Stray field and the superconducting surface spin valve effect in La$_{0.7}$Ca$_{0.3}$MnO$_3$/YBa$_2$Cu$_3$O$_{7-\delta}$ bilayers

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Abstract. Electronic transport and magnetization measurements were carried out on La$_{0.7}$Ca$_{0.3}$MnO$_3$/YBa$_2$Cu$_3$O$_{7-\delta}$ (LCMO/YBCO) bilayers below the superconducting transition temperature in order to study the interaction between magnetism and superconductivity. This study shows that a substantial number of weakly pinned vortices are induced in the YBCO layer by the large out-of-plane stray field in the domain walls. Their motion gives rise to large dissipation peaks at the coercive field. The angular dependent magnetoresistance (MR) data reveal the interaction between the stripe domain structure present in the LCMO layer and the vortices and anti-vortices induced in the YBCO layer by the out-of-plane stray field. In addition, this study shows that a superconducting surface spin valve effect is present in these bilayers as a result of the relative orientation between the magnetization at the LCMO/YBCO interface and the magnetization in the interior of the LCMO layer that can be tuned by the rotation of a small $H$. This latter finding will facilitate the development of superconductive magnetoresistive memory devices. These low-magnetic-field MR data, furthermore, suggest that triplet superconductivity is induced in the LCMO layer, which is consistent with recent reports on triplet superconductivity in LCMO/YBCO/LCMO trilayers and LCMO/YBCO bilayers.

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1. Introduction

The physics of spin-dependent transport is currently attracting much attention because it is of fundamental interest to the realization of spintronic devices [1]. A lot of studies were focused on the ferromagnet/nonmagnetic-spacers/ferromagnet (F/N/F) structures for which the giant magnetoresistance (GMR) depends on the relative orientation of the magnetization in the top and bottom F layers, giving rise to the spin valve effect [2] in a GMR memory device. When the nonmagnetic spacer was replaced with a superconductor, a novel superconducting spin valve effect was proposed and theoretically justified [3] in ferromagnet/superconductor/ferromagnet (F/S/F) structures, in which the superconductivity is switched on and off by reversing the magnetization direction of one of the ferromagnetic (FM) layers. There are several reports on the experimental realization of this effect by using metals as the S layer [4]–[6].

Recently, a surface spin valve effect was observed within a few atomic layers at the ferromagnetic/nonmagnetic (F/N) interface, which is due to the fact that the FM spins at such an interface are significantly different from the magnetic character of the spins inside the F layer and they can act as current- or field-driven spin valves with respect to the magnetization in the interior of the FM layer [7]. Based on these results, we anticipate that a superconducting surface spin valve effect could be present in a ferromagnet/superconductor (F/S) bilayer such as La_{0.7}Ca_{0.3}MnO_{3}/YBa_{2}Cu_{3}O_{7−δ} (LCMO/YBCO) because it has been shown that the magnetization of the LCMO/YBCO interface is significantly different from the bulk magnetization, inside the LCMO layer [8]–[10]. This finding will facilitate the development of superconductive magnetoresistive memory devices.

The domain structure of the FM layer has a significant influence on the superconductivity of the superconducting layer [11]; that is, both Néel and Bloch domain walls (DWs) can enhance or suppress superconductivity [12, 13], depending on the size of the coherence length of the Cooper pair \(\xi_{ab}\) relative to the width of the DW \(\delta\). In the case of the LCMO/YBCO bilayers, \(\xi_{ab} \approx 3\,\text{nm at } 45\,\text{K (with } \xi_{ab}(0\,\text{K}) = 2\,\text{nm and the superconducting transition temperature of the LCMO/YBCO bilayer } T_{c} = 82\,\text{K})\) that is much smaller than the width of the DWs of the LCMO (about 3 and 2\,\mu m at 63 and 10 K, respectively [9]). Therefore, both Néel and Bloch DWs suppress superconductivity in the LCMO/YBCO bilayers due to the effect of the exchange interaction on the Cooper pairs [14]. Moreover, the out-of-plane spins in the Bloch DWs induce vortices, which give rise to additional dissipation [15].
To study the effect of DWs on superconductivity and to search for the superconductive surface spin valve effect, we performed angular-dependent transport measurements on LCMO/YBCO bilayers by rotating the magnetic field $H$ within the $ab$-plane. This study revealed that vortices are induced in these bilayers by the out-of-plane stray field in the DWs. This latter field is induced by the stresses in the twins of the LCMO layer as a result of a structural phase transition in the substrate. The motion of these vortices gives rise to one type of angular-dependent magnetoresistance (MR) dissipation. In addition, the present study shows that one can generate a superconducting surface spin valve effect in these bilayers, in which the MR depends on the relative angle between the magnetizations of the LCMO/YBCO interface and of the LCMO bulk layer. These two types of behavior were observed in LCMO/YBCO bilayers only below the superconducting transition temperature $T_c$ of the bilayer and were not present in the normal state.

2. Experimental details

LCMO/YBCO bilayers were grown on (100)-oriented SrTiO$_3$ single crystals. The details of sample preparation are reported elsewhere [16]. The FM layer of the bilayer is 40 unit cells (u.c.) (16 nm); the superconducting layer is 4 u.c. (4.8 nm). The LCMO/YBCO interfaces are sharp and perfectly coherent [17]. All samples are $1 \times 0.5 \text{cm}^2$. For all of the data shown here, a current $I$ of 100 $\mu$A was applied in the $ab$-plane and the resistance $R$ of the bilayer was measured using a four-contact method. The applied field $H$ was rotated in the $ab$-plane and the angle $\phi$ is defined as the angle between $H$ and the [010] crystallographic direction of the LCMO layer (see the inset to figure 2(a)). We repeated the measurements with other values of the applied current in the range 1–100 $\mu$A and found that the results presented here are qualitatively independent of these values of the applied current.

A small out-of-plane misalignment of $H$ is found when $H$ is rotated in the $ab$-plane. In a one-axis rotator system, it is very hard to ensure an in-plane alignment of $H$ of better than about $\pm 3^\circ$. This misalignment, i.e. the magnetic field is not completely within the $ab$-plane of the single crystal, gives an angular-dependent resistance that is independent of the current direction. Its magnitude decreases with decreasing field and has an $180^\circ$ periodicity [18]. All of the data shown in this paper are after subtraction of this misalignment contribution to the resistance.

3. The stray field effect

3.1. Magnetoresistance (MR) and magnetization measurements

Figure 1 is a plot of the resistance $R$ (open squares) and magnetization $M$ (open circles) of an LCMO/YBCO bilayer measured at a temperature $T$ of $45 \text{ K} < T_c$ ($T_c = 82 \text{ K}$ is defined in the inset of figure 1(a)) versus the magnetic field $H$ applied in the $ab$-plane along the [010] crystallographic direction of the LCMO layer ($\varphi = 0$). The magnetic field is scanned from $-2000 \text{ Oe}$ to $+2000 \text{ Oe}$ and then back to $-2000 \text{ Oe}$. Two sharp resistance peaks are present in the $R(H)$ data measured with $I \parallel [100]$ crystallographic direction. The positions of the resistance peaks are at $+280$ and $-280 \text{ Oe}$, during increasing and decreasing $H$, respectively, corresponding to the coercive field (zero magnetization) of the sample, determined from the $M(H)$ data of this figure. (Note that since the magnetization curve is measured in the
superconducting state, there is a contribution due to the superconducting moment.) At the 
coevasive field, the LCMO layer has the maximum number of domains and hence DWs. Therefore, the stray field is the largest. Hence, the fact that the resistance peaks appear exactly at 
the coercive field of the sample indicates that they are the result of the stray field. Nevertheless, 
the question that needs to be answered next is what is the direction of the stray field?

The inset of figure 1(b) is a plot of the same \( R(H) \) data shown in the main panel but 
displayed over a larger field range. Note that a linear extrapolation of the \( R(H) \) data to high \( H \) 
values shows that an in-plane applied field of 6000 Oe would give a resistance comparable to the 
peaks value. Therefore, a 6000 Oe in-plane stray field in the DWs is required for producing the 
measured peak in \( R(H) \). However, the in-plane stray field \( H_{\text{stray}}^{ab} \) at the coercive field is much less 
than the saturation magnetization \( M_{\text{sat}}^{ab} \) [19]. As a simple estimate, \( H_{\text{stray}}^{ab} \approx 10\% \times 4\pi M_{\text{sat}}^{ab} = 0.1 \times 4\pi \times 566 \text{ emu cm}^{-3} = 710 \text{ Oe} \). Hence, the \( R(H) \) peaks are not due to an in-plane stray field since its estimated value of 710 Oe is much smaller than the required value of 6000 Oe. Therefore, the \( R(H) \) peaks can only be a result of an out-of-plane stray field. Such a conclusion 
is consistent with the sharp peaks in the \( R(H) \) data since an out-of-plane stray field would give 
rise to a substantial number of vortices and hence to sharp dissipation peaks in \( R(H) \) due to 
vortex dissipation in the YBCO layer [15].

These Bloch-type DWs (the direction of the stray field that arises in the DWs is out of 
plane) are a result of the cubic-to-tetragonal transition in the SrTiO\(_3\) substrate, which takes 
place below 105 K and induces twins in the LCMO layer [20]. The stresses in the twins are the 
onest that induce the out-of-plane stray field [20].

**Figure 1.** Applied magnetic field \( H \)-dependent resistance \( R \) (open squares) and 
magnetization \( M \) (open circles) of an LCMO/YBCO bilayer (the thickness \( d_s \) of 
YBCO layer is 4 u.c.) measured in the mixed state of the bilayer, at a temperature 
\( T \) of 45 K with \( H \) along the [010] crystallographic direction. Insets: (a) the 
\( R-T \) curve measured in zero field; (b) the same \( R-H \) curve of the main panel 
measured over a wider \( H \) range.

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3.2. Angular-dependent MR measurements

Next, we investigate how $R(\varphi)$ evolves when the magnetization changes from the saturation state to the multi-domain state. The arrows shown in the main plot of figure 1 mark the values of $H$ at which $R(\varphi)$ was measured using the protocol corresponding to the upper curve of $M(H)$ of this figure. The in-plane angular-dependent MR, defined as $R_{100}^{(100)}(\varphi)/R_{\text{min}}^{(100)}$, is shown in figure 2(a). In these measurements, $I \parallel [100]$ crystallographic direction and $R_{\text{min}}^{(100)}$ represents the minimum resistance. A fourfold symmetry is observed in the angular-dependent MR data for $H$ rotated in the $ab$-plane of the bilayer at $T < T_c$. The positions of the MR peaks are slightly shifted from, but close to $90^\circ$, $180^\circ$ and $270^\circ$. Both this shift and the magnitude of the MR peaks decrease with increasing $H$ from 400 to 1000 Oe.

The equilibrium state of $M$ is achieved when the free energy $E$ of the system is minimal. Here, $E$ is the sum of Zeeman energy and magnetocrystal anisotropy energy (MAE) [21], i.e.

$$E = -MH \cos(\alpha - \varphi) + E_{\text{MAE}}(\alpha),$$

where $\alpha$ is the angle between $M$ and the [010] crystallographic direction (see the inset of figure 2(a)). If $H \geq H_{\text{sat}}$, the first term on the right-hand side of equation (1) dominates; therefore $\alpha = \varphi$ gives the minimum $E$; hence $H$ and $M$ are along the same direction. If $H \ll H_{\text{sat}}$, the second term on the right-hand side of equation (1) dominates; therefore the minimum $E$ takes place when $M$ is along the easy axis. At intermediate $H$ values, both terms contribute to the energy $E$, and the relative angle between the $H$ and $M$ directions for the equilibrium state is determined by the minimum value of $E$.

The above discussion facilitates the understanding of the data of figure 2(a). Specifically, when $H = 1000$ Oe, the angular-dependent MR data show maxima, corresponding to the maximum stray field for this applied magnetic field (maximum number of DWs), at $\alpha \approx 90^\circ$, $180^\circ$ or $270^\circ$. The hard axes for the LCMO/YBCO bilayer are the [010] and [100] crystallographic directions since the maximum number of DWs take place when the induced magnetization $M$ is along the hard axis, while the easy axes are in the diagonal directions.

The small deviation in the MR peaks of figure 2(a) from the hard axes at lower values of $H$ is due to the fact that $M$ lags behind $H$ (the contribution of the MAE cannot be neglected), which is consistent with the fact that this deviation becomes larger with decreasing $H$. Also, the number of domains increases with decreasing $H$ from 1000 to 400 Oe, which produces an increase in the stray field with decreasing $H$. As a result, the value of the MR peaks increases with decreasing $H$.

In addition, the magnitude of the MR peak depends on the angle between the $H$ and $I$ directions. Figure 2(b) gives the angular-dependent MR for the current along [010] (solid symbols) and [100] (open symbols) crystallographic directions. Note that the MR peak is always larger when $H \perp I$ (\varphi = 90^\circ$ for the solid symbols and $180^\circ$ for the open symbols) than when $H \parallel I$ (\varphi = 180^\circ$ for the solid symbols and $90^\circ$ for the open symbols). This change in the magnitude of the MR peaks with the angle between $H$ and $I$ reflects the interaction between the stripe domain structure and the vortex motion, as discussed below.

The presence of stripe domains in the LCMO/YBCO bilayers has previously been reported [9, 22, 23]. The inset of figure 2(b) is a sketch of the cross section of the stripe domain structure in the LCMO layer at $T < T_c$ and at the coercive field. The gray regions represent the stripe domains, and the yellow regions are the DWs. The direction of the magnetization $M$ is shown along [100] and [100] and the directions of the stray field in the DWs are also represented. Note that adjacent DWs have opposite directions of the stray field [9, 22, 23].
Figure 2. (a) Angular-dependent MR $R_{[100]}^{[100]}(\phi)/R_{\min}^{[100]} - 1$ data ($R_{\min}^{[100]}$ is the minimum resistance) measured in the mixed state at 55 K and for applied magnetic fields of 400, 600, 800 and 1000 Oe, with the current applied along the [100] crystallographic direction. Inset: top view of the sample configuration. The magnetic field $H$ and magnetization $M$ are rotated in the $ab$-plane and make the angles $\phi$ and $\alpha$, respectively, with the [010] crystallographic direction. (b) Angular-dependent MR $R_{[100]}^{[100]}(\phi)/R_{\min}^{[100]} - 1$ and $R_{[010]}^{[010]}(\phi)/R_{\min}^{[010]} - 1$ data measured in the mixed state at 55 K with the current applied along the [100] (open squares) and [010] (solid squares) crystallographic directions, respectively, and in an applied magnetic field of 400 Oe. Inset: top view of the stripe DW structure in the LCMO layer. The gray regions represent domains with the moments along the [100] and [\bar{1}00] directions and the yellow regions represent the DWs with out-of-plane stray fields.

Hence, the out-of-plane stray field induces spontaneous vortices and anti-vortices in the YBCO layer [9, 22, 23]. These flux vortices are driven by the Lorentz force and move in the direction perpendicular to both $I$ and the stray field. Therefore, the smaller MR peak when $I$ is along the stripes ($I \parallel H$) is due to the fact that the flux vortices are driven across the DWs, which gives
a smaller dissipation and hence larger critical current of the superconducting film, owing to the partial pinning of the vortices by the DWs. When $I$ is perpendicular to the stripes ($I \perp H$), the flux vortices are driven along the DWs; thus their motion is not hindered by the DWs; hence the dissipation is larger and the critical current of the superconducting film smaller.

This effect of the stripe DWs on the critical current is based on the technique of pinning the flux vortices by the DWs rather than pinning the normal core of the vortices at the locally suppressed superconductivity, realized by several possible means (e.g. columnar defects, magnetic particles, etc). The effect of the DW structure on the critical current had previously been studied in bilayers of a low-$T_c$ superconductor (Nb) and an itinerant ferromagnet (SrRuO$_3$) [24]. Our results are consistent with this study despite the different nature of the materials (e.g. $d$-wave versus $s$-wave and half-metallic versus itinerant FM), suggesting that the interaction between the DWs and the flux vortices is independent of the nature of superconductivity and ferromagnetism. This is expected since the pinning of the flux vortices at the DWs is only a result of the magnetostatic interaction between the magnetic flux vortices and the magnetization of the FM layer.

The slight asymmetry at the base of the resistance peaks in figures 2(a) and (b) could be a result of the fact that $M$ lags behind $H$ when $H$ is rotated from an easy to a hard axis ($M$ prefers to lie along the easy axis), while $M$ jumps ahead of $H$, to the next easy axis, when $H$ is rotated from a hard to an easy axis.

4. The superconducting surface spin valve effect

The magnetization $M_I$ of the LCMO layer within 2–3 u.c. of the LCMO/YBCO interface is significantly different from the bulk magnetization, inside the LCMO layer [8, 9]. In fact, polarized neutron reflectometry on YBCO/LCMO superlattices has shown strongly depressed magnetization at the interface over the 1 nm length scale [25]; that is, the magnetic coupling near the LCMO/YBCO interface is very weak compared with the one of the bulk [26] and therefore the Curie temperature is expected to be less than the one of the bulk. Hence, the direction of $M_I$ could be tuned by the rotation of a small applied magnetic field while not affecting the direction of the bulk magnetization. In this way, the parallel/antiparallel alignment of the surface and bulk magnetizations could be created. Therefore, this system is a good candidate for the investigation of the superconducting surface spin valve effect.

To investigate this effect in this F/S system, one therefore needs to pin the bulk magnetization of the LCMO layer and then use a low applied magnetic field that would control the magnetization at the LCMO/YBCO interface. Since [110] is an easy axis, we applied $H$ in the [110] direction increasing its value up to +2000 Oe, to saturate the magnetization of the LCMO layer along this direction, and then we decreased $H$ to 35 Oe, so the bulk magnetization remains pinned along this [110] direction. We subsequently rotated the 35 Oe field in the $ab$-plane in order to rotate the magnetization $M_I$ of the surface layer, but not the bulk magnetization of the LCMO. (A small magnetic field cannot modulate the domain structure of the LCMO layer; hence the MAE is the dominant term in equation (1). Nevertheless, it could rotate the magnetization $M_I$ of the LCMO/YBCO interface.)

Figure 3(a) shows the angular-dependent MR data measured at 45 K < $T_c$ using the above protocol in both increasing (black square) and decreasing (red circle) angle. The fact that the angular-dependent MR data are reversible shows that the bulk magnetization is pinned along the [110] easy axis, which gives the minimum energy of the system, without following the
rotation of $H$. The angular dependence of the resistance shown in figure 3(a) is only observed in the superconducting state of the LCMO/YBCO bilayer. It could be a result of either domain nucleation at the surface layer and changes in their structure as a result of the motion of DWs (a small field of 35 Oe could not have much effect on the domains of the bulk LCMO or on the superconductivity of the YBCO) or the rotation of the interface magnetization along with the 35 Oe field rotation, which would modulate the superconductivity at the LCMO/YBCO
interface. Below we show that the present data point toward the second rather than the first scenario.

We measured also a minor magnetic loop using the following protocol. First, we applied the magnetic field along the [110] direction up to +2000 Oe, to again saturate the bulk LCMO magnetization along this direction. Then we decreased the field to zero and scanned $H$ over a small range; that is, we increased the field to +40 Oe then decreased it to −40 Oe and then increased it back to zero. This obtained minor loop is shown in the inset of figure 3(b). The fact that this $M(H)$ minor loop is linear and reversible indicates magnetization rotation under the effect of an applied magnetic field (as opposed to domain nucleation, which would give rise to hysteresis). This is consistent with the proposed superconductive surface spin valve scenario and indicates that an exchange spring wall separates bulk and surface layers, as reported earlier [27]. The existence of an exchange spring wall at the interface of the manganite is not surprising in view of a nonhomogeneous (depressed) magnetization (see [25]). This layer is typically a few nanometers thick, much thinner than the DW width, so that magnetization rotation within the thin layer is the most probable mechanism of magnetization reversal, a mechanism that saves exchange energy at the interface at the cost of Zeeman energy [27].

The MR curve of figure 3(a) is well fitted by $R^{100}(\phi)/R_{\text{min}}^{100} - 1 = 0.0067\sin^2[(\phi - 57^\circ)/2]$, as shown by the solid curve in the figure. The fitting result of 57° suggests that the pinning angle of the bulk magnetization is not exactly along the [110], but makes an angle of 57° with the [010] crystallographic direction. This 12° difference between the [110] easy axis of LCMO and the pinning angle of the bulk magnetization could be due to a small tension or shape anisotropy of the bilayer in the $a$- and $b$-directions.

The superconductive magnetoresistive memory device has a structure similar to GMR memory devices. In fact, some of us have recently reported a similar angular dependence of the MR in F/S/F trilayers based on the same materials [28], but with MR values larger by more than one order of magnitude compared with the ones reported here. In [28] it has been shown that this large MR is tracking the relative alignment between the top and bottom magnetic layers. On the other hand, the physics of superconducting memory devices, proposed based on the present data, is based on the S/F proximity effect [29]; that is, it is based on the oscillatory decay of the pair wave function predicted to occur in the FM layer due to the influence of the exchange interaction on the Cooper pairs [14]. Here we propose that the relative orientation between the surface and bulk magnetizations of the LCMO layer modulates the exchange interaction, hence the spatial dependence of the Cooper pair wave function and therefore the MR of the bilayer.

A singlet Cooper pair experiences less (more) pair breaking if the bulk magnetization of the LCMO layer and the magnetization of the LCMO/YBCO interface are antiparallel (parallel) since the different (same) sign of the exchange energies in the LCMO/YBCO interface and the LCMO layer makes the average of the exchange energy small (large) [29]. Nevertheless, the data of figure 3(a) show that for $H \parallel M$ ($\phi = 45^\circ$), MR is minimal, whereas for $H$ antiparallel to $M$ ($\phi = 225^\circ$), MR is maximal. Hence, these data suggest that triplet superconductivity is induced in the LCMO layer of the LCMO/YBCO system since the pair breaking effect is reduced when the two FM layers are parallel [30]. Furthermore, the Ginzburg-Landau coherence length in the $c$-direction is about 0.2 nm at 45 K, while the surface thickness is about 2–3 u.c. (0.8–1.2 nm) [8, 9, 26]. Therefore, the surface spin valve effect cannot be due to the singlet proximity effect, which is short range. Hence, one needs to consider a long-range proximity effect.

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The triplet created by a nonhomogeneous magnetization at the interface of the S/F junction can produce a long-range proximity effect\cite{31,32}. One possible source of inhomogeneity reported in the literature is DWs. Volkov and Efetov\cite{32} have recently shown that starting from the d-wave superconductivity, the presence of DWs perpendicular to the interface leads to the formation of both the singlet and odd triplet components of the s-wave and that the latter can penetrate the normal metal over long distances along the DWs. However, the micron-size width of the DWs in manganites is much larger than the nanometer scale coherence length. Also, the $M(H)$ loop shown in figure 3(b) measured along the [110] easy axis shows that DWs are present in the bulk LCMO at zero field (the $M(H)$ loop is not really square), while the $M(H)$ minor loop of the inset of figure 3(b) shows no evidence of domains at the surface layer (the $M(H)$ loop is reversible). Hence, this possible source of magnetic inhomogeneity is quite improbable.

Another source of nonhomogeneous (depressed) magnetization in this system could be phase segregation resulting from charge transfer or other interface related phenomena\cite{25}. Specifically, the depressed interfacial magnetization is (still) laterally nonuniform with a much shorter nanometer length scale due to phase segregation. Inhomogeneities in the Mn$^{3+}$/Mn$^{4+}$ ratio resulting from charge transfer, strain relaxation and other interface processes that cannot be microscopically followed by the La/Ca ratio are known to occur at manganite surfaces and interfaces. Charge spreads over the nanometer scale Thomas Fermi screening length to preserve charge neutrality, but nanometer scale phase separation occurs, giving rise to the stabilization of secondary phases and dead layers with depressed magnetic and conducting properties\cite{33}–\cite{36}. Direct evidence of magnetic inhomogeneity has recently been found from magnetic force microscopy\cite{37}. This is most likely the source of the nonhomogeneous magnetization that gives rise to the triplet component and it is also the basis of the exchange spring surface layer, in which magnetization at the surface layer is weakly coupled to the bulk magnetization.

It has been proposed theoretically that unpolarized supercurrents could be converted to triplet-pairing at spin-active interfaces\cite{38,39}, while it has been found experimentally that there is a 100 nm thick layer at the LCMO/YBCO interface that displays a suppressed (but nonzero) FM moment\cite{40}. Therefore, this could also be a possible source of the triplet component present at the LCMO/YBCO interface.

Regardless of its origin, our finding on triplet superconductivity is consistent with recent reports on triplet superconductivity in LCMO/YBCO/LCMO trilayers\cite{41} and bilayers\cite{42}. This triplet condensate would give rise to the observed onefold symmetry: maximum resistance when moments are antiparallel and minimum resistance when moments are parallel. These results on triplet superconductivity in an FM manganite and unconventional superconductor complement the results on spin-triplet superconductivity found at interfaces of hybrids of ferromagnets (such as CrO$_2$, Ho and Co) and conventional superconductors\cite{43}–\cite{46}.

5. Conclusions

We performed MR and magnetization measurements on LCMO/YBCO bilayers below the superconducting transition temperature $T_c$ of the bilayers and studied in detail their spin-dependent transport. We showed that the vortex dissipation, related to the out-of-plane stray field induced by the stresses in the twins of the LCMO layer as a result of a structural phase transition in the substrate, gives MR peaks at the coercive field. More interestingly, at low magnetic field values, we found a novel superconducting surface spin valve effect, in which the MR signal depends on the relative angle between the magnetizations of the LCMO/YBCO interface.
and the LCMO layer; that is, MR is minimal when the two magnetizations are parallel and maximal when they are antiparallel. Our study of the spin-dependent transport in F/S bilayers opens up a new avenue to the realization of spintronic devices. This novel superconducting surface spin valve effect can be used in a superconductive magneto resistive memory device as a magnetoresistive switching element.

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