Point Contact Spectra on YBa$_2$Cu$_3$O$_{7-x}$/La$_{0.7}$Ca$_{0.3}$MnO$_3$ bilayers

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Abstract. We present conductance characteristics of point contact junctions realized between a normal Pt-Ir tip and YBa$_2$Cu$_3$O$_{7-x}$/La$_{0.7}$Ca$_{0.3}$MnO$_3$ (YBCO/LCMO) bilayers. The point contact characteristics show a zero bias conductance peak, as a consequence of the formation of Andreev bound states at the YBCO Fermi level. The temperature evolution of the spectra reveals a depressed zero bias peak and a reduced superconducting energy gap, both explainable in terms of spin polarization effects due to the LCMO layer.

1. Introduction

The investigation of hybrid Superconducting/Ferromagnetic heterostructures aims at understanding the mechanism of electronic transport in the presence of competing superconducting and ferromagnetic orders. This research has also potential technological outlets in the context of spintronics [1]. A major step in the field has been obtained with the discovery of perovskite manganites which exhibit colossal magnetoresistance (CMR) [2]. The possibility of engineering hybrid structures based on these ferromagnetic oxide compounds and high-Tc superconducting materials, opens up appealing perspectives. At the very heart lies the fundamental interest for their physical properties, such as the modification of the density of states (DOS) of the superconducting samples due to the effects of the magnetic layer [3]. Soulen et al. [4] have shown that the Point Contact Andreev Reflection can be used to determine the spin polarization of the ferromagnetic materials. In fact in the presence of a ferromagnetic material the Andreev Reflection probability at the Superconductor/Ferromagnetic (S/F) interface is reduced by the carrier density of the minority spin band at the Fermi level. Many authors have measured the polarization of different ferromagnetic materials using this technique [5].

In this work we analyze the effect of spin-polarized electrons on the tunneling current in a heterostructure constituted by a high-Tc superconductor (YBCO) and a CMR ferromagnetic oxide (LCMO). We observe the presence of both Andreev bound states in the YBCO layer, and spin polarization in the LCMO layer. The zero bias conductance peak, appearing in the conductance spectra due to Andreev bound states at the Fermi level of the superconductor, results to be depressed by a proximity effect induced by the magnetic layer. Our results are well interpreted in the framework of the spin-polarized transport theory.
2. Samples preparation and experimental setup
Highly epitaxial, c-axis oriented $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}/\text{La}_{0.7}\text{Ca}_{0.3}\text{MnO}_3$ (YBCO/LCMO) heterostructures were grown in a pure oxygen atmosphere ($p=3.0$ mbar) on SrTiO$_3$ (0 0 1) substrates (STO) by DC sputtering technique at $T=900^\circ$C (for further details see Refs. [6, 7]). A YBCO film of 500Å was first deposited; then, by defining the geometry through a shadow mask, we sequentially realized a YBCO/LCMO bilayer with thicknesses $d_{\text{YBCO}}=1000$Å and $d_{\text{LCMO}}=75$Å, respectively. The conductance spectra were measured by using a home-built Point Contact Andreev Reflection (PCAR) setup operating from liquid-helium temperature to room temperature. To realize the Point Contact experiments, we used mechanically cut fine tips of Pt-Ir, chemically etched in a 40% solution of HCl in an ultrasound bath. Samples and tips were placed in the PCAR probe and the electrical contacts (two on the tip, and two on the first YBCO basis) were realized by indium drops. In Fig. 1 we show the geometry of the junction and the voltage-current terminals. At low temperature, we established the contact between the Pt-Ir tip and the YBCO/LCMO bilayer using a micrometric screw. The current-voltage ($I$ vs $V$) characteristics were measured by using a conventional four-probe method. A lock-in technique with an ac current of amplitude less than 1μA was used to measure the differential conductance ($dI/dV$ vs $V$) spectra as functions of the applied voltage.

3. Results and discussion
In this section we present the conductance spectra obtained between a YBCO/LCMO bilayer and a Pt-Ir tip. We remark that our transport measurements include two different interfaces, YBCO/LCMO and LCMO/Pt-Ir, both responsible for the profile of the conductance curves. The different contributions can be evidenced for instance in the lowest-temperature spectrum (see the inset of Fig. 2), characterized by an asymmetric, “V”-shaped background, with the presence of a Zero Bias Conductance Peak (ZBCP). The “V”-shaped background, similar to that reported for other metallic oxide junctions [8, 9], is a signature of the LCMO/Pt-Ir junction, while the YBCO layer is responsible for the asymmetry [10]. On the other hand, the ZBCP is a consequence of the $d$-wave symmetry of the superconducting order parameter of YBCO, indicating the formation of the Andreev bound states at the YBCO Fermi level [10, 11, 12]. Moreover, the presence of a ZBCP suggests that our tunnel junction is not completely c-axis oriented, but a component in the a-b plane is present as well.

The nature of the ZBCP can be experimentally investigated by following the temperature evolution of the conductance spectra. In the case of PCAR on pure YBCO, the literature reports a ZBCP decreasing with increasing temperature, and vanishing at the critical temperature of YBCO ($\sim 90$ K) [10]. In our YBCO/LCMO junction (see Fig. 2), we observe instead a depressed ZBCP. According to the theory of spin transport between a ferromagnetic material and a $d$-wave superconductor, the depression of the ZBCP follows from the suppression of Andreev reflections at the interface, due to the spin polarization of the ferromagnetic layer [13].
conductance spectra, the ZBCP disappears at a temperature of about $T_c \sim 30$ K, which is in agreement with the resistivity measurements on YBCO/LCMO bilayers [7]. This fact provides further evidence that the ZBCP is a consequence of the superconducting nature of YBCO and is not due to spurious effects like inelastic tunneling via localized magnetic moments in the barrier region [14].

From our conductance spectra, the amplitude of the superconducting order parameter of YBCO can be inferred as well. Namely, we can fit the background according to the model [15, 16]:

$$G(V) = \frac{dI}{dV} \propto \frac{d}{dV} \int N_{FM}(E)N_{SC}(E+eV)[f(E) - f(E+eV)]dE,$$  \hspace{1cm} (1)

where $N_{SC}$ is the DOS of the YBCO layer, and $N_{FM}$ is the DOS of the LCMO layer. The latter can be expressed as $N_{FM}(E) = N_{FM}(0)[1 + (|E|/\Lambda)^{\eta}]$, where $\Lambda$ is a constant associated with the electron correlated energy of LCMO at the interface and the exponent $0.5 < \eta < 1$ reflects the degree of disorder in LCMO near the YBCO/LCMO interface. Concerning the YBCO, we can assume that, for bias voltages larger than the superconducting energy gap, $N_{SC}$ is approximately constant, except for a linear correction taking into account for the asymmetry of the normal state of YBCO. In a window of bias voltages $V \in [-\bar{V}, \bar{V}]$, the DOS of YBCO can thus be written as $N_{SC} = 1 - \kappa(V + \bar{V})$, where $\kappa$ is the asymmetry factor and the total conductance is normalized such that $G(-\bar{V}) = 1$.

In Fig. 3, we show the lowest-temperature conductance spectrum, together with the best fitting curve for the background, following Eq. (1). The superconducting energy gap of YBCO corresponds to the bias voltage at which the theoretical curve for the background deviates from the experimental conductance spectrum. From Fig. 3, we can estimate an energy gap $\Delta \sim 8$ meV. The contribution of the YBCO layer to the conductance characteristic can then be obtained dividing the measured differential conductance (at the lowest temperature) by the modeled background curve: $G_{YBCO}(V) = G(V)_{exp}/G(V)_{back}$. We can satisfactorily fit the spectrum $G_{YBCO}(V)$ with a $d$-wave BTK model [12], regarding as fitting parameters the

**Figure 2.** Temperature dependence of a highly stable junction between the YBCO/LCMO bilayer and the Pt-Ir tip. We notice that a ZBCP appears at low temperatures and disappears at about 30K. The lowest-temperature spectrum is detailed in the inset.

**Figure 3.** The conductance spectrum with the fitted background. In the inset the YBCO conductance curve is shown with the best fit with $d$-wave symmetry of the order parameter.
superconducting gap \( \Delta \), the barrier strength \( Z \), the angle \( \alpha \) of the order parameter and the smearing factor \( \Gamma \). Remarkably (see the inset of Fig. 3), the fitting provides a gap \( \Delta = 8 \) meV, consistent with our previous findings. This value, smaller than the reported gap value of 20 meV for YBCO [10], can be explained by the proximity effect of the Cooper pairs from YBCO to LCMO, or by the injection of spin-polarized electrons from LCMO to YBCO [16].

It has been theoretically predicted that, in a S/F interface, the amplitude of the spin polarization of the ferromagnetic layer can be estimated from the temperature dependence of the ZBCP. The latter is expected to be proportional to the inverse of the temperature for intermediate temperatures [18]. In Fig. 4 we show the temperature dependence of the ZBCP as obtained by the experimental conductance spectra of Fig. 2, together with the best fitting curve. With an extrapolation of the best fitting curve at low temperatures \( (T \to 0) \), we can directly compare our ZBCP evolution to the theoretical model of Ref. [18]. This allows us to estimate a spin polarization of the LCMO layer of about 67%, meaning that the electron spins are not fully polarized. This is consistent with the observation of a (depressed) ZBCP: in fact, it would have been completely suppressed if the LCMO polarization had approached unity.

In conclusion, PCAR measurements on the heterostructure constituted by a YBCO/LCMO bilayer and a Pt-Ir tip have resulted in conductance spectra with a ZBCP, signature of the \( d \)-wave symmetry of the order parameter of YBCO. A reduced height of the ZBCP, as compared to the case of superconductor/normal metal junctions, has been observed. We have shown that this effect is due to a partial polarization of the LCMO layer.

A deeper analysis of the effects of one or more magnetic layers on the superconducting properties of high-Tc compounds awaits further investigation.

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