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Magnetism and superconductivity in oxide ferromagnet/superconductor heterostructures

P. PRZYSŁUPSKI[1*], A. TSAROU[1], I. KOMISSAROV[1], K. DYBKO[1], P. DŁUŻEWSKI[1], M. SAWICKI[1], B. DĄBROWSKI[2], C. KIMBALL[2]

[1]Institute of Physics, Polish Academy of Sciences, 02-668 Warszawa, Poland

[2]Department of Physics, Northern Illinois University, DeKalb, Il, 60115, U.S.A.

We report on transport and magnetic properties of $La_{0.67}Sr_{0.33}MnO_3/YBa_2Cu_3O_7/La_{0.67}Sr_{0.33}MnO_3$ (LSMO/YBCO/LSMO) trilayer structures. The onset of the superconducting transition temperature in trilayer structures starts from the sample with a 6 nm (5 unit cells) thick YBCO layer. The $M(H)$ hysteresis loop indicates an indirect exchange coupling between LSMO layers across the YBCO layer. Magnetoresistance studies demonstrate a change in the magnetoconductance of the trilayer structure with magnetic field variation, indicating an indirect exchange coupling between LSMO layers across the non-superconducting YBCO layer.

Key words: *trilayer structure; superconducting transition; exchange coupling; magnetoresistance*

1. Introduction

Studies of oxide ferromagnet/superconducor (F/S) heterostructures have attracted much attention. Using such structures, it is possible to probe the interplay between superconductivity and ferromagnetism on the nanometer length scale. Superconducting and magnetic orders are generally incompatible with each other: it is known that the exchange field of magnetic systems reduces the superconducting order parameter. A possibility of indirect exchange coupling between F layers across S layers in manganite/cuprate heterostructures has been predicted theoretically [1]. A signature of this effect has been recently demonstrated experimentally in LSMO/YBCO superlattices [2, 3]. The interplay between spin-polarized materials also has potential applications.

*Corresponding author, e-mail: przys@ifpan.edu.pl

2. Experimental

$La_{0.67}Sr_{0.33}MnO_3/YBa_2Cu_3O_7/La_{0.67}Sr_{0.33}MnO_3$ (LSMO/YBCO/LSMO) trilayer structures were deposited on (100) $[(LaAlO_3)_{0.3}(Sr_2TaAlO_6)_{0.7}]$ (LSAT) substrates by high pressure sputtering [2, 3]. Magnetic measurements were performed in a SQUID magnetometer in the temperature range 5–300 K. Transport measurements were carried out with the four-point probe method. For tunnelling magnetoconductance (TMC) measurements, we have synthesized the trilayer heterostructure using a shadow mask, with the bottom electrode 2 mm in width and separated by a YBCO spacer layer (7.2 nm thick) from the upper electrode of the same width and perpendicular to the bottom electrode. Differential conductance dI/dV was measured using a lock-in amplifier with an amplitude of 10 μV. The measurements were performed with a magnetic field parallel to the trilayer, with a DC bias voltage of 0.15 mV in a current perpendicular to the plane configuration (CPP).

3. Results and discussion

In this report, we present the measurements of LSMO/YBCO/LSMO trilayer structures, with YBCO layer thickness varying from 5 to 7 unit cells (u.c.) and LSMO layer thickness kept at 10 nm (25 u.c.). Figure 1 shows the temperature dependence of the resistance of trilayers with 5 (LaY114), 6 (LaY115), and 7 (LaY116) u.c. thick YBCO layers. It can be seen that the onset of the transition to the superconducting state is observed beginning from the sample with a 5 u.c. thick YBCO layer. In all measured samples, the Curie temperature was higher than 300 K. The in-plane *M-H*

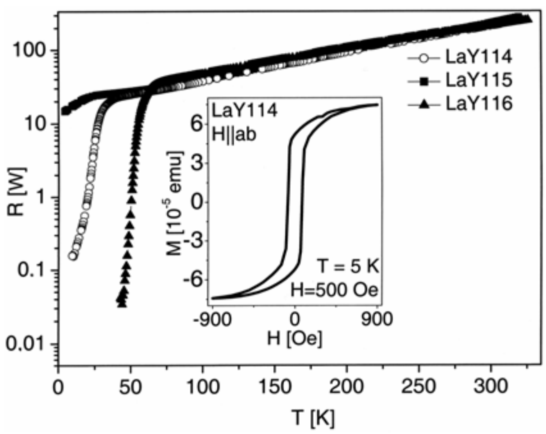

Fig. 1. Temperature dependences of resistance in trilayers with 6 nm (LaY114), 7.2 nm (LaY115) and 8.4 nm (LaY116) thick YBCO layer. Inset: hysteresis loop measured at $T = 5$ K in the sample LaY114

loop recorded at 5 K represents two magnetic contributions (see the inset in Fig. 1). At relatively small magnetic fields (below 100 Oe), the soft part of ferromagnetic LSMO layers is observed, whereas the reversal of magnetic moments takes place at higher fields and saturates at about 650 Oe. This observation can be interpreted as a signature of indirect exchange coupling between LSMO layers across the YBCO superconducting layer. According to the theoretical model [1], there is a possibility of such a coupling, both above and below the superconducting transition. To confirm this

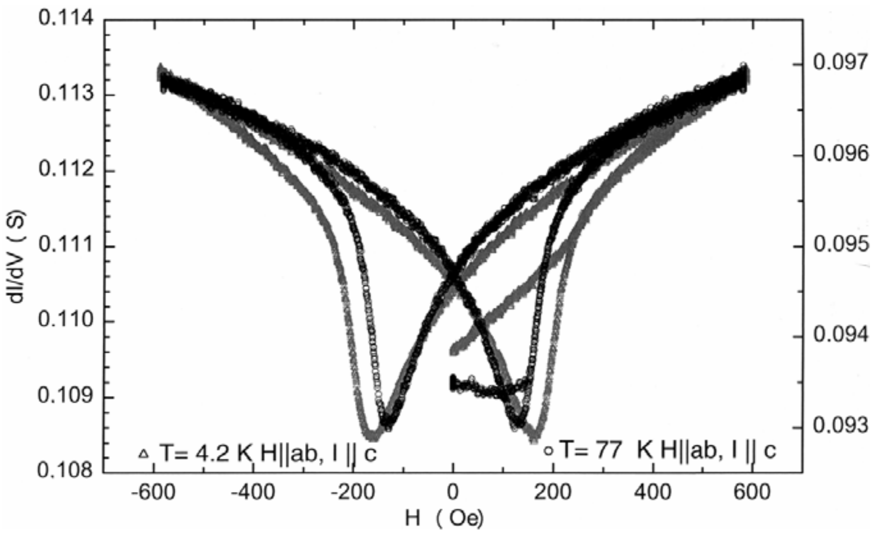

Fig. 2. Dynamical conductivity vs. applied magnetic field of LSMO (100 nm)/YBCO (7.2 nm)/LSMO (100 nm) trilayer measured at $T = 4.2$ and 77 K

effect, we measured the magnetoresistance (MR) effect in the LSMO (100 nm)/YBCO (7.2nm)/LSMO (100nm) trilayer. Our preliminary results are shown in Fig. 2. As in tunnel junctions [4], MR demonstrates conductivity variation when the magnetic configuration of magnetization changes from parallel to antiparallel, and back to parallel. Maximum conductivity is observed when the magnetic moments in LSMO layers are parallel, and conductivity decreases when the magnetic moments in LSMO layers are oriented antiparallel. For this particular sample, however, the YBCO layer is not superconducting, because of the suppression of superconductivity due to the exchange field of the thick LSMO ferromagnetic layer. The tunnelling effect observed in the magnetic field indicates the existence of indirect exchange coupling between LSMO layers through YBCO being in normal state. This indicates that the suppression of T_{c0} in the YBCO layer can be attributed to the injection of polarized spins from the highly polarized LSMO layer to the YBCO layer. Due to the *d*-wave symmetry of the order parameter in YBCO [1], there is a large population of quasi-particle excitations. The effect of MR is larger for quasi-particles with spins parallel to LSMO layers.

M-H hysteresis loops for superlattices [2, 3] with YBCO layers 1, 4, 6, and 8 unit cells thick demonstrate the antiparallel orientation of magnetic moments in consecutive LSMO layers at low temperatures. On the other hand, superlattices with YBCO layers 2, 3, and 5 unit cells thick demonstrate only parallel alignment. This observation suggests an oscillating nature of the coupling. Recent experimental results also demonstrate a change from antiparallel to parallel alignment of the magnetic moments of LCMO layers in LCMO/YBCO/LCMO trilayers [5]. On the other hand, measurements on LSMO/YBCO/LSMO trilayer structures [6] suggest only an antiparallel alignment of magnetic moments in LSMO layers. More work is necessary to explain the nature of indirect exchange coupling between LSMO layers across YBCO layers.

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