

Influence of d-wave pairing on electrical properties of d_0 - d_0 submicron $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ bicrystal grain boundary junctions

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Abstract. We have fabricated submicron $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ grain boundary junctions using [100] tilt bicrystal substrates. In these substrates, crystal planes are tilted around the b-axis, parallel to the bicrystal line. We have obtained high-quality junctions and fitted experimental data using a recently theory accounting for d-wave symmetry of the order parameter in layered superconductors with arbitrary orientation. In our experiment, sensitive to the amplitude of the pairing state, lobes of different signs do not influence the electrical transport in the junction. Nevertheless, the effects of a non-conventional symmetry are clearly observed on the temperature dependence of the critical current.

Since their discovery, an impressive number of papers dedicated to the understanding of physical mechanisms in high-critical temperature superconductors has been produced. Among these materials, intensive studies have been pursued on $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ (YBCO) superconductor, that has generated large curiosity in the researchers, because of its complicated phenomenology. One of the methods largely used for analyzing properties of superconductive materials is the Josephson effect [1]. The study of the Josephson effect allows the analysis of several electrical and magnetic phenomena, mirroring intrinsic properties of the junction. Typically planar technologies, used for the fabrication of tunnel junctions with conventional superconductors, generally failed. Indeed, the coherence lengths extremely short in YBCO, of the order of 2 nm in the plane and even shorter along the c-axis, forced the scientific community to look for alternative techniques for the fabrication of Josephson devices. Since then, several technologies have been introduced, as for instance junctions known as step-edge [2], ramp-edge [3], or grain boundary junctions [4]. The simplest and most used method was the fabrication of grain boundary junctions (GBJs) through the employment of bicrystal [4], tricrystal [5], or tetracrystal [6] substrates. This was also the fastest method for fabricating YBCO junctions and starting the analysis of electrical properties of such fascinating superconductors. Thanks to such technologies, most of exotic properties have been determined. In particular, the most important difference with respect conventional superconductors is the d-wave symmetry of the order parameter, in the form $d_{x^2-y^2}$ [7]. This important result has been determined through phase-sensitive experiments using peculiar properties of dc-SQUIDs [5,7,8] (Superconducting Quantum Interference Devices) or rf-SQUIDs [9]. About this point, more than one convincing experiment has been carried out. However, to date, whether the symmetry of the order parameter in YBCO is fully represented by a $d_{x^2-y^2}$ symmetry [5, 10] or small components of other symmetries [11] are present, is still matter of debate. A step forward



the understanding of physics of YBCO junctions came from the introduction of nanotechnologies. Indeed, as long as qualitative phase-sensitive tests are the core of the experiment, the use of junctions with micrometric dimensions is adequate. However, once experiments involve quantitative measurements, micrometric grain boundary junctions do not guarantee reliable devices with repeatable properties. Considering the difficulties for fabricating sub-micron YBCO devices, only few experiments involving these type of junctions are available in the literature, see for instance [9, 12, 13]. Moreover, as far as we know, the literature is lacking of experiments testing the amplitude of the order parameter, which is a quantitative test. In the present paper we show experiments on the temperature dependence of the critical current ($I_c(T)$) for submicron YBCO GBJs, in which the transport of the Josephson current is regulated only by d-wave lobes with the same sign (d_0 - d_0 junctions). In such structures, the relevant phases never change sign and we show that different electrical behaviors, with respect conventional s-wave symmetries, can be ascribed exclusively to the different symmetry itself and, more specifically, to the presence of nodes in the pairing state function.

The behaviour of the temperature dependence of the critical current strongly depends of interface properties. The shape, as well as the slope of the $I_c(T)$ curves and its anomalies are direct expression of both the superconducting gap at the interface and the current-phase relation in the junction. Essentially, $I_c(T)$ behaviors can be fitted by theoretical expressions only if the interface properties for that junction are well known (for an extended review, see [14]). In particular, relevant parameters at the interface influencing the current-phase relation of the Josephson current are the pairing state, the barrier transparency, the dispersion relation of quasiparticles crossing the barrier, etc. On the contrary, for phase-sensitive experiments, only considerations based on general aspects of the Josephson effect are necessary [7].

We have fabricated [100] tilt submicron YBCO bicrystal grain boundary junctions, as shown in Fig. 1. We would like to outline here that, in such a junction configuration, the positive lobes of the two electrodes are aligned along a direction perpendicular to the junction interface (d_0 - d_0 junctions). In the particular case of YBCO junctions, the effect on the transport critical current coming from the nodes of the order parameter should be manifested. Based on previous experiments carried out on bicrystal YBCO GBJs, in order to have a deterministic behaviours of the

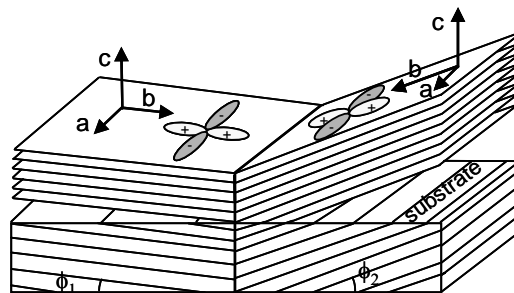


Fig. 1 Scheme of [100] tilt bicrystal geometry. For the experiment we used $\phi_1 = 0$ and $\phi_2 = 45^\circ$

transport current, we developed a suitable technology for fabricating submicron junctions [15]. We have fabricated [100] tilt submicron YBCO GBJs starting from high-quality YBCO films deposited by DC diode on [100] 45° tilt bicrystal substrates. Films showed zero-resistance critical temperatures in the range 89-91 K. Electrodes 100 nm thick are covered by a Au cap layer 20 nm thick. Nanolithography is obtained by lift-off technique of Ti/Au bilayer (100 nm/10 nm in thickness) deposited on PMMA resist, previously exposed through an electron beam lithography [15].

Another important aspect for setting up our experiment was certainly the theoretical framework. Indeed, many theoretical models have been developed for describing the phenomenology of high-temperature superconductive junctions. In particular, it is worth mentioning the work by Tanaka and Kashiwaya [16] describing the electrical transport in d-wave junctions constituted by YBCO electrodes with their c-axis perpendicular to the substrate plane. Starting from the Bogoliubov-de

Genes equations, the authors describe the transport of quasiparticles across a barrier with arbitrary transparency. Although very complete, using their theory for describing [100] tilt YBCO junctions was not an immediate task, because in our case the c-axis (only one or both of them) are tilted with respect the substrate surface. Similar considerations apply in the case of other theoretical approaches as well, see for instance [17]. Then we decided to develop an original theoretical model for describing the electrical transport in this specific case [18]. Although some differences exist, we can consider our model as an extension of the theory by Tanaka and Kashiwaya [16]. Indeed, we have solved the Bogoliubov-de Gennes equations in the case of twofold-tilted Josephson junctions made by pure d-wave anisotropic layered superconductors, i.e. YBCO. The misalignment of the superconductive YBCO planes in the two electrodes (angles ϕ_1 and ϕ_2 in Fig. 1) is responsible for the appearance of an intrinsic electrical resistance in the junction, producing an effective barrier given by:

$$Z_{eff} = \sqrt{[4Z(\theta)^2 + (\cos \phi_1 - \cos \phi_2)^2] / 4 \cos \phi_1 \cos \phi_2} \quad (1)$$

where $Z(\theta) = Z_0 \cos \theta$, and Z_0 is the barrier amplitude parameter [18]. With this approach we find the Andreev bound states at the junction interface [18]. Then, the Josephson current is derived using the following expression:

$$I_x(\varphi, \phi_1, \phi_2) = \frac{2e}{\hbar} \frac{k_F L_y}{2\pi} \sum_n \int_{-\pi/2}^{\pi/2} d\theta \cos(\theta) \frac{dE_n(\theta, \varphi)}{d\varphi} f[E_n(\theta, \varphi)] \quad (2)$$

where the index n labels the bound Andreev energy levels, θ is the quasiparticle incidence angle, e is the electron charge, \hbar is the Plank constant divide by 2π , k_F is the Fermi momentum, L_y is the GB length, and $f[E_n(\theta)]$ is the Fermi function. Using Eq. 2 we can derive the temperature dependence of the critical current for d-wave junctions with arbitrary orientations. Similarly, in order to compare our results with conventional s-wave junctions, we have found the Andreev energy states for layered s-wave superconductors. With this tool in our hands we can describe the $I_c(T)$ behaviors for any d-wave or s-wave junctions, with electrodes oriented arbitrarily, and arbitrary barrier transparency.

We have measured the $I_c(T)$ behaviors of several [100] tilt YBCO GBJs with submicrometer dimensions. In Fig. 2 we show the current voltage characteristics (IV) of a junction $0.3 \mu\text{m}$ wide at several temperatures. In the inset, the $I_c(T)$ behavior (open dots) and the fit (solid line) obtained from Eq. (2) are shown respectively. The only free parameter is the barrier transparency Z_0 . The agreement with experimental data is obtained in the clean limit ($Z_0 = 0$), that implies that the junction behaves as a SNS structure, where N indicates a vanishing size normal layer. No fit was possible with low-transparency barriers or using conventional s-wave symmetries. We also have measured the $I_c(T)$

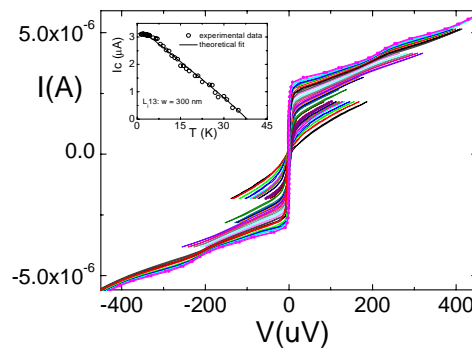


Fig. 2 Current-Voltage characteristics at several temperatures for a junction $0.3 \mu\text{m}$ wide. In the inset the $I_c(T)$ behavior (open dots) and the fit (solid line) using Eq. 2 are shown.

dependence of another junction $0.7\ \mu\text{m}$ wide on the same chip, that showed similar behavior than reported in Fig. 2 [15]. It is important to outline that all the junctions on the chip showed a linear dependence of the critical current vs the junction dimension, giving a best fit value for the critical current density $J_c = 7.62 \times 10^3\ \text{A/cm}^2$. This aspect confirms the high-transparency of barriers in our junctions and the uniformity of our devices along the substrate.

In conclusions, we have developed a suitable technique for fabricating high-quality d_0 - d_0 submicron YBCO bicrystal junctions, showing high-transparency barriers. In this geometry, no effect due to the different signs of the d-wave lobes is expected. Hence, the electrical transport is sensitive only to the amplitude of the order parameter. The $I_c(T)$ behaviors have been described starting from Andreev energy states at the interface. A very good agreement between experiment and theory has been obtained, confirming the influence of nodes in the pairing state on the electrical transport in the junctions.

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