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Stray field and spin-imbalance effects in $La_{0.7}Ca_{0.3}MnO_3/YBa_2Cu_3O_{7-\delta}$ multilayers

T. Hu[a,*], H. Xiao[a], C. Visani[b], Z. Sefrioui[b], J. Santamaria[b], C.C. Almasan[a]

[a]*Department of Physics, Kent State University, Kent, OH 44242, USA*
[b]*Departamento Fisica Aplicada III, Universidad Complutense de Madrid, 28040 Madrid, Spain*

Abstract

In-plane resistance and magnetization measurements were performed on $La_{0.7}Ca_{0.3}MnO_3/YBa_2Cu_3O_{7-\delta}/La_{0.7}Ca_{0.3}MnO_3$ (LCMO/YBCO/LCMO) trilayers below the superconducting transition temperature of the YBCO layer. Two magnetoresistance (MR) peaks were found: The first MR peak is consistent with the suppression of superconductivity due to the stray fields generated by the domain walls and the second one is most likely the result of the antiparallel orientation of the net magnetic moment of the top and bottom LCMO layers.
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Recently, more and more research has been focused on superconductor/ferromagnet (S/F) heterostructures in order to reveal the interplay between competing superconducting and magnetic order parameters. Novel physical phenomena including the predicted domain-wall superconductivity [1,2] and spin imbalance were found in S/F systems, which are responsible for an anomalous superconducting transition temperature (T_c) and magnetoresistance (MR) behavior observed in these materials. It has been reported that the MR of $La_{0.7}Ca_{0.3}MnO_3/YBa_2Cu_3O_{7-\delta}/La_{0.7}Ca_{0.3}MnO_3$ (LCMO/YBCO/LCMO) trilayers depends on the relative orientation of the magnetization in the top and bottom LCMO layers [3], which can be explained by the spin-imbalance theory. In this paper, we show that the MR behavior of LCMO/YBCO heterostructures is also related to domain wall stray fields.

LCMO/YBCO bilayer and trilayer heterostructures were grown on (1 0 0)-oriented $SrTiO_3$ single crystal substrates. The details of sample preparation can be found elsewhere [4]. The ferromagnetic LCMO layer is 40 unit cells (u.c.) thick while the superconducting YBCO layer is $d_s = 4$ or 9 u.c. A buffer layer of $PrBa_2Cu_3O_{7-\delta}$ of 6 u.c. was deposited between the substrate and the first LCMO layer. The LCMO/YBCO interfaces are perfectly coherent and free of disorder [5]. All the samples have the same dimensions. In-plane resistance and magnetization measurements were performed on bilayers and trilayers below the zero-field T_c, which is defined as the onset of the drop in the temperature (T) dependence of the resistance (R) of the heterostructure. The magnetic field (H) and current are applied in the *ab* plane of the heterostructure, along the [1 0 0] crystallographic direction. The $R(H,T)$ was measured using four contacts in the current-in-plane geometry.

Fig. 1 is a plot of the field H dependent normalized resistance $[R(H)/R(0)-1]$ of LCMO/YBCO bilayers with $d_s = 4$ u.c., measured up to 2000 Oe and at 45 K ($T_c = 81$ K). (Here the T_c of the bilayer is suppressed due to the proximity effect.) Note that $R(H)$ changes nonmonotonically. Specifically, in scanning H from −2000 to 2000 Oe, $R(H)$ displays two minima, at ~ ± 1000 Oe and one maximum at ~290 Oe, while in decreasing H from 2000 to −2000 Oe, $R(H)$ displays the two minima at the same H

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*Corresponding author. Tel.: +1 330 6722402.
E-mail address: thu@kent.edu (T. Hu).

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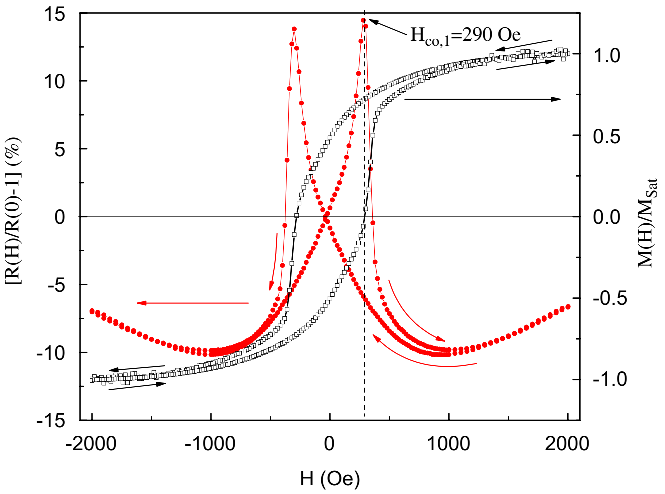

Fig. 1. Plot of normalized magnetoresistance $R(H)/R(0)-1$ and normalized magnetization $M(H)/M_{\mathrm{sat}}$ (M_{sat} is the saturation moment of LCMO layer) vs magnetic field H of a LCMO/YBCO bilayer with thickness $d_s =$ 4 u.c.

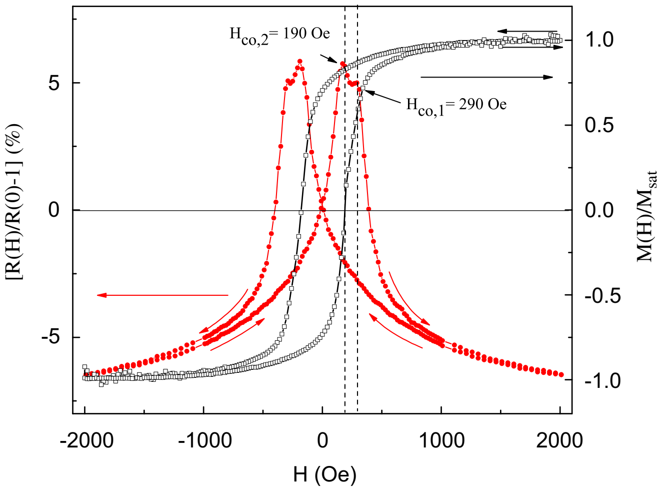

Fig. 2. Plot of normalized magnetoresistance $R(H)/R(0)-1$ and magnetization $M(H)/M_{\mathrm{sat}}$ (M_{sat} is the saturation moment of LCMO layer) vs magnetic field H of LCMO/YBCO/LCMO trilayers with thickness $d_s =$ 9 u.c.

values and the maximum at ~ -290 Oe. Therefore, $R(H)$ is irreversible for $-1000 < H < 1000$ Oe.

Fig. 1 is also a plot of the hysteresis curve $M(H)$ measured over the same H range and at the same T. This curve measures the magnetic response of the LCMO layer, which is in the ferromagnetic state. At the coercive field $H_{\mathrm{co,1}}$ of the LCMO layer [$M(H) = 0$] the density of domain walls is highest, while at the saturation field there is only one domain. Hence, the number of domains increases with increasing H from -2000 Oe to $H_{\mathrm{co,1}}$ and it decreases with further increasing H. The high density of domain walls at $M(H) = 0$ leads to large stray fields since stray fields generally originate from domain walls within the FM layer [6].

Note that the maximum in $R(H)$ is at the coercive field. Hence, this maximum in $R(H)$ is a result of the stray field present in the FM layer [6].

The minimum in $R(H)$ at $\sim$1000 Oe (see Fig. 1) is a result of the competition between the decrease in $R(H)$ due to the decrease in the stray field as H increases, for $H_{\mathrm{co,1}} < H < H_{\mathrm{sat}}$, and the increase in $R(H)$ due to the suppression of the superconductivity with increasing H. Nevertheless, note that the increase in $R(H)$ for $H > 1000$ Oe is only about 2%. Therefore, these data show how the domain structure in the FM layer modifies the superconducting properties, i.e. the T_c of the YBCO layer. This result is consistent with a previous report that the stray fields of the magnetic domains lead to the suppression of superconductivity [6].

Fig. 2 is a plot of the normalized resistance and of M vs H for a trilayer heterostructure with $d_s = 9$ u.c. measured at $T = 65$ K ($T_c = 89$ K). The $R(H)$ curve displays two peaks: the first one is at $H_{\mathrm{co,1}} \approx 290$ Oe while the second one is at $H_{\mathrm{co,2}} \approx 190$ Oe. The position of the first peak is the same as the coercive field of the *bilayer* sample. Also note that $M(H_{\mathrm{co,1}})/M_{\mathrm{sat}} \approx 0.5$. Therefore, in the trilayer sample, at $H_{\mathrm{co,1}}$ the moment of the bottom LCMO layer saturates, which is consistent with a previous report that the coercive field of the bottom layer is smaller than the one of the top layer [3].

The position of the second peak ($H_{\mathrm{co,2}} \approx 190$ Oe) is at the coercive field of the *trilayer* sample, since at this H value $M(H) = 0$ (see Fig. 2). This implies that the magnetic moments in the top and bottom LCMO layers have opposite directions but same magnitude, i.e. the spins in the two LCMO layers are aligned antiparallel. According to previous reports [3], an antiparallel orientation of the net magnetic moment of the top and bottom LCMO layers in the LCMO/YBCO/LCMO trilayers leads to a peak in $R(H)$, which is explained by the spin-imbalance theory.

Note that there is no peak in $R(H)$ at the coercive field of the bottom layer. The reason is the following. The $R(H)$ measurements are done in the current-in-plane configuration which implies that the current density is inhomogeneous and decreases from the top to the bottom of the heterostructure. Hence, the top LCMO layer and not the bottom dominates the $R(H)$. Furthermore, since the stray field is a local effect, the stray fields of the bottom layer do not contribute to the resistance which is dominated by the top part of the heterostructure (high current density).

In summary, two $R(H)$ peaks are observed in trilayer samples. The first $R(H)$ peak is a result of stray fields, while the second one is due to spin imbalance. These two effects coexist and compete, hence modulate the superconductivity of heterostructures.

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