Investigation of the current injection on $J_C$ of a HTS YBCO ring

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Abstract. The effect of the current injection from the ferromagnetic La$_{0.7}$Sr$_{0.3}$MnO$_3$ (LSMO) electrode into high temperature superconducting Y$_1$Ba$_2$Cu$_3$O$_{7-x}$ thin film ring on the critical current of the ring was investigated at 77 K using contactless method. The structures were prepared using magnetron sputtering, conventional photolithography and wet etching procedures. The critical current was determined from the response of the HTS ring to the AC magnetic field. The experiments demonstrated a sensitivity of the critical current to the current injection process, especially in the case of LSMO current-injecting electrode. The paper presents the experimental results and discusses possible mechanisms of the observed effects.

1. Introduction

Spintronics involves the exploitation of the spins of the charge carriers rather than their charge. Superconducting spintronic devices use spin-dependent properties of superconductors in superconductor/ferromagnet heterostructures [1-4]. Spin-polarized quasiparticle injection from colossal magnetoresistance materials into high temperature superconductors (HTS) causes strong nonequilibrium effects and able to affect the electronic transport properties of the superconducting films [4-6]. Ferromagnetic manganites La$_{0.7}$Sr$_{0.3}$MnO$_3$ (LSMO) and high temperature superconductors (HTS) Y$_1$Ba$_2$Cu$_3$O$_{7-x}$ (YBCO) can be used as components of such structures [7-9]. The similar lattice constants and growth conditions of HTS YBCO with $T_C \sim 92$ K and the half-metal manganite compound LSMO that exhibits a FM state below $T_{Curie} \sim 350$ K make it possible to epitaxially grow superlattices and heterostructures using various techniques [7-9]. A high spin polarization ratio is characteristic for hole-doped rare earth manganites as La$_{0.7}$Sr$_{0.3}$MnO$_3$ the spin polarization of $e_g$ – electrons of which is close 100%. For this reason La$_{0.7}$Sr$_{0.3}$MnO$_3$/Y$_1$Ba$_2$Cu$_3$O$_{7-x}$ thin film heterostructures are perspective for spintronic experiments.

It was shown experimentally, that the spin injection process in LSMO/YBCO/LSMO and LCMO/YBCO/LCMO thin film structures can reduce the critical temperature of the structures by up to 15% [4]. It was demonstrated also that the suppression of the critical current density caused by injection of the spin polarized quasiparticles into YBCO thin film through thin insulating SrTiO$_3$ or metallic Au barriers exceeds the suppression caused by the unpolarised quasiparticles by several times [6,10]. In spite of the great efforts of the researchers, many aspects of the physical processes in FM/HTS structures and interfaces remain not clear yet. In this paper we propose to investigate the...
spin-injection process using contactless methods and present our preliminary experimental results obtained in a structure containing HTS YBCO and FM LSMO components.

2. Experimental structure

The RF and DC magnetron sputtering equipments were used for in-situ growing of HTS YBCO and FM LSMO thin films and FM/HTS double-layers on LaAlO$_3$ substrates. The growing procedure and conditions of the HTS YBCO and FM LSMO films and sandwiches were described elsewhere [11,12]. Figure 1 shows a diagram of the YBCO/LSMO structure used in this study. It consists of a thin film HTS YBCO ring, placed on a dielectric substrate, and two electrodes which are used for injection of DC current into the ring. The electrode electrically contacting with the narrow part of the ring was either an HTS YBCO (sample 1) or a FM LSMO thin film strip (sample 2), while the second electrode was an HTS strip for both samples. For preparing of structure 2 first the FM LSMO thin film electrode (with the thickness of ~30 nm) was deposited by RF magnetron sputtering on 10 × 5 mm LAO substrate as a stainless steel mask was used to form a necessary configuration of the electrode during the deposition process. Afterwards the HTS YBCO thin film with the thickness of ~60 nm was grown on the top of this structure. Conventional photolithography and chemical etching were used for patterning of the HTS part of the structure and forming sample 2. Sample 1 consisted of HTS thin film components only.

Measurements were performed at 77 K in liquid nitrogen bath. AC current in the HTS ring was excited by a magnetic field of small coil, placed near the ring. Another small coil was used to register the third harmonics of the response signal, which arises when the current in the HTS ring reaches its critical value. Measurements were performed at different magnitudes of the injected DC current. If the injected DC current is not strong and the patterned structure is absolutely symmetric, it can not affect noticeably the measured value of the critical current, but can affect the parameters of the superconducting ring causing a change of the critical current. The power $W$ associated to electric losses in the samples at 77 K caused by the injected current $I_{inj}$ was small (figure 2) and was not able to affect the temperature of the samples immersed in a liquid nitrogen bath.

3. Results and discussion

The amplitude of the 3-d harmonics $U_{res}$ of the response signal on the amplitude $I$ of the screening current induced in the YBCO ring 1 and 2 as a function of the magnetic field of the driving coil are presented in figures 3 and 4 respectively. It can be seen that the amplitude of the third harmonics of
the response signal is negligible at small amplitudes of the driving current and it increases drastically when the current in the HTS ring reaches its critical value. The critical currents $I_C$ of these samples were 0.024 A and 0.23 A, respectively, in the absence of the injected current $I_{inj}$. The current injection process affects the critical current density (figures 3 and 4). The injected current $I_{inj}$ and the change of the critical current $\Delta I_C$ in each sample can be expressed in dimensionless forms as $I_{inj}/I_C$ and $\Delta I_C/I_C$, respectively. Dependence of the dimensionless critical current density on the normalized injected current strength for both samples 1 and 2 are presented in figure 5.

It can be seen that the effect of the current injection on the critical current of the HTS ring is much stronger for the sample 2 with an LSMO electrode (figure 5) than for the sample 1 with HTS electrodes. Some change of $I_C$ in completely HTS structure 1 at presence of small injected current is possibly due to presence of local unhomogeneities (i.e. weak links) of this sample which are characterized with low critical current densities and non symmetrical positions of these unhomogeneities along the sample. Change of $I_{inj}$ polarity did not cause a noticeable change of $I_C$ for both samples. Possibly this is due partly to great area of the interface, which includes magnetic domains of LSMO with different orientations and leads to some averaging of the effect in sample 2.
There are several microscopic mechanisms of the coupling at the interface of HTS/LSMO structure [2,4,5,8,9] which affect the critical parameters of the HTS component. The proximity effect related to tunneling of Cooper pairs into the non-superconducting FM side can lead to both, a reduction and an oscillation of the critical temperature of the superconducting part of the heterostructure. On the other hand, the large exchange energy of the magnetic layer prevents Cooper pairs from tunneling into the LSMO film and this mechanism is less effective [5] for reduction of the critical parameters of HTS in the structure.

There is also an inverse proximity effect, when spin polarized quasiparticles penetrate into HTS layer on a certain length scale [1,5] of order ~10 nm [5]. According to results of [5] in HTS/manganite structure an existence of a long-range inverse magnetic proximity effect which affects the properties of YBCO films up thicknesses of more than 100 nm is possible as well. The effect is due to the anisotropy of the d-wave parameter, because the coherence length tends to approach infinity in the (110) nodal direction of the YBCO Fermi surface.

The injected current strength and polarity affect the effectiveness of the above processes and leads to modification of the critical parameters of FM/HTS structure. In the last case the changes of the electrical properties of HTS component is possible if a main part of the quasiparticles in the injected current crosses the interface without “losing” their spin-orientations. The spin-diffusion length in cuprate superconductors is of order ~ 10-20 nm [4] or more in some directions. So, a reduction of \( T_c \) and \( J_c \) in HTS can occur in the same length scale in the HTS component of the structure. Above mechanisms provide sensitivity of the critical parameters of HTS film to the current injection process in FM/HTS structures, as it was observed by contactless way in our experiments as well. Because of complexity of the processes in FM/HTS interfaces, additional investigations are required to explain the reflection of the effects related to the injected current polarity on the experimental results.

4. Conclusion
The effect of the current injection (from the LSMO electrode) into an HTS YBCO thin film ring on the critical current density of the ring was investigated at 77 K using contactless method. The structures were prepared using magnetron sputtering, conventional photolithography and wet etching procedures. The critical current density was determined from the third harmonics response of the HTS ring to the AC magnetic field. The experiments demonstrate a sensitivity of the critical current density to the current injection process to the HTS ring, especially in the case of FM LSMO current-injecting electrode, which injects spin polarized quasiparticles into the superconductor.

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