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# Electric transport measurements on $\text{La}_{0.7}\text{Ca}_{0.3}\text{MnO}_3/\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ heterostructures

T. Hu<sup>1</sup>, H. Xiao<sup>1</sup>, C. Visani<sup>2</sup>, J. Santamaria<sup>2</sup>, and C. C. Almasan<sup>1</sup>

**Abstract.** Charge transport measurements were performed on  $\text{La}_{0.7}\text{Ca}_{0.3}\text{MnO}_3/\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$  (LCMO/YBCO) trilayer samples. They reveal that the out-of-plane stray field gives rise to flux vortices whose dissipation produces resistance peaks at the coercive fields of the top and bottom LCMO layers. A superconducting surface spin valve effect, similar to the one present in bilayer samples, was also observed in trilayers. These results were observed in the LCMO/YBCO trilayers below the superconducting transition temperature of the trilayers and are not present in the normal state, which shows the typical two fold magnetoresistance behavior.

<sup>1</sup>Department of Physics, Kent State University, Kent, Ohio, 44242, USA

<sup>2</sup>GFMC, Departamento Fisica Aplicada III, Universidad Complutense de Madrid, Madrid, 28040, Spain

## 1. Introduction

The superconductor/ferromagnet heterostructures have attracted a lot of research interest since (1) novel physics arises at the interface as the result of the interaction between superconductivity and magnetism and (2) they have potential application in the development of superconductive magnetoresistance memory devices. A few examples of the novel physics present in these materials are long range proximity effect [1], domain wall superconductivity, spin imbalance effect, and induced triplet superconductivity [2]. The principle behind a giant magnetoresistance (GMR) memory device is the spin valve effect present in ferromagnet/nonmagnetic-spacer/ferromagnet (F/N/F) structures. GMR depends on the relative orientation of the magnetic moments of the top and bottom F layers [3]. A surface spin valve effect was reported in F/N structures [4] as a result of the fact that the interface magnetization differ significantly from the bulk magnetization of the F layer. It is of great interest to know if a similar spin valve effect can be observed when replacing the N layer with a superconducting S layer.

Our previous work on  $\text{La}_{0.7}\text{Ca}_{0.3}\text{MnO}_3/\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$  (LCMO/YBCO) *bilayers* has shown presence of resistance peaks [5], due to stray field, and superconducting surface spin valve effect [6], due to the fact that the magnetization of the LCMO/YBCO interface is significantly different from bulk LCMO magnetization. Here we present charge transport measurements on LCMO/YBCO *trilayer* performed in order to study their spin dependent transport properties.

### 1.1. Experimental Details

LCMO/YBCO trilayers were grown on (100)-oriented  $\text{SrTiO}_3$  single crystals. A buffer layer of  $\text{PrBa}_2\text{Cu}_3\text{O}_{7-\delta}$  (PBCO) (6 u.c.) was deposited between the substrate and the first LCMO layer in order for the two LCMO layers to be magnetically similar. (The PBCO and YBCO are very

similar in unit cell size). The LCMO/YBCO interfaces are sharp and perfectly coherent [1]. The details of sample preparation can be found elsewhere [7]. The thickness of the LCMO layer in these trilayer samples is 40 u.c., while the thickness of the superconducting layer is 4 u.c. (4.8 nm), 9 u.c. (10.8 nm), or 12 u.c. (14.4 nm); the superconducting transition temperature  $T_c$  (defined as 10% drop in resistance) for the three different trilayers studied is 30.0, 84.5, and 90.0 K, respectively. All samples have an area of  $1 \times 0.5 \text{ cm}^2$ .

A four-contact method was used to measure the resistance  $R$  of the trilayers in an applied current  $I$  of 100  $\mu\text{A}$ , with  $I \parallel [100]$  crystallographic direction. The angle  $\varphi$  dependent  $R$  was measured by rotating the magnetic field  $H$  within the ab-plane of the sample, with  $\varphi$  measured from the [010] direction of the LCMO layer. The contribution to  $R(\varphi)$  from a small out-of-plane misalignment of  $H$  has been subtracted. Details of the misalignment produced by a one-axis rotator and its subtraction are given elsewhere [8].

## 2. Results and Discussions

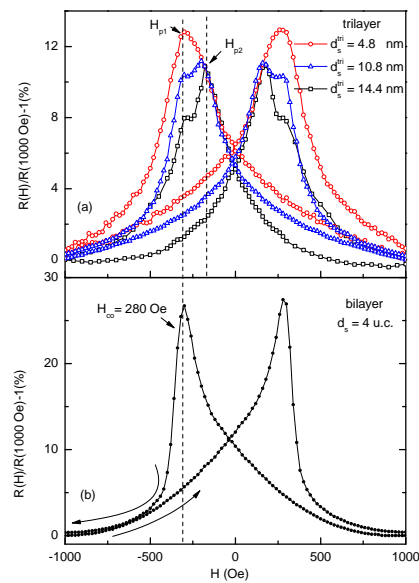
We performed  $R(H)$  measurements ( $H \parallel [100]$ ) on trilayers with three different thicknesses of the YBCO layer, namely,  $d_s^{tri} = 4, 9, \text{ and } 12$  u.c. Fig. 1(a) shows the normalized resistance data  $R(H)/R(1000 \text{ Oe}) - 1$  vs  $H$  for increasing and decreasing  $H$ , measured at  $T < T_c$  of trilayers. With increasing/decreasing  $H$ , two resistance peaks are present in  $R(H)$  of the samples with  $d_s^{tri} = 9$  and 12 u.c, while they become one broader peak for the  $d_s^{tri} = 4$  u.c. trilayer. For example, the position of the first and second peak are  $H_{p1} = 280 \text{ Oe}$  and  $H_{p2} = 170 \text{ Oe}$ , respectively, for the  $d_s^{tri} = 12$  u.c. trilayer.

The  $H_{p1}$  peak has the same position as in bilayers [Fig. 1 (b)]. Hence, it corresponds to the coercive field (zero magnetization and largest stray field) of the bilayer and it is a result of the dissipation of flux vortices generated by the out-of-plane stray fields present in the domain walls, as previously observed in bilayers [5]. This stray field is produced by the stresses in the twins of LCMO layer induced by the cubic-to-tetragonal transition in the  $\text{SrTiO}_3$  substrate [9].

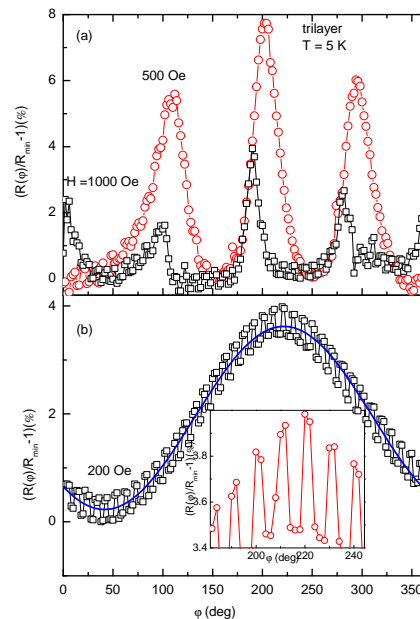
Note that, as the thickness of the YBCO layer increases, the ratio of the amplitude of the first to second peak decreases. This result is consistent with a decrease of the effect of the substrate on the top LCMO layer with increasing the thickness of the YBCO layer, such that the first peak eventually would vanish when  $d_s^{tri}$  is large enough. However, the effect of the substrate on the bottom LCMO layer is always present and should not change from sample to sample. So, we conclude that the peaks at  $H_{p1}$  and  $H_{p2}$  are a result of increased vortex dissipation due to the largest stray field present at the coercive field of the top and bottom LCMO layer, respectively.

We note that recent work on trilayers without buffer layer shows that spin dependent scattering effect (in the antiparallel orientation of the net magnetic moments of the top and bottom layer) dominates their resistance, producing much larger magnetoresistance values [10]. The buffer layer in the present samples makes the two LCMO layers magnetically similar, thus giving rise to a different physics than in trilayers without buffer layers, if a good antiferromagnetic state (antiparallel LCMO moments) is never established; i.e., the physics revealed here is vortex dissipation as a result of the out-of-plane stray field produced by the stresses in the twins in the LCMO layer induced by the cubic-to-tetragonal transition in the  $\text{SrTiO}_3$  substrate.

Figure 2(a) is a plot of the normalized resistance  $R^{[100]}(\varphi)/R_{min}^{[100]} - 1$  vs the angle  $\varphi$ , measured at  $5 \text{ K} < T_c$  in 500 and 1000 Oe on a trilayer sample with  $d_s^{tri} = 4$  u.c. The  $\varphi$  dependent MR data show maxima, corresponding to the maximum stray field for these  $H$  values (maximum number of domain walls), at 90, 180, or 270°. This is consistent with the fact that the hard axes for the LCMO/YBCO are the [010] and [100] crystallographic directions since the maximum number of domain walls takes place when the induced magnetization  $M$  is along the hard axis, while the easy axes are in the diagonal directions. Also, since this 4-fold symmetry is similar with what we have recently reported in bilayer samples [6], it shows that the magnetic coupling between top and bottom LCMO layers at these  $H$  values does not determine the overall dissipation, but



**Figure 1.** (a) Normalized resistance  $R(H)/R(1000 \text{ Oe}) - 1$  vs. magnetic field  $H$  for trilayer samples with thickness  $d_s^{tri}$  of YBCO layer of 4, 9, and 12 unit cell measured at  $T < T_c$ . (b)  $R(H)/R(1000 \text{ Oe}) - 1$  vs.  $H$  for LCMO/YBCO bilayer with thickness  $d_s$  of YBCO layer of 4 u.c. measured at a temperature  $T$  of 45 K ( $< T_c$ ).



**Figure 2.** (a) Normalized resistance  $R^{[100]}(\varphi)/R_{min}^{[100]} - 1$  vs. angle  $\varphi$  measured at 5 K for trilayers with  $d_s^{tri} = 4 \text{ u.c.}$  The current is applied along the [100] crystallographic direction. (a)  $H = 500, 1000 \text{ Oe}$ . (b)  $H = 200 \text{ Oe}$ . Inset: the enlarged plot of the oscillation.

that these peaks in dissipation are a result of vortices produced by the out-of-plane stray field and their magnitude reflects the vortex - stripe domain structure interaction [6].

Note that the resistance peaks are not located exactly at the hard axes and also that the peaks are closer to the hard axis for the 1000 Oe data than for the 500 Oe data. We have also shown on bilayers [6] that the larger the applied magnetic field, the smaller this deviation is. The reason is the following. There are two contributions to the total free energy of the system, namely, the Zeeman energy, which tends to align  $M$  along  $H$ , and the magnetocrystal anisotropy energy which forces  $M$  to be along the easy axis. For a large magnetic field, e.g. 1000 Oe, the magnetization is close to saturation, hence the Zeeman energy dominates and the peaks take place at the hard axes. However, for a smaller field, e.g. 500 Oe, the contribution of the magnetocrystal anisotropy energy can not be neglected anymore and, therefore,  $M$  lags behind  $H$ . This gives the small deviation of the resistance peaks from the hard axes.

Recent measurements of in-plane angular-dependent resistance of LCMO/YBCO bilayers at low  $H$  values have shown a one fold symmetry, associated with the surface spin valve effect [6]. A surface spin valve effect was initially reported within a few atomic layers at a F/N interface [4]. This phenomenon is a result of the fact that the ferromagnetic spins at the interface differ significantly 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 bulk magnetization in the ferromagnetic layer. There is evidence that the magnetization of the LCMO layer at the LCMO/YBCO interface is significantly different from the bulk magnetization inside the LCMO layer [11, 12, 13]; namely, the magnetic coupling near the interface is much weaker than that of the bulk [14]. Hence the direction of the interface magnetization can be tuned by the rotation of a small magnetic field without changing the direction of the bulk magnetization in the LCMO layers. Therefore,

a superconducting surface spin valve effect is produced in the LCMO/YBCO *bilayers* [6] in which the magnetoresistance depends on the relative angle between the magnetization at the LCMO/YBCO interface and the bulk magnetization of the LCMO layer. We searched for such a phenomenon in LCMO/YBCO trilayers at small applied magnetic fields.

Figure 2(b) is a plot of the normalized resistance  $R^{[100]}(\varphi)/R_{min}^{[100]} - 1$  vs  $\varphi$  for the trilayers measured in a low  $H$  of 200 Oe using the following protocol. A magnetic field is applied along the [110] direction (easy axis) and is increased up to +2000 Oe to saturate and pin the bulk magnetization along the [110] direction. Then the magnetic field is decreased to 200 Oe and rotated within the ab-plane while measuring the resistance. The magnetoresistance curve of Fig. 2(b) is well fitted with  $R^{[100]}(\varphi)/R_{min}^{[100]} - 1 = 0.035\sin^2[(\varphi+41.4^\circ)/2]$  as shown by the solid curve of the figure. This one-fold symmetry is similar to what we observed in bilayer samples. This indicates that the interface spin valve effect is responsible for this behavior. It is worthwhile to comment that in trilayers with no buffer layer, where a good antiferromagnetic state can be established, a similar result is found but with much larger magnetoresistance values arising from the rotation of the magnetization of one of the layers (with a small anisotropy field), while the magnetization of the other LCMO layer (with a larger anisotropy field) is kept frozen at these small values of the rotating field [10]. Furthermore, note that in addition to the one-fold symmetry curve of Fig. 2(b), there are additional periodic oscillations [see Fig. 2(b) and its inset]. Further experiments are needed to explore the origin of these periodic oscillations.

### 3. Summary

In summary, charge transport measurements were performed on YBCO/LCMO trilayer heterostructures with a buffer layer between the substrate and the first LCMO layer. The vortices induced by the stray field give rise to two resistance peaks located at the coercive fields of the top and bottom LCMO layers. A superconducting spin valve behavior is observed in trilayers at low fields, which indicates that the interface effect dominates the charge dissipation.

### Acknowledgments

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