Non-collinear magnetic profile in $(Rh/Fe_{1-x}Co_x)_2$/Rh(001) bilayer probed by polarized soft x-ray resonant magnetic reflectivity

M. Przybylski,[1,2,a)] J.-M. Tonnerre,[3,b)] F. Yildiz,[1] H. C. N. Tolentino,[3] and J. Kirschner[1]
[1]*Max-Planck-Institut für Mikrostrukturphysik, Weinberg 2, D-06120 Halle, Germany*
[2]*Faculty of Physics and Applied Computer Science, AGH University of Science and Technology, al. Mickiewicza 30, 30-059 Kraków, Poland*
[3]*Institut Néel, CNRS and UJF, BP 166, 38042 Grenoble Cedex 9, France*

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Magnetization configuration in $Fe/Rh/Fe_{0.5}Co_{0.5}$/Rh(001) can be non-orthogonal due to competition between the anisotropy and the exchange coupling. Soft x-ray resonant magnetic reflectivity allows us to probe the magnetic profile along the growth axis with in-plane and perpendicular magnetization components. By using different modes of acquisition, we show that it is possible to determine separately the magnetic profile of both magnetization components. Measurements at the Co L_3-edge enable us to investigate the magnetism of the alloy layer independently from the layer of Fe. © *2012 American Institute of Physics*. [doi:10.1063/1.3670507]

I. INTRODUCTION

The competition between interlayer exchange coupling and magnetic anisotropy of coupled films may result in a non-orthogonal magnetization configuration.[1] Such structures are important for magnetic recording, sensor technology,[2] and spin transfer torque devices.[3] A detailed (i.e., layer resolved) picture of the magnetic configuration cannot be determined from the hysteresis loops. Soft x-ray resonant magnetic reflectivity (SXRMR) overcomes this limitation, since it allows a depth-resolved analysis of magnetic structure on a sub-nanometer scale with in-plane and perpendicular components resolution.[4–9]

In this work, we show that by using circularly polarized light and different acquisition modes it is possible to separately analyze the in-plane and perpendicular components of a complex magnetic configuration along the growth axis. It is particularly useful when the orientation of the magnetic moments are departing either from the easy axis of magnetization and/or from the direction of an external magnetic field. A model system is provided by $Fe/Rh_{sp}(3\,ML)/Fe_{0.5}Co_{0.5}$ bilayer grown on Rh(001).

II. EXPERIMENTAL DETAILS

The sample has been grown in a multi-chamber ultra-high vacuum (UHV) system. Rh(001) substrates were prepared with cycles of 1 keV Ar ion sputtering and subsequent annealing at 900 K. The $Fe_{1-x}Co_x$ films and Rh spacer layer were grown at room temperature (RT) by molecular beam epitaxy (MBE).[10] The bottom $Fe_{0.5}Co_{0.5}$ layer is 8 ML thick, and shows as a single layer an easy magnetization axis perpendicular to the sample plane.[11] The top Fe layer is 6 ML thick and as a single layer shows ferromagnetic order below RT with an in-plane easy magnetization axis. The Rh spacer is known to mediate an exchange coupling, which can orient the magnetization either parallel or antiparallel, depending on the spacer thickness.[1] For a 3 ML thick Rh layer the coupling is expected to be antiferromagnetic (AFM).[1]

In order to gain insight into the depth-resolved magnetic configuration of the $Rh_{cap}/Fe/Rh_{sp}(3\ ML)/Fe_{0.5}Co_{0.5}$ bilayer, SXRMR experiment was carried out. The reflectivity was collected over a large incident angular range to separate out the in-plane and perpendicular magnetization component.[8,9] The measurements were conducted at RT at the SIM beamline of the Swiss Light Source at the Paul Scherrer Institut (PSI),[12] using circularly polarized light and the RESOXS end-station[13] in the vicinity of the Fe and Co L_3 edge (706.8 and 778.1 eV, respectively). In order to probe perpendicular magnetization component (m_p), the measurements were performed in polar geometry, where the sample is magnetized by a permanent perpendicular magnet of $\mu_0 H = 0.4$ T brought to the sample surface, followed by data collection in remanence.[8] In this case, the reflectivity I_p and I_m were obtained by reversing the x-ray helicity, which is equivalent to reversing the orientation of the net magnetization in each layer (so-called acquisition mode A). The measurements for probing the in-plane component m_l were also performed in longitudinal geometry using an electromagnet for the sample magnetization.[13] I_p and I_m were obtained by reversing a longitudinally applied (i.e., at the intersection of the sample plane and the diffraction plane) magnetic field ($\mu_0 H$ up to 0.16 T) while keeping the x-ray helicity unchanged (mode B). Here, only the in-plane magnetization component is expected to flip.

The magnetic profile is derived from the refinement of the magnetic asymmetry $R = (I_p - I_m)/(I_p + I_m)$, while keeping the structure parameters constant. The magnetic film can be subdivided into slices. The magnetization vector of each slice can be described by an amplitude term and two angles. The magnetic amplitude of each slice is refined by adjusting

a)Author to whom correspondence should be addressed. Electronic mail: mprzybyl@mpi-halle.de.
b)Electronic mail: jean-marc.tonnerre@grenoble.cnrs.fr.

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a weighting factor w_m, which modifies the amplitude of the magnetic resonant terms. The Fe and Co charge and magnetic resonant terms used in the energy-dependent refraction index, or atomic scattering factor, are obtained from XMCD data for thick films.[14] A value of $w_m = 1$ corresponds to 2.1 μ_B and 1.7 μ_B for Fe and Co, respectively. The simulations are performed using the Zaks approach[15] and taking into account the interfacial roughness issue.[16]

III. RESULTS AND DISCUSSION

We first discuss the out-of-plane magnetization component by analyzing the measurements carried out in the mode A. We start with the magnetic profile of the Co atoms in the bottom layer (Fig. 1). Figure 1(a) shows I_p and I_m collected at 777.4 eV, close to the first inflexion point of the Co L_3 edge, optimizing the intensity of the real part of the charge and magnetic resonant scattering factor while keeping the absorption low. The refined thickness and roughness parameters for each layer (given in nm) are 2.24 (5), 0.33 (7)/0.99 (7), 0.28 (9)/0.48 (4), 0.34 (7)/1.18 (5), 0.08 (3). Figure 1(b) shows the analysis of the magnetic asymmetry. A strong asymmetry at large angles and the lack of asymmetry at small angles are in agreement with a net perpendicular magnetization of the sample.[8,9] The dotted (blue) line displays the calculated asymmetry by considering a uniform perpendicular Co magnetization along the growth axis and the magnetic amplitude derived from the XMCD experiments on a single layer. The solid (red) line displays the fit of the data [the corresponding I_p and I_m calculated curves are shown in Fig. 1(a)]. The very good agreement is obtained by allowing inhomogeneity in the magnetic amplitude throughout the layers. The layers are divided into three equally thick slices of 0.3 to 0.4 nm. The net magnetization at the interface slices is reduced by 5% to fit the data. Since SXRMR is sensitive to the product of concentration and magnetization, the reduction is likely to be related to the changes in concentration due to intermixing and/or the lateral averaging of local thickness variations.[4]

We turn to the magnetization profile of the Fe atoms in both layers (Fig. 2). Figure 2(a) shows I_p and I_m collected at 706.2 eV, close to inflection point below the Fe L_3 edge. Figure 2(b) shows the analysis of the magnetic asymmetry. The lack of asymmetry at small angles indicates that there is no in-plane magnetization component and the Fe magnetization is oriented perpendicular to the sample plane. Because of the strong perpendicular anisotropy in the $Fe_{0.5}Co_{0.5}$ layer, a uniform perpendicular Fe magnetization is first considered only in the bottom layer [dashed (blue) line]. Taking into account the possibility of inhomogeneity inside the layer, like for the Co magnetization, does not allow a significant improvement of the fit with respect to the large discrepancy in the 40°–60° angular range. This prompts us to consider the existence of an additional perpendicular magnetization component from the 6 ML thick top Fe layer.[17] Analyzing the asymmetry by considering a uniform magnetic profile in both layers leads to a better result [dash-dotted (green) line]. Although paramagnetic at RT, the Fe layer reveals a net magnetization component, oriented opposite to the magnetization in the bottom layer in agreement with the expected AFM coupling. The amplitude of that component is 40–45 % smaller than the one of Fe in the $Fe_{0.5}Co_{0.5}$ layer. The best refinement [solid (red) line] is again obtained taking into account a lowering of the magnetization at the interfaces of both layers. Figure 2(a) displays the corresponding I_p and I_m calculated curves.

Since the easy magnetization axis of the Fe top layer should be in-plane with no interlayer exchange coupling, the acquisition mode B is employed to probe the modification of the magnetization profile in the $Fe_{0.5}Co_{0.5}$ layer either due to the applied magnetic field or due to the in-plane orientation of the magnetic moment in the top Fe layer (Fig. 3). First, we

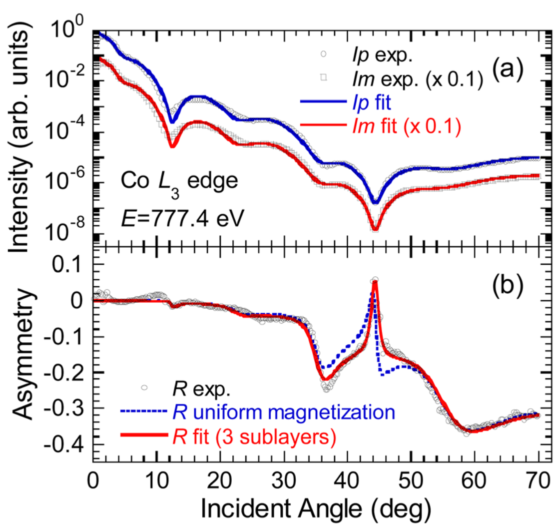

FIG. 1. (Color online) (a) Reflectivity and (b) magnetic asymmetry measured in mode A at the Co L_3 edge at RT. Asymmetry is calculated by considering homogeneous magnetization in the $Fe_{0.5}Co_{0.5}$ layer and after allowing magnetization inhomogeneity throughout the layer.

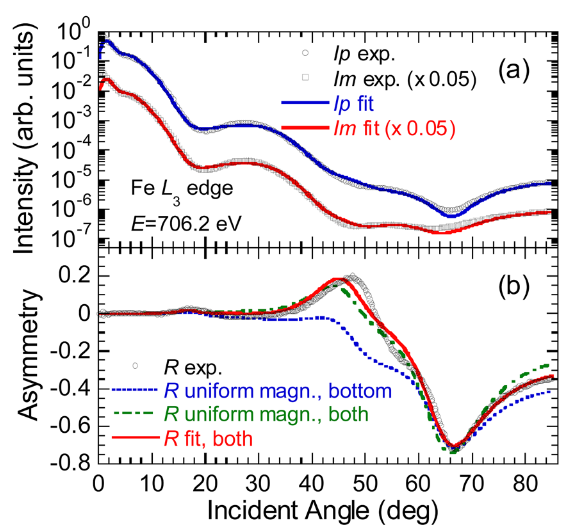

FIG. 2. (Color online) (a) Reflectivity and (b) magnetic asymmetry measured in mode A at the Fe L_3 edge at RT. Asymmetry is calculated at first by considering homogeneous magnetization in the $Fe_{0.5}Co_{0.5}$ layer. Then the homogeneous magnetization is assumed in both layers and, finally, magnetization inhomogeneity is allowed throughout both layers.

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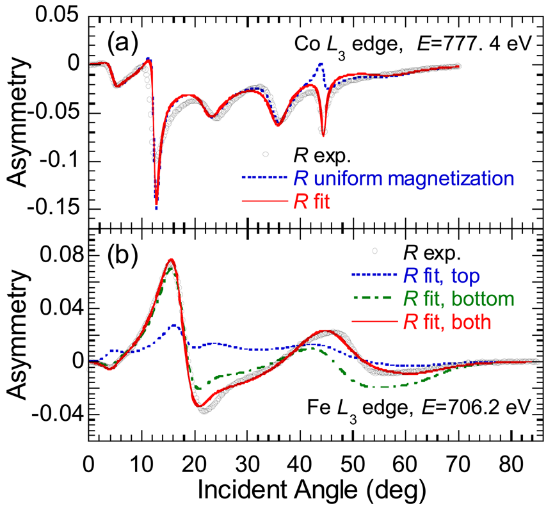

FIG. 3. (Color online) Magnetic asymmetry measured in mode B at the Co L_3 (a) and Fe L_3 (b) edges. Asymmetry is calculated by allowing the inhomogeneous magnetization throughout the Fe layer only, throughout the $Fe_{0.5}Co_{0.5}$ layers only, and finally throughout both layers.

measured the reflectivity at the Co L_3 edge in order to track the apparition of an in-plane component in the $Fe_{0.5}Co_{0.5}$ layer. Although much smaller than the asymmetry related to the perpendicular component, a significant magnetic asymmetry is observed at low angles and displayed in Fig. 3(a). The dotted (blue) line corresponds to the refinement of asymmetry performed by considering a homogeneous distribution of the in-plane component. Again, the best fit is derived by allowing the net magnetization to be reduced by about 5% at the interfaces. From the ratio of the in-plane to the perpendicular magnetization component, we estimate the tilting of the Co magnetic moment of $9^\circ \pm 4^\circ$ apart from the perpendicular easy magnetization axis in the $Fe_{0.5}Co_{0.5}$ layer. Second, we measured the reflectivity at the Fe L_3 edge and observed a small asymmetry related to the net in-plane magnetization of Fe both in the Fe and in the $Fe_{0.5}Co_{0.5}$ layers. Figure 3(b) shows the analysis of the magnetization asymmetry. The refinement, performed by considering a net homogeneous magnetization only in the top Fe layer [dotted (blue) line] or only in the bottom $Fe_{0.5}Co_{0.5}$ layer [dash-dotted (green) line], does not allow a fit to the experimental asymmetry. Beyond the effect of an inhomogeneous distribution of the magnetization, it is required to involve a net magnetization in both layers with that of the top layer oriented opposite to the net magnetization in the bottom $Fe_{0.5}Co_{0.5}$ layer [solid (red) line in Fig. 3(b)]. It is worth to point out that the comparison of the amplitude derived in mode A and B for the Fe magnetization of the $Fe_{0.5}Co_{0.5}$ layer leads the same tilting angle, within the error bars, as for the Co magnetization. The amplitude of the net in-plane magnetization of the top Fe layer is small and oriented opposite to the applied magnetic field due to the strong AFM coupling to the magnetization of the bottom $Fe_{0.5}Co_{0.5}$ layer.

IV. CONCLUSIONS

A depth resolved knowledge of the spin structure of the Fe/Rh/$Fe_{0.5}Co_{0.5}$/Rh(001) system is achieved from the soft x-ray resonant magnetic reflectivity experiment. This allows us to describe the effect of an external magnetic field on the magnetic configuration and the interactions between both layers due to the interlayer exchange coupling. Strong deviation from in-plane magnetization can be observed in the Fe layer and tilting of the magnetization in the $Fe_{0.5}Co_{0.5}$ layer toward the film plane is evidenced.

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