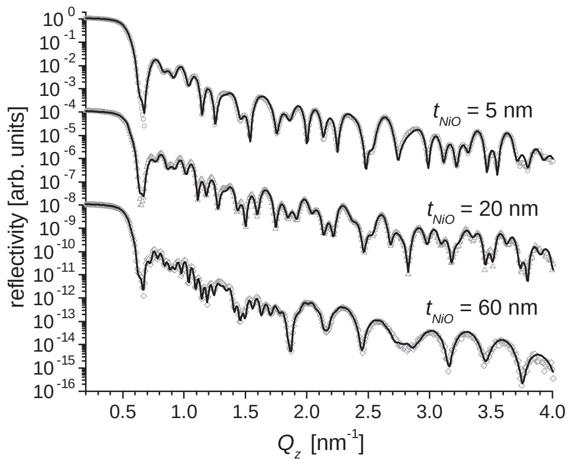

Fig. 1. XRR of FeCoV/NiO (t_{NiO})/FeCoV trilayers. The symbols represent the experimental data whereas the solid lines show the computed reflectivities. The curves are shifted for clarity.

computed reflectivities. The thickness and interface roughness of the layers are obtained from the refinement of the experimental data with a suitable model [9]. Consistently, all samples can be fitted with one set of parameters except for a variation of the NiO thickness and the roughness starting from the NiO layer towards the top of the samples. The roughness of the NiO layer increases from ≈ 0.4 to 3 nm for $t_{\mathrm{NiO}} = 1.5$ and 100 nm, respectively. Consequently, the roughness of the subsequent FeCoV and Ti layers also increases with increasing t_{NiO}. In addition, the formation of oxide layers with a thickness of 0.1–0.5 nm at the interfaces between the FeCoV and NiO layers can be identified in every sample.

Bulk magnetic properties of the films are obtained from magnetization measurements. The $M-H$ loops are shown in Fig. 2. A dependence of the magnetization reversal on t_{NiO} is observed. For $t_{\mathrm{NiO}} < 20$ nm, the reversal occurs via a single transition whereas for $t_{\mathrm{NiO}} \geqslant 20$ nm the reversal occurs in two steps, separated by a plateau with nearly zero net magnetization. The width of the plateau increases with increasing t_{NiO} for $20\,\mathrm{nm} \leqslant t_{\mathrm{NiO}} \leqslant 40$ nm.

The layer resolved magnetic structure at saturation ($H = 5000$ Oe) and during the magnetization reversal is determined via PNR. The NSF (R++, R−−) and SF (R+−, R−+) reflectivities are modeled [9] using the structural parameters from the refinement of the XRR data and adjusting the magnetic state of the FM layers. In saturation (not shown here), no significant intensity is present in the SF channels after correcting the experimental data for the finite polarization. The best agreement of the computed reflectivities with the experimental data is found consistently for a magnetic moment of $\approx 2.1\,\mu_B$ per f.u. of the FM layers and full alignment along the applied field. The results from modeling and the absence of SF scattering confirm the existence of a magnetically saturated state present at a field of 5000 Oe.

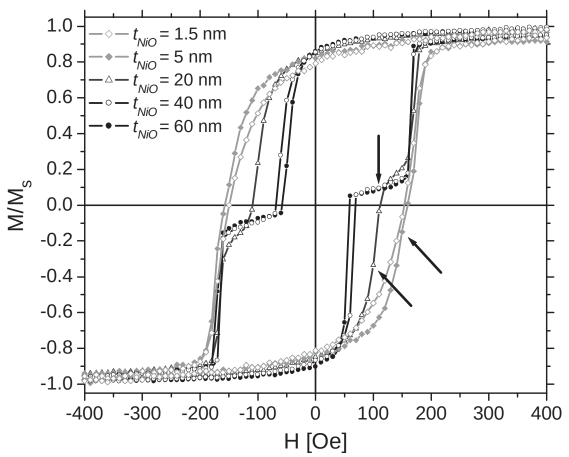

Fig. 2. $M-H$ loops of FeCoV/NiO (t_{NiO})/FeCoV trilayers: for $t_{\mathrm{NiO}} < 20$ nm, the magnetization reversal occurs via a single process and for $t_{\mathrm{NiO}} > 20$ nm, it occurs in two steps. The arrows indicate the positions where PNR is measured (see Fig. 3).

At intermediate fields PNR is measured during the magnetization reversal. In order to tune the desired magnetic state as indicated in Fig. 2, all samples are exposed to $H = -5000$ Oe prior to the application of the positive field. Fig. 3 shows experimental data together with computed reflectivities. The components of the magnetic moments of individual FeCoV layers parallel and perpendicular to the applied field are obtained from modeling the NSF and SF reflectivities. Table 1 summarizes the magnetization parameters of the models. The total magnetic moments of the FeCoV layers are reduced in comparison to their saturation moment. The reduction indicates that the magnetization breaks up into lateral domains and the coherent neutron beam probes an average across different orientations. In summary, the net magnetic moments parallel to the applied field determined from PNR are in good agreement with the results from bulk magnetization measurements.

Additional PNR experiments are performed on the sample with $t_{\mathrm{NiO}} = 60$ nm. For these experiments, the sample is prepared in a state with the magnetization of the two FeCoV layers being antiparallel with respect to each other. As this state is remanent, the experiment can be performed in a field and a neutron polarization perpendicular to the magnetization. Practically, this configuration is realized by rotating the sample by 90° after the magnetization procedure. PNR data together with computed reflectivities are shown in Fig. 4 for two different applied fields. From model calculations it is found that with increasing magnetic

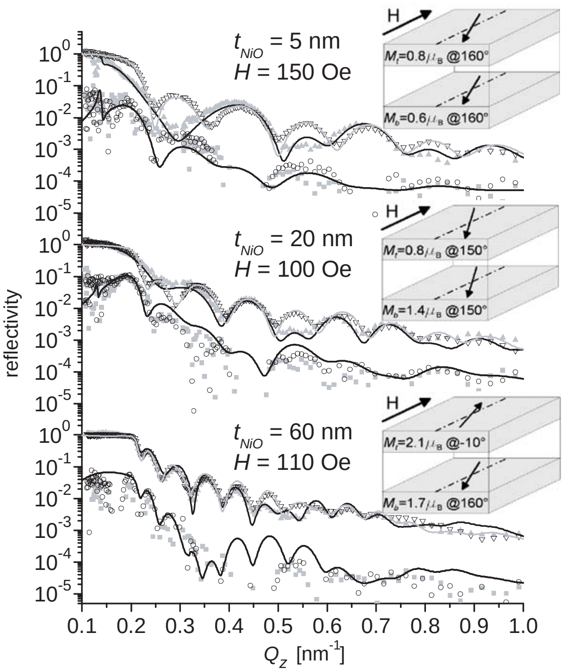

Fig. 3. PNR of FeCoV/NiO ($t_{\rm NiO}$)/FeCoV trilayers measured at selected positions during the magnetization reversal as indicated in Fig. 2. Experimental data are represented by symbols: ▲, R+ +; ▽, R− −; ■, R+ −; ○, R− +. Computed reflectivities are represented by lines. The insets show the average magnetization of individual FeCoV layers as obtained from modeling. Note that PNR is identical for the configurations which are mirrored at the field axis.

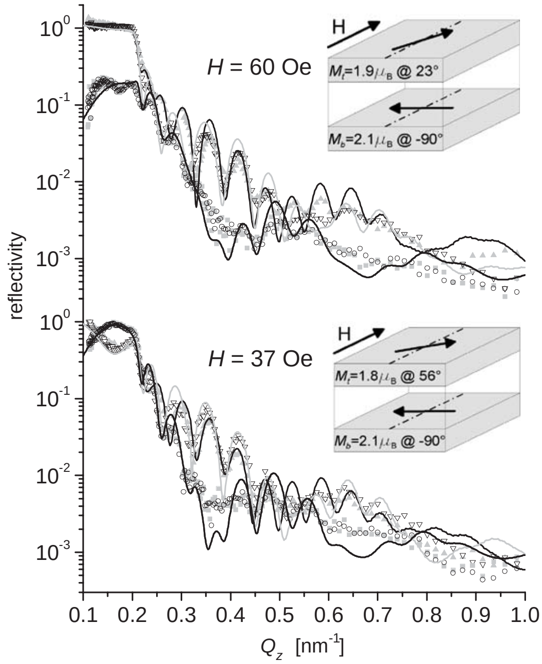

Fig. 4. PNR of FeCoV/NiO (60 nm)/FeCoV trilayers measured at two different fields after preparing the sample in a state with the magnetization of the two FeCoV layers being antiparallel with respect to each other and perpendicular to the applied field. Experimental data are represented by symbols: ▲, R+ +; ▽, R− −; ■, R+ −; ○, R− +. Computed reflectivities are represented by lines.

Table 1
PNR results of FeCoV/NiO/FeCoV trilayers

Sample ($t_{\rm NiO}$)	5 nm	20 nm	60 nm
H [Oe]	150	100	110
$\langle M_{\rm t,\parallel}\rangle$ [μ_B/f.u.]	−0.75	−0.69	+2.07
$\langle M^2_{\rm t,\perp}\rangle^{1/2}$ [μ_B/f.u.]	0.27	0.40	0.36
$\langle M_{\rm b,\parallel}\rangle$ [μ_B/f.u.]	−0.56	−1.21	−1.60
$\langle M^2_{\rm b,\perp}\rangle^{1/2}$ [μ_B/f.u.]	0.21	0.70	0.58
$M_\parallel/M_s$ (PNR)	−0.3	−0.4	+0.1
M/M_s (bulk)	−0.2	−0.3	+0.1

H is the applied field. $M_{\rm t(b):\parallel(\perp)}$ are the parallel (perpendicular) components of the magnetic moments of the top (bottom) FeCoV layers, respectively $\langle\cdot\rangle$ denotes the lateral average within the coherence length of the neutron beam. $M_\parallel$ is the resulting net magnetic moment parallel to the applied field. Negative values indicate a component antiparallel to the field.

field, the magnetization of the top FeCoV layer rotates towards the field axis whereas the bottom FeCoV layer remains mostly in its original perpendicular orientation.

In the following, we discuss the dependence of the magnetization reversal on the NiO layer thickness $t_{\rm NiO}$, which is observed in the $M-H$ loops (Fig. 2). The simplest explanation is that the coercivity of the top FeCoV decreases with increasing thickness of the underlying NiO layer but is not affected by the bottom layer. In order to test this possibility we analyze bilayer samples with FeCoV on top of NiO, and NiO on top of FeCoV, respectively, representing the top and bottom part of the trilayers. Regarding the structural properties, like roughness, chemical composition or texture, the bilayer and trilayer samples are identical [11]. We find that for NiO on top of FeCoV the latter is rather rigid with a coercivity of

$\approx$160 Oe. The coercivity of FeCoV on top of NiO is drastically reduced to $\approx$20–30 Oe for the whole range of NiO thickness $5 \leqslant t_{\mathrm{NiO}} \leqslant 60$ nm. Therefore, the individual properties of top and bottom FeCoV layers cannot explain the t_{NiO} dependence of the magnetization reversal in the trilayers; rather the comparison suggests that the magnetization reversal of the top FeCoV is influenced by the presence of the bottom FeCoV layer due to an IEC mediated by the NiO layer.

Interfacial coupling between the FeCoV and NiO layers is established from the occurrence of exchange bias at room temperature when $t_{\mathrm{FeCoV}} = 5$ nm [11]. The PNR results for trilayers with $t_{\mathrm{NiO}} = 5$ and 20 nm show that the bottom FeCoV layer breaks up into domains already before its coercivity is reached. This is in contrast to the properties of the bottom case bilayer where the FeCoV layer is very rigid up to its coercive field. It implies that the top FeCoV layer influences the reversal of the bottom FeCoV and we conclude that the FM layers are coupled through the NiO layer.

For $t_{\mathrm{NiO}} = 60$ nm, we find from PNR that top and bottom FeCoV layers are oriented almost fully antiparallel with respect to each other at the plateau within the two steps in the magnetization reversal. The antiparallel orientation of the magnetization of adjacent FeCoV layers appears for all samples with $t_{\mathrm{NiO}} \geqslant 40$ nm (Fig. 2). Interestingly, this minimum thickness is consistent with a realistic domain wall width reported for NiO films [6,10]. Therefore, we believe that a 180° domain wall in the NiO layer parallel to the interfaces is formed when the magnetization of the FeCoV layers are oriented antiparallel rather than the possibility of uncoupled FM layers with different coercivities.

In addition, the creation of a domain wall in NiO seems to be supported by the PNR results from Fig. 4. Here the rigid bottom FeCoV layer remains perpendicular to the applied field. Apparently, the top FeCoV layer rotates coherently towards the field rather than breaking up into domains. The coherent rotation requires a net anisotropy that may be given here by the pinned magnetization of the bottom FeCoV layer and mediated through the NiO layer.

In conclusion, we have presented a study of FM/AF/FM trilayers via polarized neutron reflectometry which allows us to resolve the magnetization orientation of the individual FM layers. For thin AF layers, the FM layers are coupled and reverse together, while for large AF thickness the FM layers switch at different fields. For the latter, the results of our systematic investigations suggest the formation of a domain wall within the AF layer parallel to the interface during the magnetization reversal. For unambiguous proof, whether a domain wall is formed or the FM layers are decoupled, new experiments are in progress.

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