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Asymmetric magnetization reversal on exchange biased CoO/Co bilayers

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Abstract

We study magnetic hysteresis loops after field cooling of a CoO/Co bilayer by MOKE and polarized neutron reflectivity. The neutron scattering reveals that the first magnetization reversal after field cooling is dominated by domain wall movement, whereas all subsequent reversals proceed essentially by rotation of the magnetization. In addition, off-specular diffuse scattering indicates that the first magnetization reversal induces an irreversible change of the domain state in the antiferromagnet. © 2002 Elsevier Science B.V. All rights reserved.

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Since the discovery of the exchange bias (EB) effect [1,2], much effort has been devoted to a basic understanding of the exchange interaction across ferromagnetic/antiferromagnetic (F/AF) interfaces [3,4]. Extensive data has been collected on the exchange bias field, H_{EB}, and the coercivity fields, H_c, from a large number of bilayer systems [4]. The experimental results reflect the following characteristics: (1) H_{EB} and H_c increase as the system is cooled in an applied magnetic field below the blocking temperature of the AF layer; (2) the magnetization reversal might be different for the ascending and descending part of the hysteresis loop, as was first pointed out in Ref. [5]; (3) time relaxation effects of H_{EB} and H_c indicates that a stable magnetic state is reached only at very low temperatures. Several theoretical models have been proposed for describing possible mechanisms of the EB effect [6–11]. So far none of them is able to explain satisfactorily all macroscopic characteristics of EB systems. One of the problems is to describe properly the asymmetry of the magnetization reversal and the relaxation processes.

Here we present magnetization and neutron reflectivity studies of a Co/CoO bilayer grown by RF-sputtering methods. The sample is a Co (≈ 200 Å) layer deposited on a Ti(2000 Å)/Cu(1000 Å)/Al_2O_3 template. The CoO (30 Å) layer is formed on top of the Co layer by oxidation in air. The sample was characterized by X-ray diffraction at the HASYLAB, by AFM, MOKE, and by polarized neutron reflectometry (PNR). The sample is polycrystalline with a strong (1 1 1) texture growth along the growth direction. The surface roughness measured by AFM is about 3 Å, which has been confirmed by X-ray reflectivity measurements.

Fig. 1a shows the magnetic hysteresis loop measured by MOKE at $T = 50$ K, after cooling in an applied field of $+2000$ Oe. Upon descending the field for the first time to negative values, an abrupt magnetization reversal is observed at the coercivity field H_{c1}. Ascending again to positive field values, the magnetization curve at H_{c2} is more rounded. In subsequent cycles the magnetization curves at H_{c1} and H_{c2} are of about the same shape characterized by $H_{EB} = 30$ Oe and $\Delta H_c = 200$ Oe.

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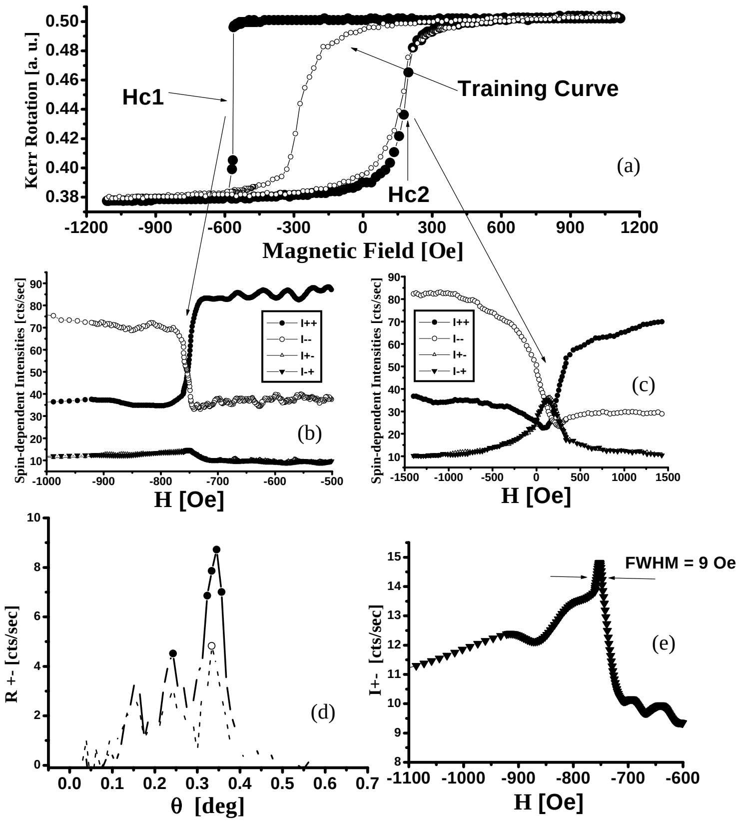

Fig. 1. (a) MOKE hysteresis loop of a CoO/Co bilayer after field cooling to 50 K in an external field of 2000 Oe. The black dots denote the first hysteresis loop, the open circles the second loop. Any further loops are not significantly different from the second. (b) and (c) Neutron hysteresis loops from the same sample but at 10 K. $I++$, $I--$, $I+-$ and $I-+$ are non-spin flip and spin-flip intensities as a function of external magnetic field. They are measured at special scattering vector values of the reflectivity curves (see text); (d) Off-specular diffuse spin-flip scattering taken at $H_{c1} = -750$ Oe (full dots) and in saturation at -1400 Oe (open dots). (e) Specular spin-flip at H_{c1} enlarged from panel (b) for better recognition.

From these measurements, we conclude that the first magnetization reversal of the virgin sample after field cooling is conspicuously different from any subsequent 'trained' reversals. This difference also becomes obvious by a strong thermal relaxation process, which is observable only in the virgin state of the sample at constant field value $H < H_{c1}$, i.e. just before the sharp magnetization reversal [12].

MOKE is a fast method for determining hysteresis loops but cannot reveal the spin configuration at the interface. Therefore we measured, in addition, neutron hysteresis loops (NHL) of the same sample at $T = 10$ K using the ADAM reflectometer at the ILL. Fig. 1b and c show corresponding neutron results. The NHL method will be detailed in a forthcoming paper [12]. Briefly, the non-spin-flip intensities ($I++$ and $I--$) are measured at the wave vector transfer Q corresponding to the inflection point of the non-polarized neutron reflectivity (near the critical edge for total external reflection), while the spin-flip intensities ($I+-$ and $I-+$) are measured at the resonance peak near the critical edge. While the magnetic field is swept like in a conventional MOKE set up, the sensitivity to any neutron spin-flip processes from spin-canting, magnetic roughness, domain walls, or rotation is enhanced (about 10 to 40 times) due to the sample design as a neutron resonator, in analogy to a Fabry Perot interferometer [13,14].

In Fig. 1b and c the non-flip intensities $I++$ and $I--$ are plotted as a function of external field. The normalized intensity difference $\Delta I/I = ((I++) - (I--))/((I++) + (I--))$ is proportional to the magnetization component parallel to the neutron polarization axis and proportional to the magnetization curve as determined, for instance, by MOKE. The points where the two curves $I++$ and $I--$ intersect (and, more precisely, where the spin-flip intensities $I+-$ and $I-+$ reach maximum) are defined as the coercive fields H_{c1} and H_{c2}. The sharp intensity change at H_{c1} and the more rounded change at H_{c2} reflects the corresponding parts of the hysteresis loops in the MOKE measurements. Note that the neutron data are taken at 10 K as compared to 50 K for the MOKE measurements, which explains the different H_{EB} and $H_c$in panels (a) and (b-e) of Fig. 1.

The different shapes of the $I++$ and $I--$ intensities at H_{c1} and H_{c2} are also reflected in the different spin-flip intensities. We first discuss the specular spin-flip intensities shown by triangles in panels (b) and (c). The magnetization reversal at H_{c2} exhibits strong spin-flip intensities I+− and I−+. This is always observed for round or 'trained' hysteresis loops and is characteristic for a magnetization reversal via (domain) rotation. Magnetization reversal by rotation provides a large magnetization component perpendicular to the polarization axis, giving rise to neutron spin-flip. Vice versa, the rather low spin-flip intensities ($I+-$ and $I-+$), which are observed during the first magnetization reversal of the virgin sample at H_{c1} are indicative of a domain wall movement. The step like intensity change at $H_{c1} = -750$ Oe from high to low, which is enlarged in panel (e) for better recognition, is followed by a steady decrease as the system approaches saturation. From this figure, it is quite obvious that the enhanced spin-flip scattering takes place in a very narrow field range of not more than 15 Oe [FWHM = 9 Oe]. This could be easily attributed to the domain walls in the ferromagnet during the magnetization reversal.

The striking differences noticed for the specular spin-flip scattering are also expressed in the off-specular diffuse scattering. While the diffuse spin-flip intensity at H_{c2} (not shown here) is rather low in intensity and symmetrically centered around the specular peak, this is not the case at H_{c1}, as seen in panel (d). The off-specular diffuse intensities (corrected for efficiency and footprint contributions) taken at $H_{c1} = -750$ Oe and in saturation at $H = -1400$ Oe are rather strong. Therefore, we infer that the dominant part of the off-specular spin-flip scattering is due to the antiferromagnetic domains since the ferromagnetic Co layer is already in saturation.

The specular spin-flip intensity, both near H_{c1} and in saturation, indicates the presence of domain walls at the interface [9]. The off-specular spin-flip signal, as was pointed out by experimental and theoretical studies [15,16], arises from magnetic domains smaller than the lateral coherence length (micron size range) of the neutron beam. A Zeeman splitting in the external field takes place as well, but is usually not strong enough to explain the off-specular intensity [14]. To strengthen this conclusion, we have recorded the $I+-$ rocking curve at $H = -200$ Oe, after first magnetization reversal, and not detected any significant shift of the specular and off-specular pattern. Thus, our data suggests that during the first field reversal at H_{c1} the CoO layer brakes into antiferromagnetic domains. The weak spin-flip signal is then due to AF domain walls and uncompensated spins. Another interpretation for the off-specular reflectivity would be spin misalignment at the interface or magnetic roughness [17]. At the present stage, we cannot distinguish whether the off-specular signal is a characteristic of the interface only or of the interface plus the whole antiferromagnet layer. However, the question may be answered by measuring samples with increasing antiferromagnetic layer thickness. An increase of the off-specular signal will then verify the formation of antiferromagnetic domains by the increase of the domain wall lengths.

In conclusion, we have shown that polarized neutron scattering results give deep insight into the origin of the striking difference between the first magnetization reversal at H_{c1} and all subsequent reversal characteristic for CoO/Co bilayers with very thin CoO layer.

The results suggest that the field cooling forces the thin AF-layer into a single domain state with the sublattice magnetization direction essentially parallel (or antiparalel) to the Co magnetization direction. This metastable original state characterized by very large exchange bias field H_E is destroyed upon the first magnetization reversal and transformed into a stable multidomain state with a much lower H_E.

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