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Uncompensated magnetization and exchange-bias field in $La_{0.7}Sr_{0.3}MnO_3/YMnO_3$ bilayers: The influence of the ferromagnetic layer

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ABSTRACT

We studied the magnetic behavior of bilayers of multiferroic and nominally antiferromagnetic o-$YMnO_3$ (375 nm thick) and ferromagnetic $La_{0.7}Sr_{0.3}MnO_3$ and $La_{0.67}Ca_{0.33}MnO_3$ (8…225 nm), in particular the vertical magnetization shift M_E and exchange-bias field H_E for different thickness and magnetic dilutions of the ferromagnetic layer at different temperatures and cooling fields. We have found very large M_E shifts equivalent to up to 100% of the saturation value of the o-YMO layer alone. The overall behavior, including XMCD magnetization shift measured at the Mn-L edge of the LSMO layer only, indicates that the properties of the ferromagnetic layer contribute substantially to the M_E shift and that this does not correlate straightforwardly with the measured exchange-bias field H_E.

1. Introduction

In bilayers composed of antiferromagnetic (AFM) and ferromagnetic (FM) phases a "horizontal" shift in the field axis of the hysteresis loops is generally observed after cooling them in a field applied at temperatures between the Néel T_N and Curie T_C temperatures [1,2]. This "exchange-bias field" H_E has been studied in different systems due to its fundamental importance as well as its technological relevance in spin-valve sensors, actuators and in high-density recording media [3] and some details of the origin of H_E are still a matter of discussion [2].

Less studied is the shift in the magnetization axis, i.e. the "vertical" M_E shift in the hysteresis loop, probably because of its rather small relative values [4,5] and its dependence on the cooling field H_{FC} [6,7]. Recently, a maximum shift of 16% of the saturation magnetization was found in $Fe_xNi_{1-x}F_2$/Co bilayers, which appeared to have an exchange-bias field of its own [8]. It was proposed that M_E is related to uncompensated moments (UCM) at the AFM/FM interface and should have a direct correlation to H_E [8,9]. Element specific X-ray magnetic studies of FeF_2/Co [10,11] and CoO/Fe [12] layered structures confirmed the existence of this M_E shift and revealed its relation to specific UCM in the AFM material. Using polarized neutron reflectometry, Ref. [13] studied the magnetization depth profile and its pinned and unpinned components at the interface of the system Co/FeF_2, revealing the existence of pinned moments in the FM layer and not just in the AFM layer, as commonly assumed.

Due to the limited number of studies on the M_E effect it is of general interest to find systems with larger magnetization shifts, not only because of its fundamental interest but also because this shift provides a new degree of freedom in the hysteresis loop that may be well have some applicability in future devices. In this work we studied the exchange-bias shifts H_E and M_E of the hysteresis loops as a function of temperature T and H_{FC} for three AFM/FM bilayers having the same AFM layer but different thickness and dilution of the FM layer. Superconducting quantum interference device (SQUID) measurements indicate an unusually large uncompensated magnetization shift M_E that is not simply correlated with H_E and does not originate only from the AFM layer but from the FM one. Soft X-ray magnetic circular dichroism measurements indicate also that the FM layer contributes to the magnetization shift.

2. Sample preparation details and X-ray characterization

We prepared bilayers composed of a FM $La_{0.7}Sr_{0.3}MnO_3$ (LSMO) layer (selected for its weak anisotropy and small coercivity)

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covering an AFM orthorhombic o-$YMnO_3$ (o-YMO) layer grown on (100) $SrTiO_3$ substrates of area 5×5 mm^2 for samples A and B and 6×6 mm^2 for sample C. For the depositions a KrF excimer laser (wavelength 248 nm, pulse duration 25 ns) was used and the optimal parameters found for o-YMO were 1.7 J/cm^2 with 5 Hz repetition rate, 800 °C and 0.10 mbar for the substrate temperature and oxygen pressure during preparation. We have measured three bilayers, all of them with the same 375 nm thick o-YMO layer on STO substrates prepared always under the above-mentioned conditions. To check the reproducibility of the found effects we have prepared a fourth bilayer with identical thickness as in sample A but instead of the LSMO FM layer we used $La_{0.67}Ca_{0.33}MnO_3$ (LCMO) deposited on o-YMO and this last one on a (100)LSAT substrate.

For the FM layer we used LSMO deposited immediately on the o-YMO layer with the following parameters: 10 Hz repetition rate and 0.35 (0.38) mbar oxygen pressure, 8 (30) nm thickness and at the same laser fluency and substrate temperature, for sample A (B). In order to corroborate the contribution of the FM layer in the M_E-shift we have decreased further the oxygen concentration to deposit the LSMO film in sample C (oxygen pressure 0.10 mbar) with a larger thickness of 225 nm decreasing in this way its coercivity. For the fourth LCMO/YMO bilayer the YMO layer was grown under similar conditions as before but the LCMO layer under an oxygen pressure of 0.55 mbar; all other conditions as for the LSMO layers.

The epitaxial growth in the 0 0 l direction for the o-YMO and l 0 0 for LSMO phases was confirmed by X-ray diffraction using Cu $-$ K_α line. As an example we show in Fig. 1 the X-ray spectrum of the single o-YMO layer on STO. The preferential growth of the (0 0 l) planes of the orthorhombic phase YMO is clearly seen. Within the experimental resolution no maxima due to the hexagonal phase are observed. Fig. 2 shows the X-ray spectrum obtained for sample B. The main diffraction peaks from the LSMO layer are observed as a weak shoulder near the STO main maxima. Magnetization measurements were performed with a SQUID from Quantum Design in the temperature range between 5 and 350 K. The SQUID measurements were done at different applied fields and different field sweep conditions taking into account the particular purpose of the measurement. For example, to obtain the transition temperatures we measured at remanence or at relatively low fields (Figs. 4 and 8(a)) or in ZFC-FC states (Fig. 3). Furthermore, because both exchange-bias effects depend on the magnitude of the field applied on cooling H_{FC} from a temperature

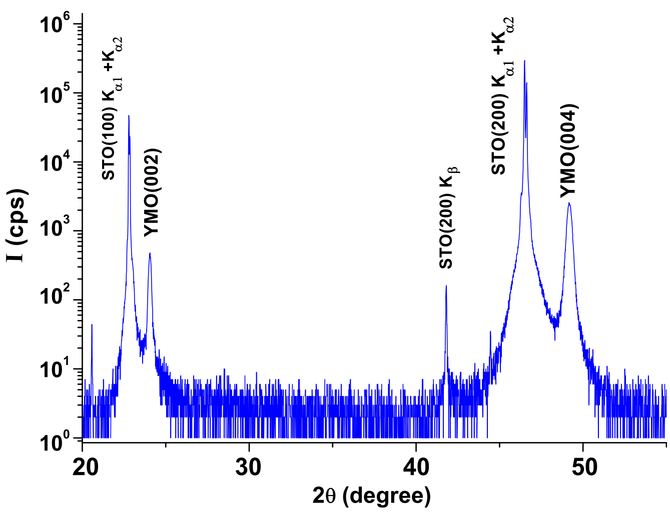

Fig. 1. X-ray spectrum of the single YMO AFM layer on STO substrate.

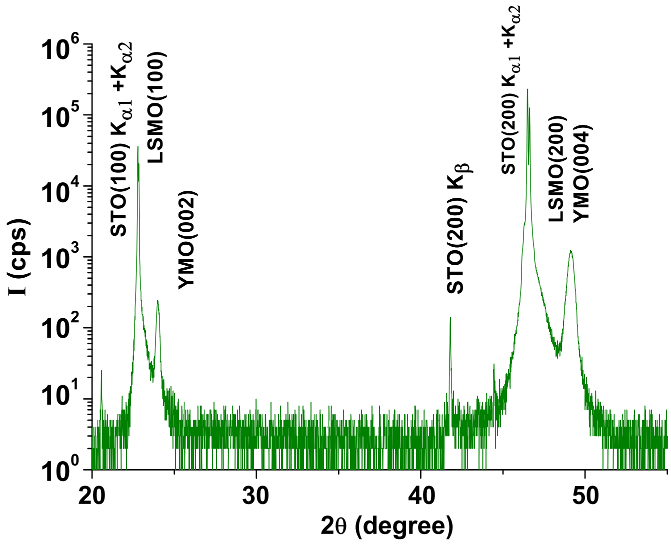

Fig. 2. X-ray spectrum of the bilayer sample B. The labels indicate the corresponding the main diffraction peaks.

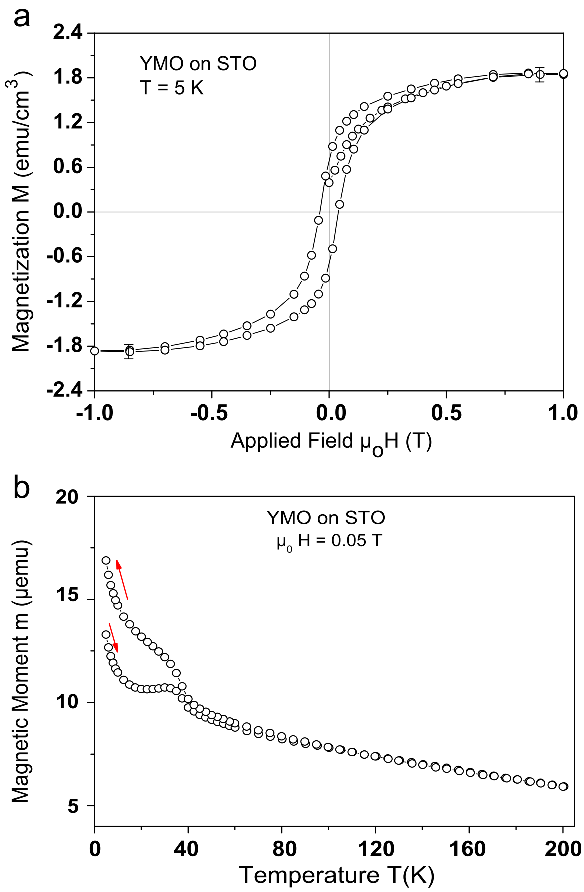

Fig. 3. (a) Hysteresis loop of the magnetization at 5 K for the 375 nm thick YMO layer on STO. The error bars indicate the maximum error due to the SQUID and geometry measurements. (b) Temperature dependence of the magnetic moment of a single YMO layer on STO in ZFC and FC states at an applied field of 0.05 T. An error bar of ±0.3 μemu is the expected maximum error from our SQUID measurements.

above the T_N of the AFM layer, hysteresis loop measurements were performed at different H_{FC}'s.

In addition, we performed soft X-ray absorption and circular dichroism measurements using the bending magnet beamline

6.3.1 at the Advanced Light Source in Berkeley, CA (USA) and the elliptical undulator beamline 13.1 at the Stanford Synchrotron Radiation Lightsource, Stanford, CA (USA). For these measurements the sample was mounted between the poles of an electromagnet so that the X-rays are incident on the sample under a grazing angle of 30° parallel to the direction of the applied magnetic field. The X-ray absorption intensity was monitored using the electron yield method. Hysteresis loops were acquired by sweeping the external field while monitoring the electron yield at the Mn L_3 and L_2 absorption resonance (≈ 640 eV). This approach is surface sensitive and in general it yields information only on the first ~ 5 nm of the sample. Assuming an exponential escape depth of 2.5 nm, then 95% of the signal comes from the top 6 nm of the sample. This is essentially our probing depth. For a more detailed description of the technique see Refs. [10,11].

3. Results

3.1. Single $YMnO_3$ layers

According to the literature [14,15] the o-YMO phase is AFM with Néel temperature $T_N = 42 \pm 2$ K and with a ferroelectric transition at ~ 31 K. In spite of its low T_N this material has several advantages for exchange-bias studies. It belongs to the family of the perovskite manganite $RMnO_3$ and the magnetic and electrical properties can be changed by cation substitution keeping similar lattice constants and therefore without drastic changes in its structural properties. On the other hand, o-YMO is a phase that was not thoroughly studied yet and the influence of its ferroelectric behavior, in spite of the low temperature, might be used as a paradigm for potential applications in magnetoelectric devices [16].

Fig. 3(a) shows the magnetization loop of single o-YMO layer. The hysteresis loop indicates a magnetization at saturation of 1.8 emu/cm^3 at 5 K and at applied fields $\mu_0 H > 0.5$ T in agreement with reported values [17]. Fig. 3(b) shows the magnetic moment of a single o-YMO layer ($6 \times 6 \times 0.375\ 10^{-3}$ mm^3) on STO measured as a function of temperature in ZFC and FC states at an applied field of 0.05 T. A clear increase in $m(T)$ decreasing temperature is observed at $T \simeq 42$ K. An hysteresis between ZFC and FC is observed already below $T \sim 60$ K. As was shown in earlier studies on YMO we may expect to have persistent spin waves at temperatures above T_N [18].

From the hysteresis loop shown in Fig. 3(a) one may speculate that the YMO film behaves as a ferro- or ferrimagnet and not, as expected, as an antiferromagnet. In fact, a recent study suggests a change of the usual bulk antiferromagnetic state to a strain-dependent non-collinear magnetic one in thinner ($\lesssim 120$ nm) o-YMO films [19]. Taking into account that our YMO layers are much thicker and show a different $m(T)$ behavior as those reported in Ref. [19], i.e. at ZFC and low applied fields the measured $m(T)$ of our YMO films alone resembles practically the usual T-dependence found for antiferromagnets, the magnetic behavior of our o-YMO layers may correspond to the one observed in diluted antiferromagnets in external magnetic field (DAFF). It is well known that DAFF develop a domain state when cooled below T_N (sometimes with a spin-glass-like behavior) and this leads to a net magnetization, which couples to the external field, see e.g. Refs. [4,7,20–22].

From the measured temperature dependence of the magnetic moment and the observed scaling of the exchange-bias field H_E with the inverse of the thickness of the LSMO layer for samples A and B, see Section 3.2, and the quantitative agreement of the obtained H_E and M_E shifts for the fourth sample (similar to sample A but with LCMO instead of LSMO) we may conclude that YMO behaves as an AFM or DAFF layer for the exchange-bias effects. Whatever the real magnetic equilibrium state of our o-YMO films is, we may expect to see exchange-bias effects when these films are coupled to a ferromagnet. Further examples for exchange-bias effects in heterostructures with different ferro- or ferrimagnets can be seen in Refs. [23,24] and H_E effects, positive as well as negative, has been also observed in ferrimagnetic based bilayers [25].

3.2. $La_{0.7}Sr_{0.3}MnO_3/YMnO_3$ bilayers

Fig. 4 shows the remanent moment for samples A and B measured increasing temperature at zero field, after cooling them to 5 K in a field of 0.1 T applied in-plane, i.e. a or b direction. Changes in slope of the remanence moment are observed near the Néel temperature onset $T_N \sim 50$ K of the o-YMO layer. This increase of ~ 8 K in T_N might be related to the an exchange-bias [26,27] or strain [28] effect. An anomaly is also observed at $T \sim 20$ K, as shown in Fig. 3(b), and already reported in the literature [14,29]. The temperature dependence of the remanence measured in sample B shows a clear change of slope near the Curie temperature of the LSMO layer. In contrast, due to the smaller LSMO thickness the remanent moment of sample A does not show a clear anomaly at T_C; similarly for sample C (not shown). For sample C we show in Fig. 4 the field cooled (FC) curve at 0.1 T; the absence of a marked anomaly at T_C and the smooth decrease of the magnetic moment with T demonstrates the expected strong magnetic dilution of the LSMO film. The existence of the FM state in this layer was confirmed through hysteresis loop measurements up to its ferromagnetic onset at $T_C \sim 300$ K. The FC results presented below were obtained always after cooling the samples from $T > T_C$ at zero field and after applying an in-plane field H_{FC} at 100 K $> T_N$.

Fig. 5(a) and (b) shows the hysteresis loops for ZFC and FC measurements at 5 K for samples A and B. A remarkable M_E shift of the same order of the saturation magnetic moment m_s is observed for sample A after FC from 100 K at $\mu_0 H_{FC} = 0.5$ T. For sample B the M_E shift is also clearer measured but it is smaller relative to m_s. The sign of the M_E-shift changes when the direction of H_{FC} changes, i.e. it has the same sign as that of H_{FC}. This indicates that the effective UCM layer is pinned in the direction of the cooling field, which means a ferromagnetic coupling.

In the determination of the M_E and H_E shifts we took special care to rule out effects due to minor hysteresis loops [30]. Studying the behavior of the loops at different H_{FC} we conclude that no minor loops and a clear saturation behavior of the

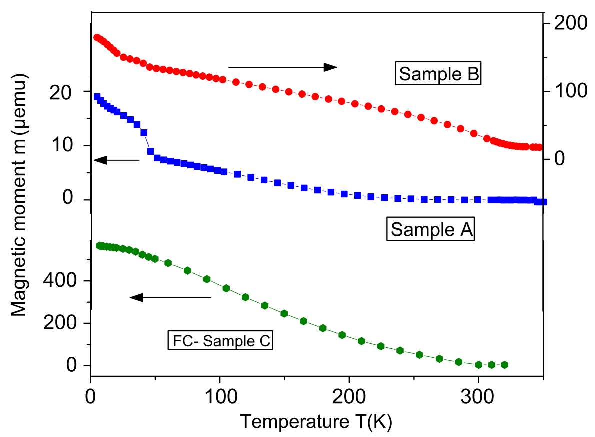

Fig. 4. Temperature dependence of the remanence for samples A and B measured at zero field after cooling them to 5 K at 0.1 T in-plane field. Also shown is the field cooling curve at 0.1 T for sample C. Note the difference scales of the y-axis for each sample.

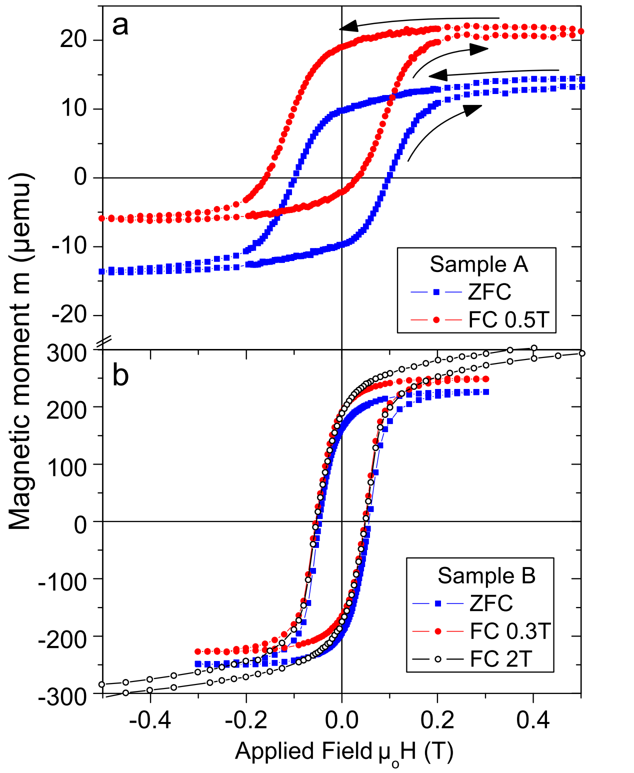

Fig. 5. Hysteresis loops at 5 K measured for samples A (a) and B (b) after zero field cooled (ZFC) and field cooled (FC) states at the fields shown in the figures. The arrows indicate the sweeping field direction starting the loop always from positive fields.

magnetic moment are obtained for $\mu_0 H_{FC} \geq 0.2$ T at $T \geq 5$ K for samples A and B, see Fig. 5. For sample C, which has a more diluted and inhomogeneous FM layer, the hysteresis loops reveal no complete saturation at $\mu_0 H_{FC} < 0.4$ T. However minor loop effects can be neglected also for this sample at $\mu_0 H_{FC} \geq 0.2$ T, as the behavior of the coercive field H_c vs. H_{FC} indicates (see Fig. 7 below).

We note that the value of m_s obtained from the hysteresis loops depends on the applied H_{FC}. As example we show this effect for sample B where the hysteresis loop was measured after cooling the sample at $\mu_0 H_{FC} = 2$ T, see Fig. 5(b). This effect is due to the LSMO layer and indicates that the number of aligned domains can be changed with H_{FC}. In this case we expect that the M_E effect will be strongly influenced by the FM layer since, as in the case of a diluted AFM layer [9,7], the formation and number of its domains that take part in the exchange-bias coupling with the AFM layer can be enhanced leading to an increase of M_E. Note however that the M_E effect should decrease with H_{FC}, i.e. $M_E \to 0$ for $H_{FC} \to \infty$, as well as at $H_{FC} = 0$.

Note the opening of ~ 1 μemu of the hysteresis at the end of the loop at 0.5 T for sample A, see Fig. 5(a). A similar opening is measured for all samples in agreement with the numerical results obtained with the domain state model for exchange-bias proposed by Nowak et al. [9,20]. The fact that the loops do not close indicates that *some* uncompensated spins—pinned earlier during the field cooling—rotate and remain pinned in the opposite direction during the field sweep loop, reducing the final saturation moment. We note that in all three bilayers this opening remains of the order of $1\ldots2$ μemu, i.e. several times smaller than the M_E shift, as we show below.

To characterize quantitatively the exchange-bias M_E effect and for a direct comparison with the saturation magnetic moments of each of the layers we define it as $m_{shift} = (m_s^+ + m_s^-)/2$, where m_s^+ and m_s^- are the saturation moments at positive and negative fields. The shift in the field axis is defined as $H_E = (H_c^+ + H_c^-)/2$, where H_c^+ and H_c^- are the coercive fields in upward and descending loop branches, respectively. We note that the H_E values were obtained only after centering the hysteresis loop, subtracting the upward M_E shift.

Fig. 6 shows the coercivity H_c (a), the exchange-bias H_E (b) and the vertical shift in magnetic moment m_{shift} (c) as a function of $T \leq 80$ K for sample B, measured after $\mu_0 H_{FC} = 0.3$ T, as an example. A similar behavior is observed for samples A and C. Both, H_C and H_E show an anomaly at $T \lesssim 20$ K, in agreement with the behavior found in the remanence curve, see Fig. 4, suggesting that the transition at that temperature influences the exchange interaction. At $T \gtrsim 35$ K H_E crosses zero and changes to positive. This sign change of H_E from negative to positive increasing temperature was observed also in CoO/Co bilayers[21] and suggests a change from direct ($J_{interface} > 0$) to indirect ($J_{interface} < 0$) interface interaction. As expected, $H_E(T)$ as well as m_{shift} vanish at $T \gtrsim T_N$. In contrast to $H_E(T)$ no anomalous behavior is observed in $m_{shift}(T)$ at $T < T_N$, with exception of the slope change at $T \sim 20$ K, see Fig. 6(c).

Fig. 7 shows the H_{FC}-dependence of H_c, m_{shift} and H_E for the three samples measured at 5 K. The decrease of H_E from samples A to B agrees with the expected inverse proportionality of H_E with the thickness of the FM layer. According to this thickness dependence sample C should show nearly one order of magnitude smaller H_E than for sample B, in clear disagreement with the obtained result, see Fig. 7(c), suggesting that the magnetic dilution of this sample is responsible for the large observed H_E field. This interesting and original behavior is in agreement with the theoretical study published recently by Usadel and Stamps [31] where they consider the influence on H_E of the dilution of the FM layer alone. These authors found theoretically that an increase

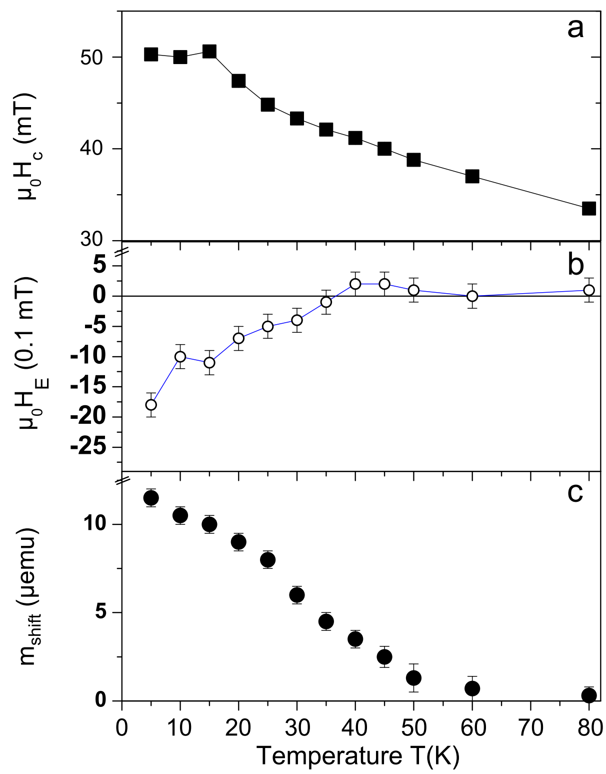

Fig. 6. Temperature dependence of the coercivity (a) and exchange-bias (b) fields and of the shift in magnetic moment m_{shift} due to the M_E effect (c) for sample B after cooling it in a field of 0.3 T.

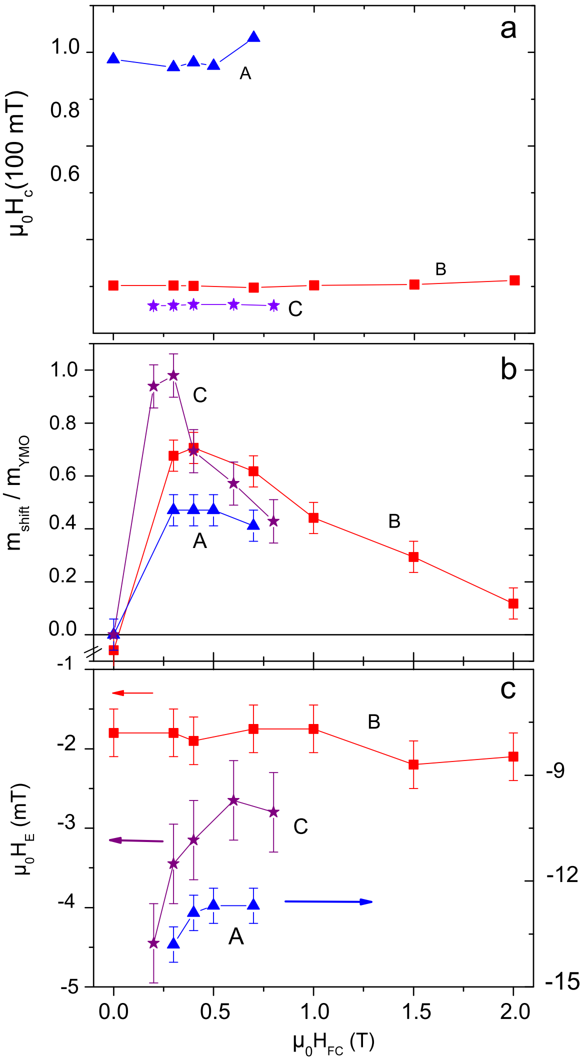

Fig. 7. Dependence of the coercive field (a), shift in magnetic moment m_{shift} (b) and exchange-bias field H_E (c) on the cooling field H_{FC} for the three measured bilayers at 5 K. In (b) we plot m_{shift} normalized by the *maximum saturation moment* m_{YMO} of the o-YMO layer, i.e. $m_{YMO} = 17$ μemu for samples A and B and 24.5 μemu for sample C. Note that the values of $m_{shift} \sim 0$ at $H_{FC}=0$ were obtained using maximum fields between 0.3 and 0.5 T for the hysteresis loops. For all the other points the maximum field of the loops coincides with H_{FC}.

in the magnetic dilution of the FM layer produces an increment in H_E in agreement with our results. Namely, sample C, which has a larger dilution of the FM LSMO layer, shows a larger H_E that sample B, although this last sample has a much smaller thickness.

Regarding the M_E effect and in agreement with the results in Co/CoO bilayers [7] we observe a vanishing effect at zero and at large enough values of H_{FC}, see Fig. 7(b). Under the assumptions done in Refs. [20,9] the M_E shift is mainly due to the AFM layer. According to this model, the largest m_{shift} expected from our o-YMO layer, assuming complete saturation in the whole 375 nm thick layer, would be $m_{YMO} = 17$ and 24.5 μemu from samples A or B and C, respectively. To estimate those numbers we have taken into account the measured magnetization at saturation of the single layers. The normalized m_{shift} by the corresponding m_{YMO}, see Fig. 7(b), would indicate that it is necessary that from 50% to 70% of the YMO layer should be responsible for the measured m_{shift} at $H_{FC} \sim 0.5$ T for samples A and B. This percentage increases further for the diluter sample C at $0.2\,\text{T} \leq H_{FC} \leq 0.4$ T. Taking into account the 375 nm thickness of the YMO layer this assumption appears unlikely.

It is known that unexpected phenomena can occur at oxide interfaces. A recent study, for example, found an excess magnetization produced at the interface between STO and an AFM $La_{1/3}Ca_{2/3}MnO_3$ layer [32], which origin remains unclear. In our case the large m_{shift} values—actually a giant M_E effect—indicate that a large contribution should come from the FM layer. Taking into account the saturation moments of the LSMO layers alone, we estimate for example that a thickness of the LSMO layer of less than 1.3 nm for sample B and < 10 nm for sample C should be enough to produce the observed m_{shift} at $H_{FC} = 0.5$ T.

3.3. *$La_{0.67}Ca_{0.33}MnO_3/YMnO_3$ bilayer*

Further evidences for the reproducibility and robustness of the effects observed in the three LSMO/YMO bilayers reported in the last section are provided by the results of a LCMO/YMO bilayer with similar geometry and preparation conditions as sample A. Fig. 8(a) shows the remanent magnetic moment of this bilayer after cooling the sample at 1 T applied field. The transition at the Néel temperature of the YMO layer is clearly seen as well as the change of slope at ~ 20 K. In Fig. 8(b) the hysteresis loops for three field cooled states at fields $H_{FC} = \pm 1$ T and 2 T are shown. At low H_{FC} fields both exchange-bias effects are clearly observed

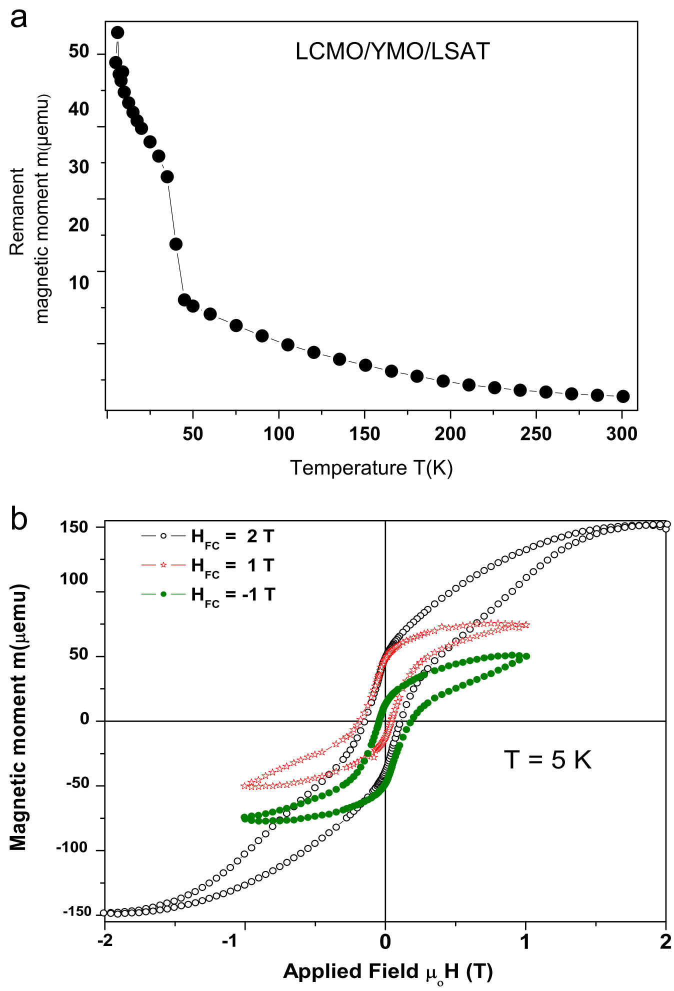

Fig. 8. (a) Temperature dependence of the zero field remanent magnetic moment measured after field cooled at 1 T of a bilayer $La_{0.67}Ca_{0.33}MnO_3$ (8 nm)/$YMnO_3$ (375 nm), similar to sample A, but the YMO layer first deposited on a (100)LSAT substrate. (b) Hysteresis loops at 5 K measured for the same sample after field cooled (FC) at the fields shown in the figure.

whereas the M_E effect vanishes at high enough fields, see Fig. 8(b). Fig. 9 shows the H_{FC}-dependence for the three characteristics parameters. The observed m_{shift} at $H_{FC} \lesssim 1$ T, see Fig. 9(b), is as large as the magnetic moment at saturation of the 375 nm thick YMO layer alone clearly indicating that the FM layer near the interface should contribute to this effect.

Although in the LSMO/YMO bilayers we did not find any correspondence between the coercive field $H_c(H_{FC})$ and $m_{shift}(H_{FC})$, see Fig. 7, one may expect some correlation between them in case of a bilayer with a very-thin (and diluted) FM layer. This may be so if we take into account the amount of the FM layer that remains pinned at the interface. In this case the smaller the effective thickness of the remained unpinned ferromagnetic layer the smaller might be H_c. Apparently this is observed in the (thin)LCMO/(thick)YMO bilayer. Indeed, the results shown in Fig. 9 indicate that when m_{shift} decreases at $H_{FC} > 0.25$ T, i.e. when the amount of UCM decreases, H_c increases.

We did SQUID measurements in bare LSMO and LCMO films at different cooling fields (not shown). The results show, as expected, an increase of the magnetic moment m_s when H_{FC} increases, indicating that more domains are aligned with the cooling field. However the hysteresis loops are neither asymmetrically shifted in the magnetization axis nor in the field axis. The M_E effect observed in the bilayers is not strictly related to the observed increase of m_s in the single layers with H_{FC}. However it indirectly supports our interpretation of the m_{shift}, which resides in the coupling of the diluted FM layer and the pinning of its domains at the interface with the AFM layer.

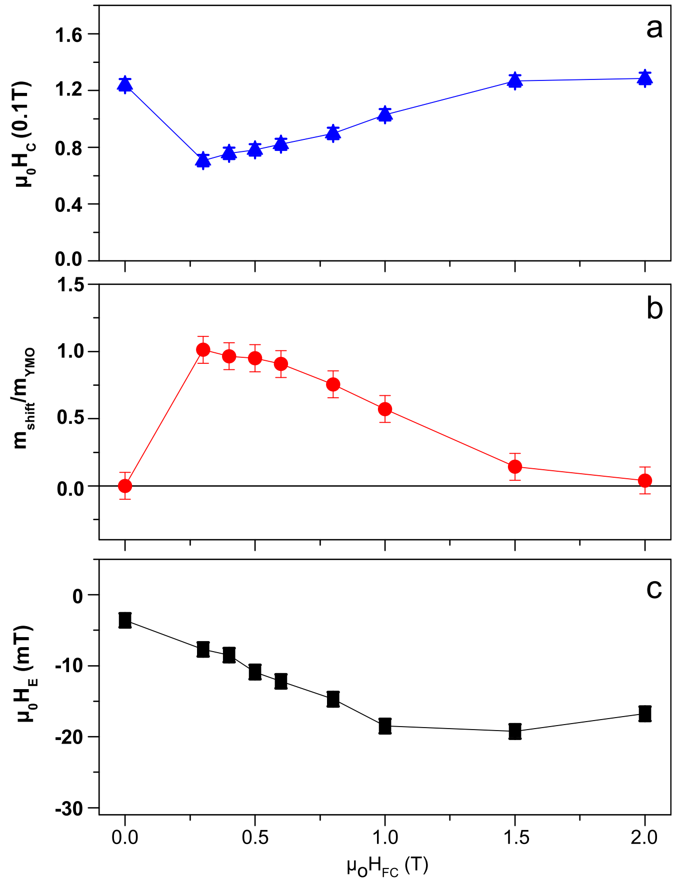

Fig. 9. Similar to Fig. 7 but for the YMO/LCMO bilayer: Dependence of the coercive field (a), shift in magnetic moment m_{shift} normalized by the maximum saturation moment m_{YMO} of the o-YMO layer alone (b), and exchange-bias field H_E (c), on the cooling field H_{FC} at 5 K.

4. Discussion and conclusion

To further corroborate our conclusion that the observed vertical shift is mainly due to the FM and its interface region with the AFM layer we show the hysteresis loops acquired using X-ray magnetic circular dichroism in Fig. 10. For sample A we find a shift of $\simeq 5\%$ using the surface sensitive approach measuring the response of the Mn ions within the LSMO FM layer only. That one observes a vertical shift in the dichroism signal coming from the FM layer, whatever its magnitude, is a clear indication that this FM layer is contributing to the M_E effect and that the magnetization shift is not confined to the bulk or at the interface of the AFM layer only. Because 95% of the secondary electrons detected in our XMCD experiment originates from the top 6 nm [10,11], just 2 nm below the interface region (sample A has 8 nm thin LSMO layer on top of the YMO layer), we can conclude that the interfacial region of the FM/AFM layer should contribute significantly more to the m_{shift} compared to the rest layers of the FM. This result agrees with the estimates from the bulk SQUID measurements, i.e. one needs about 1 nm thick FM layer (e.g. for sample A) to account for the observed m_{shift}.

Note that our XMCD measurements have been performed at 15 K, hence it is expected that the XMCD results should show lower m_{shift} values compared with those from the SQUID measurements performed at 5 K. In fact, if H_{FC} is 0.4 T, a reduction of $\sim 15\%$ is observed in M_E at 15 K respect to the 5 K measurement for sample A. For sample B a similar behavior is observed (see Fig. 6), being this reduction $\sim 20\%$ for $H_{FC} = 0.3$ T.

Taking into account the previous statement that it is highly unlikely that the entire AFM bulk contributes to the shift we can conclude that the excess magnetization is produced predominately at the FM interface during the field cooling process due to interfacial exchange coupling between the AFM and the FM as shown previously for the case of Co/FeF_2 [11].

Using similar arguments on the importance of the magnetic dilution of the AFM layer [20,9], we argue that in our system the dilution of the FM layer may play a mayor role in the M_E shift. In other words, the robust AFM layer influences the magnetic behavior of the FM one, within a certain thickness from the interface. Recently, a magnetization shift was reported for ferrimagnetic very-thin hard/soft (3 nm/12 nm) $DyFe_2/YFe_2$ heterostructures [23]. We note

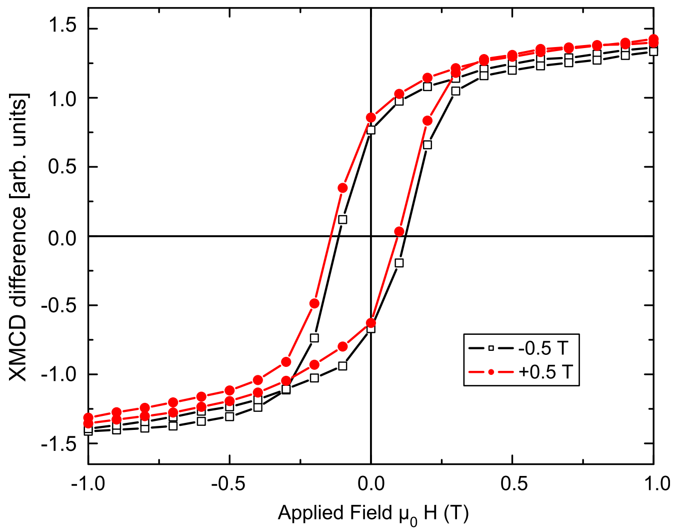

Fig. 10. Hysteresis loops of sample A acquired at 15 K after cooling in a field of either +0.5 or −0.5 T using X-ray magnetic circular dichroism and the Mn L-absorption resonance. The loops exhibit a horizontal loop shift H_E of 0.014 T as well as a vertical shift $m_{shift} \simeq 5\%$ of the saturation value.

however that in that work the M_E effect is in the opposite direction to that of the applied H_{FC}, in clear contrast to our observations.

Furthermore, a comparison between the overall behavior obtained for $m_{shift}(H_{FC})$ and $H_E(H_{FC})$ indicates that there is no simple correlation between the two exchange-bias effects. Note that H_E decreases strongly from sample A to B, whereas m_{shift} increases. Although element selective X-ray magnetic measurements would help to determine the penetration depth of the UCM in each of the layers, it is clear from our SQUID measurements that the o-YMO layer alone cannot be the reason for the observed giant M_E effect, this is the main message of our work.

In conclusion, our studies on LSMO/o-YMO bilayers and on a single LCMO/o-YMO bilayer found large uncompensated M_E shifts, whose sign correlates with the direction of the cooling field H_{FC}. Both, the exchange-bias H_E and M_E effects, vanish near T_N of the YMO layer. The large m_{shift} values indicate that the AFM layer cannot be the only responsible but a certain thickness of the FM layer near the interface. This behavior can be actually understood taking similar arguments as those used for the AFM layer in the domain state exchange-bias model of Refs. [9,20]. Tuning the thickness and magnetic dilution of the FM layer one should be able to obtain large M_E shifts making it an effect worth to study in systems with $T_N > 300$ K. The different behaviors of H_E and M_E with temperature, cooling field and FM layer thickness indicate that these two phenomena are not correlated in a simple way.

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