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Magnetic field reversion by SC/FM bilayers in the critical temperature vicinity

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Abstract. The electrical properties of bilayer structures consisting of a superconducting (SC) and a ferromagnetic (FM) layer deposited on a LAO substrate were studied by a contactless technique in the temperature range from 77 K in the vicinity of the critical temperature. Two series of bilayers were investigated: - SC (YBCO) layers with thickness varying from 35 to 80 nm on a FM (LSMO) layer with a fixed thickness of 40 nm, and - a fixed-thickness YBCO layer (70 nm) on LSMO layers with thickness varying from 10 to 40 nm; YBCO layers deposited under the same conditions as reference. An interesting effect was observed, namely, when the temperature is reduced below the critical value, the bilayer inverts the magnetic field passing through it - the signal picked up by the receiving coil inverts its phase. The measurements of the critical current and temperature showed that when the YBCO layer is thicker than the LSMO layer, the latter acts as a buffer layer improving the SC performance. These is in contrast with the results published earlier by other authors on proximity effect and spin injection for bilayers and super lattices of SC/FM layers that are an order of magnitude thinner. The SC performance worsens only in the case when the YBCO and LSMO layers have a thickness of approximately 40 nm.

1. Introduction
Cuprate bilayers of SC over FM deposited on a monocrystal with a matching crystal lattice are interesting from a fundamental [1, 2, 3] as well as experimental [4, 5] points of view; it is also believed that they have a potential for spintronics applications [6]. Most of the experimental work has been performed for superlattices with layer thickness of several nm (lattice cells). They show worsening of the electrical characteristics of SC (compared to the single SC layers), namely a decrease of the critical temperature up to a complete loss of superconductivity [4]. These results are useful for theoretical considerations; however, structures consisting of thicker SC and FM layers are also interesting from a practical point of view.

The aim of the present work is to investigate the electrical properties – critical temperature and critical current density at a given temperature (77 K) - of the bilayer structures YBCO on LSMO on LAO with various thicknesses of the SC and FM layers.

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2. Experiment

The LSMO layers were deposited in an off-axis single RF magnetron sputtering system at a substrate temperature of 780 °C. Immediately after deposition, they were annealed (in the same system) for 30 minutes in a 600 Torr O₂ ambient at 540 °C. The working gas mixture was 50:50 Ar + O₂ at a pressure of 30 mTorr. The YBCO layers were deposited over the LSMO layers in an off-axis dual DC magnetron sputtering system at a substrate temperature of 780 °C. Immediately after deposition they were annealed (in the same system) for 60 minutes in 600 Torr O₂ ambient at 540 °C. The working gas mixture was 70:30 percent Ar + O₂ at a pressure of 300 mTorr.

The critical temperature \( T_{cr} \) and critical current density \( J_{cr} \) were measured by a contactless technique using the dual coil system shown in figure 1.

The \( T_{cr} \) measurements were carried out at the fundamental frequency, while to measure \( J_{cr} \), the third harmonic technique [7] was used.

3. Results

Two groups of samples were prepared and measured. In the first one, the LSMO thickness was varied from 10 to 40 nm, while the YBCO thickness was fixed at 70 nm. Two samples with a YBCO layer only were also prepared and measured and the results were added to those of the first group. In the second group, the LSMO thickness was fixed at 40 nm and the YBCO thickness was varied. The critical temperatures and critical current densities (at 77 K) of the first group are shown in figures 2 and 3.

![Figure 1](image1.png)

**Figure 1.** Measuring contactless technique with dual coil system.

![Figure 2](image2.png)

**Figure 2.** Critical temperatures \( T_{cr} \) for the 70 nm YBCO group of samples.

![Figure 3](image3.png)

**Figure 3.** Critical current densities (at 77 K) for the 70 nm YBCO group of samples.

The critical temperature of the single YBCO layer is somewhat lower than in the case of YBCO over LSMO. The theory predicts in some cases a positive \( \Delta T_{cr} \) due to the contact with the FM [3]. On the other hand, no substantial dependence of the \( T_{cr} \) on the LSMO thickness is observed (within the reproducibility of the experiment). This suggests an alternative explanation – the LSMO acts as a buffer layer and improves the YBCO crystal structure. The critical current density dependence on the FM thickness shows a similar behavior.

The critical temperatures and critical current densities (at 77 K) of the second group are shown in figure 4 and figure 5 respectively.
The SC performance of the bilayers shows a sharp drop at YBCO thickness of 40 nm – the same as of the LSMO underlayer. At higher YBCO thicknesses, the SC electrical characteristics are improved as the SC thickness is raised.

![Figure 4](image1.png)  
**Figure 4.** Critical temperatures $T_{cr}$ for the 40 nm LSMO group of samples.

![Figure 5](image2.png)  
**Figure 5.** Critical current densities (at 77 K) for the 40 nm LSMO group of samples.

A very interesting effect is observed in the plots of the signals picked up during the critical temperature measurements using the dual coil system shown in figure 1. The plots are shown in figure 6 for FM thicknesses 35, 40 and 45 nm.

![Figure 6](image3.png)  
**Figure 6.** Signals picked up during the critical temperature measurements for FM thicknesses: a) 35 nm, b) 40 nm, c) 45 nm.

The phase of the reference signal is chosen so as to give zero sine signal at room temperature; thus, the cosine signal is the main signal. The critical temperature is located at the onset of the diamagnetic screening.

For a thickness of 45 nm, the cosine signal received has the same sign at all temperatures with only its value changing. Similar curves were obtained for thicker bilayers and single YBCO layers, the only difference being a shift in the critical temperature – the temperatures of SC screening onset are shown in figures 2 and 4. In the cases of layers with thickness 35 nm and 40 nm, a temperature interval appears where the received signal changes its sign.

The amount of FM material in the layers studied is too small to produce a measurable magnetic field, as checked at room temperature.
4. Discussion
In 1964, Ginsburg [8] pointed out that the surface of a SC can exhibit properties different from those of the bulk and specific surface SC can exist. A surface related phenomenon was also observed in high-T superconductors [9]. The authors measured the critical temperature using a single coil contactless setup and obtained a higher $T_{cr}$ value when the probe coil was placed on the SC side covered with Ag than when the probe coil was on the opposite side.

The phase sensitive measurements of YBCO layers with thicknesses 35 and 40 nm show that the received signal changes its sign within a certain temperature interval. This means that the averaged magnetic field on the plane of the receiver coil has a direction opposite to the usual case. We assume that this is an effect of surface superconductivity. The latter amplifies the SC response to the external magnetic field; it is overscreened within a temperature interval below but close to the critical temperature when the induced current reaches the critical value.

5. Conclusion
For YBCO thicknesses exceeding that of the LSMO underlayer, the latter acts as a buffer and improves to some extent the electrical SC characteristics.

An unexpected effect is observed. For specific combinations of SC an FM layer thicknesses, the magnetic field changes its direction when penetrating the bilayer structure. This effect arises at temperatures when critical current densities are reached by the diamagnetic currents induced. A sine component appears in the received signal (together with higher odd harmonics [7]). This effect is the result of currents induced in the SC, rather than magnetization of the FM.

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