SFS heterostructures prepared by focused-ion-beam technique

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Abstract. *We present initial investigation of the superconductor-ferromagnet-superconductor (SFS) heterostructures of nanometer dimensions prepared by gallium focused ion beam (FIB) technology. The SFS heterostructures were realized using high-Tc superconducting* $YBa_2Cu_3O_x$ *and ferromagnetic* $La_{0.67}Sr_{0.33}MnO_3$ *thin films. SFS weak link junctions require dimensions of weak link connection in a range of nanometer size realizable by FIB patterning. Presented results show that FIB offers suitable procedure for realization of nanometer size devices but some degradation of ferromagnetic and superconducting properties was observed. The solution of this problem will be solved in the next stage of our investigations.*

Keywords: Superconductor-Manganite Junctions, Proximity Effect, Magnetic Domain Wall

1. Introduction

Superconductor-ferromagnet (SF) bilayer and SFS trilayer heterostructures, in a form of weak links or Josephson junctions, are very attractive objects for the study of mutual interplay between superconductity and ferromagnetism [1]. In addition, their potential applications are very promising in cryoelectronic or superconducting spintronic circuits [2] (e.g. qubits, 0-, pi-junctions, spin valves, etc.). However, utilization of high-Tc superconductors (HTS) in these fields was until now not successful due to their very small coherence length. In case of SFS junction with high-Tc cuprate superconductor $YBa_2Cu_3O_x$ (YBCO) one appear manganites as convenient ferromagnetic (F) materials, e.g. $La_{0.67}Sr_{0.33}MnO_3$ (LSMO) - ferromagnetic perovskite half metal, which may be totally spin polarized in one spin direction. YBCO/LSMO heterostructures, prepared on single crystal MgO or $SrTiO_3$ substrates, are able to create high quality thin films and SF interfaces necessary for the study of physical properties. Generally, electron transport through interface between superconductor and normal (N) or F metal in close proximity with S, is mediated by Andreev reflection, the process in which an electron with energy smaller than the energy gap of S, is reflected as hole preserving in N (F) phase coherence of Cooper pairs (CP) over some distance from the interface. There are essential differences between the proximity effect in SN and SF structures due to different coherence lengths ξ_N and ξ_F which characterize the penetration depth of CP in N (F) material. Fortunately, in addition to the short coherence length ξ_F (~1-2nm) « ξ_N there was discovered long range proximity effect (LRPE) in FS structures, in case if inhomogeneous magnetization in the vicinity of SF interface is present [3]. LRPE is consequence of such inhomogeneity (e.g. domain wall, spin active interface) which generates a triplet spin CP [4], with amplitude comparable to the singlet one, containing phase correlations between electrons with the same spin projections (↑↑), on the coherence length ξ_{FL}. The penetration depth in case of LRPE should be of the order ξ_N as in the case of singlet spin CP into a normal metal. The realisation of high quality high-Tc SF or SFS structures manifesting LRPE is complicated task. The magnetic inhomogeneity, in the so called *series geometry*, must be localized immediately at the SF interface what is experimentally extremely difficult, otherwise the triplet current amplitude is negligible small. Recently, it was analysed

[5] that, in comparison with the *serial geometry*, amplitude of triplet current component may be in the so called *lateral geometry* (Fig. 1) enhanced by a factor l_d/d, where l_d is the domain wall width and d is the thickness of F thin film. In this paper we report on first approaches to prepare and study the properties of YBCO/LSMO/YBCO nanometer heterostructures, using technology of gallium focused ion beam (FIB) patterning, to find out whether this technology is suitable tool for realization of superconductor weak link structures.

2. Experimental

The dc magnetron sputtering was used for in situ growing the bilayer heterostructure $YBa_2Cu_3O_x$ (YBCO) and $La_{0.67}Sr_{0.33}MnO_3$ (LSMO) on single crystal MgO (100) substrate. The single LSMO thin films showed transition to the metallic ferromagnetic state at about 200K and their resistivity ρ was in the range of $\rho \approx 10^{-3}$ Ωcm at liquid nitrogen temperature [6]. Thickness of LSMO layers was in the range 20-50 nm where the LSMO thin film is still ferromagnetic. The LSMO crystallizes as pseudocubic perovskite, it has a fully spin-polarized conduction band and bulk material exhibits ferromagnetic transition around room temperature. The YBCO films were deposited applying high pressure on-axis dc magnetron sputtering carried out at oxygen pressure 300 Pa, substrate temperature T_s = 810 °C, and dc power 200 W, with a deposition rate of 1 nm/min [7]. The thickness of the YBCO superconducting films was about 150 nm. Patterning of the basic bilayer structures, for four points measuring of transport properties, was carried out by optical photolithography and wet (1% H_3PO_4) or Ar ion beam (300 eV, 20 mA/cm^2) etching, with substrate cooled to temperature minus 20 °C. Subsequently Ga^{+3} focused ion beam patterning was applied (Quanta 3D 200i) to receive the convenient *lateral geometry* (Fig. 1).

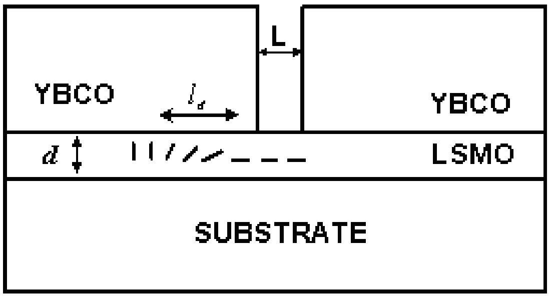

Fig. 1. *Lateral geometry* of the SFS microstrip structure. Magnetic inhomogeneity in LSMO of thickness d is intended to be realized by domain wall of width l_d. The two YBCO electrodes are separated by the length L, as shown.

3. Results and discussion

Zero resistance critical temperature T_{C0} of single c-axis oriented YBCO films, deposited directly on single crystal MgO substrate, was typically somewhat below 90 K, critical current density at 77 K $j_C(77\text{ K}) \approx 3\times10^6$ A/cm^2 and a FWHM for the rocking curves of the (005) YBCO peak of 0.2°. Small decrease of T_{C0} and j_C(77 K) is due to lattice mismatch between YBCO and MgO. Zero resistance critical temperature of the YBCO/LSMO bilayers was above 80 K, in the presented sample T_{C0} = 87.5 K. In Fig. 2 we show SEM picture of YBCO/LSMO microstrip (5×0.5 μm^2) prepared by Ar ion beam etching. Subsequently the sample was transferred in Quanta 3D 200i and the gap of length L in the YBCO film was realized by FIB etching. In addition the FIB etching was used for smoothing the microstrip edges. The resistance vs. temperature (R-T) dependence of the YBCO/LSMO microstrip bilayer indicates small decrease of T_{C0} to 85 K due to the gallium ions irradiation. In the following step, to realize *lateral geometry* of the SFS structure (Fig. 1), it was crucial to remove YBCO (without removing the LSMO very thin film) as a narrow lateral gap of length L (Fig. 2, inset). This is the most critical step of the sample preparation, because during the sample irradiation adjusted on the 30 keV Ga^{+3} ions, the properties of superconductor and manganite films can be influenced.

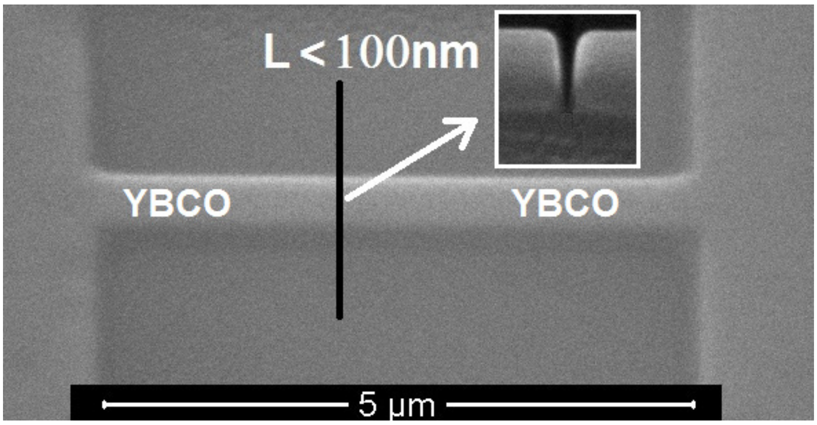

Fig. 2. SFS structure realized as YBCO/LSMO/YBCO junction of *lateral geometry.* The inset shows gap in YBCO thin film of length L ≈ 70-80 nm created by FIB etching of YBCO in YBCO/LSMO microstrip.

After this procedure T_{C0} of SFS structure was decreased to ~ 45 K and current-voltage characteristics (IVC) at various temperatures were measured (Fig. 3).

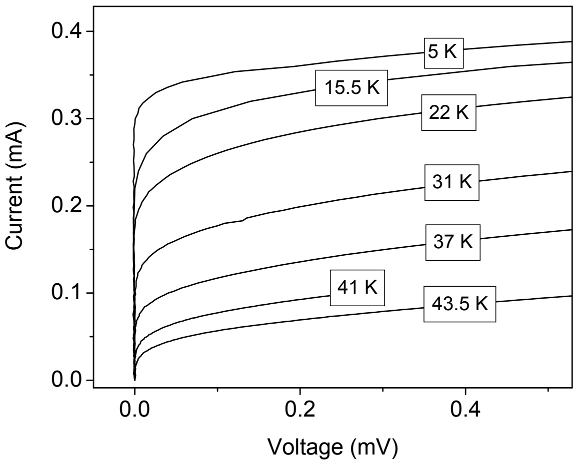

Fig. 3. The current-voltage characteristics of SFS structure at various temperatures.

The IVC exhibit superconducting properties of the SFS junction but the part of IVC at V>0 did not correspond to weak link RSJ model. The quasi-linear critical current vs. temperature, $I_C(T)$ dependence, is frequently indicated in SNS weak link junctions [8]. Moreover, we observed only very weak dependence of the critical current on external magnetic field. Therefore, we suppose so far that in the gap of the SFS structure remains very thin residual YBCO film with above indicated critical current. After further application of additional FIB etching we did not observed superconducting properties of the sample, for that reason we conclude that YBCO was completely removed and the LRPE was not observed due to large length L of the gap, or the inhomogeneous magnetization near the SF interface was not realized. These conclusions confirm typical LSMO R-T dependence measured on the SFS structure. At the same time we observed small shift in LSMO resistance maximum to lower temperature, as a result of FIB application during the YBCO film cutting.

4. Conclusions

The realization of high quality superconducting weak links or Josephson junctions based on high-Tc superconductors is at present very difficult task. Some achievements are expected using advanced microcircuit technologies (e.g. FIB) for preparation of nanometer dimension SNS or SFS structures. SFS heterostructures, in addition offer opportunity of new physical effects, LRPE, as well as new modes of operation in cryoelectronic or superconducting spintronic circuits. In the paper we present preliminary results on the high-Tc superconducting SFS structure in the so-called lateral geometry [5]. In the YBCO/LSMO bilayer the top YBCO layer was disconnected by narrow ($L \approx 70$-80 nm) lateral gap in the YBCO microstrip using focused ion beam (FIB) patterning. Results show that FIB offers suitable procedure for realization of nanometer size devices but problems of films degradation by FIB irradiation have to be solved. Another separate problem, generation of LRPE in SFS structure, is connected with creating of local magnetic inhomogeneity in the ferromagnetic half metal LSMO film. Solution of these problems is the aim of our following investigations.

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