Study of the long-range proximity effect in LSMO/YBCO bilayers

V Štrbík1,3, Š Beňačka1, E Mateev2, B Blagoev2, T Nurgaliev2 and S Miteva2

1Institute of Electrical Engineering, Slovak Academy of Sciences, 9 Dúbravská cesta, 841 04 Bratislava, Slovak Republic
2Emil Djakov Institute of Electronics, Bulgarian Academy of Sciences, 72 Tzarigradsko Chaussee, 1784 Sofia, Bulgaria
E-mail: elekstrb@savba.sk

Abstract. Superconductor-ferromagnet thin film heterostructures in lateral geometry were prepared to study the long-range proximity effect. The high temperature superconductor YBa2Cu3Ox (YBCO) as superconductive electrode and La0.67Sr0.33MnO3 (LSMO) as ferromagnetic separation were used. The length of the ferromagnetic layer between two YBCO microstrip electrodes was about 3 μm. The temperature dependence of the resistance of these structures was measured. The results obtained showed that the separation of the superconducting YBCO microstrips is too large for observation of a long-range proximity effect; further optimization of the structures is, therefore, needed.

1. Introduction
The interplay between superconductive and spin-polarized materials has potential applications in spin cryoelectronics. The perovskite half metals, which are completely spin polarized in one spin direction, are particularly interesting because of their ability to form high-quality heterostructures with high-Tc cuprate superconductors. Electron transport through contact of superconductor (S) with normal (N) or ferromagnet (F) metal is mediated by Andreev reflection, the process in which an electron with energy less than the energy gap of S is reflected as a hole with phase coherence preserved over some distance from the interface [1]. There are two essential features of the proximity effect in FS structures, which make it different from that in SN structures. In SN structures the penetration depth of Cooper pairs (CP) into the N metal is determined by the N metal coherence length \( \xi_N = (\hbar D_N/2 \pi k_B T)^{1/2} \), where \( D_N \) is the diffusion coefficient of N, T is temperature, and \( \hbar \) and \( k_B \) are the Planck and Boltzmann constants. In case of a SF bilayer, the penetration depth of CP into a ferromagnet is much shorter \( \xi_F = (\hbar D_F/2 \pi E_{ex})^{1/2} \) provided the magnetic exchange energy \( E_{ex} \gg k_B T \), or the Thouless energy \( E_{Th} = D/L^2 \) (L is the length of F) are rather large, which is fulfilled in the case of perovskite (half metal) materials. Despite the short coherence length \( \xi_F \) in the F material, there is a possibility of a long-range proximity effect (LRPE) in FS structures if inhomogeneous magnetization is present in the vicinity of the SF interface. It has been shown [2] that, besides the ordinary singlet spin structure of CP (↑↓), the inhomogeneity (e.g. a domain wall) generates a triplet spin structure with amplitude comparable to the singlet one containing phase correlations between electrons with the same spin projections of CP (↑↑).

3 To whom any correspondence should be addressed.
The penetration depth $\xi^F*$ of a triplet CP, in the case of LRPE, should be in the order of $\xi_N$. Thus, the research attention has also been focused on investigating Josephson effects in SFS structures because of the much larger variety of Josephson junction properties realized in combinations of these materials [3].

The magnetic inhomogeneity (domain wall, spin active interface) necessary for the LRPE to arise must be localized, in the case of serial SF geometry, immediately at the SF interface, which is experimentally very difficult to realize; the triplet amplitude is otherwise extremely small. It was found recently [4] that the triplet Andreev reflection amplitude may, in the so called lateral geometry (figure 1), be enhanced by the factor $l_d/d$ in comparison with the serial geometry, where $l_d$ is the domain-wall width and $d$ is the thickness of the F film. In addition, in lateral geometry the LRPE should be independent from the domain-wall location with respect to the SF interface, which is a very significant simplification of the experimental situation. The present contribution is an experimental attempt to verify the theoretical result in [4].

2. Experimental
RF and DC magnetron sputtering systems were used to grow F (LSMO) and S (YBCO) bilayer heterostructures. The polycrystalline $\text{La}_0.7\text{Sr}_0.3\text{MnO}_3$ thin films were directly deposited by RF off-axis single magnetron sputtering on LaAlO$_3$ single crystal substrates. During the sputtering in Ar:O$_2$ (1:1) atmosphere with total pressure of 5.3 Pa, magnetron RF power of 30 W and substrate temperature of 780°C were used. The thickness of the LSMO layer was about 40 nm [5]. DC off-axis double magnetron sputtering was used for deposition of YBCO films on the top of the LSMO layer. The film deposition was carried out at a substrate temperature of $T_{dep} = 780°C$ and the optimal annealing temperature was $T_A = 530°C$. The thickness of the YBCO layer was 70 nm [6].

Patterning of the structures was carried out using optical photolithography and wet etching in a 0.1% solution of HNO$_3$. The lateral cross-section of the structure is shown in figure 1; figure 2 is a photograph of a real SFS sample with three YBCO microstrips with widths of 15, 10 and 5 μm and separation $L$ of 3 μm. The electrical current flows from one part of the YBCO strips to the other through the ferromagnetic LSMO layer.

Before patterning, the bilayer SF heterostructure was investigated by the dc four-point technique and by a contactless inductive method. After patterning the lateral geometry of the structure, the dc technique was used to study the transport properties. X-ray diffraction (XRD) was used to characterize the growth of both films.

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**Figure 1.** Cross-section of the sample used to study the long-range proximity effect. The domain-wall width $l_d$ and the YBCO separation $L$ by a LSMO layer of thickness $d$ are shown.

**Figure 2.** Experimental lateral structure consisting of three YBCO strips (wide 15, 10, and 5 μm) with 3 μm long separation.
3. Results and discussion
The XRD spectrum of the FS heterostructure (figure 3) shows preferential c-axis growth of both LSMO and YBCO films on the LaAlO$_3$ single-crystal substrate. The corresponding LSMO lattice parameter is $a = 0.391$ nm which matches very well the YBCO lattice parameters.

Resistance vs temperature dependences of both an as-prepared YBCO film and a lateral proximity structure (5 $\mu$m wide strip) are shown in figure 4. While the zero-resistance critical temperature $T_{CO}$ of the as-prepared YBCO film is 86 K (figure 4, squares), the $T_{CO}$ of the bilayer structure is below 77 K. The transition width of this structure is significantly larger and a low resistance tail appears. This is confirmed by the similar results obtained by inductive measurement (figure 5). The non-zero resistance of the lateral microstrip geometry was constant below 80 K, indicating absence of LRPE, apparently due to the large YBCO microstrip separation ($L \approx 3$ $\mu$m).

The Cooper pairs transparency between the S and F films is too small, and/or the superconductivity is suppressed (figures 4 and 5), probably due to the ex-situ deposition of the YBCO/LSMO bilayers.

4. Conclusions
In the case of a successful implementation of bilayer structures, and to confirm the theoretical analyses [4], i.e. the presence of LRPE in the LSMO separating YBCO microstrips, the resistance $R$ should be zero at temperature $T < T^*_{CO}$, where $T^*_{CO}$ is the onset of a constant resistance of the sample. The resistance of our samples $R \approx 9$ $\Omega$ was constant below about 80K which allows us to draw several conclusions concerning the samples and the effect investigated:

- the length $L \approx 3$ $\mu$m of the LSMO between YBCO thin film microstrips is very large in comparison to the penetration depth $\xi_F$ of triplet correlations;
- no magnetic inhomogeneity in the LSMO thin film is present near the lateral SF interface;
- the Cooper pairs transparency between the S and F films is too small, and/or the superconductivity is suppressed, probably due to the ex-situ deposition of the YBCO/LSMO bilayers;
- the quality of the very thin ferromagnetic LSMO layer deteriorated during the samples preparation.
In order to perform successful future studies, new samples are in preparation to eliminate the above mentioned problems using both electron-beam lithography and optimized ion-beam etching in view of achieving superconducting films separation $L < 1 \mu$m and larger transparency of the SF interfaces.

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