Fabrication and properties of sub-micrometric YBCO biepitaxial junctions

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Abstract. We report on the fabrication procedure and the transport properties of submicron grain boundary biepitaxial YBCO Josephson junctions. These first results are very encouraging and justify further expectations on improved performances for such types of devices. A reduced and more controlled faceting along the grain boundary interface, for instance, will better preserve intrinsic d-wave effects, and favour the study of fluxons dynamics.

1. Introduction

Among the properties of HTS materials, one of the most interesting, especially for electronic applications, is the anisotropy of the order parameter. Since the reckoning of the d-wave symmetry of the HTS order parameter [1], many devices taking advantage of such symmetry have been proposed [2]. One of the unique cells is the π-ring characterized by a naturally degenerate ground state, and the spontaneous generation of the half flux quantum[1,3].

Until now, applications based on HTS junctions have been hindered by the quality and poor reproducibility of the devices [4,5]. A common way to obtain HTS Josephson junctions exploits the weak coupling properties of grain boundaries (GBs), where two different crystalline orientations of the superconductor connect. It is very difficult to control the multiple growth mechanisms taking place at GBs. Besides the presence of impurities, alien and non conductive phases, the GB is also affected by the formation of facets whose unpredictable distribution is one of the main responsible for the lack in reproducibility of the junctions’ properties [4]. Facets in the GB line also bring to the generation of randomly distributed semifluxons, as was demonstrated with scanning SQUID measurements [5-7].

In this work, we focus on all-HTS off-axis biepitaxial junctions. This type of junctions have already shown high quality properties, favorable for various “electronic” applications [8-10], controlled by the d-wave symmetry of the order parameter [9]. Of course, disorder in these junctions is still present; the key, in our opinion, is that the off-axis structure is less sensitive to it and determines a tunnel-like low transmissive barrier. More recently, macroscopic quantum tunneling and energy level quantization were also demonstrated in these junctions [10]. Nevertheless, in the view of electronic applications and for a deeper understanding of the mechanism behind GB transport, it is essential to improve the yield and reproducibility of the devices and also to find the way to get more control over junctions structure.
Figure-1. I-V curves of sub-micrometric junctions (width w=0.8µm): (a) device 11a (b) device 11c; both measurements were taken at T=0.3K in zero applied magnetic field. In the inset of panel (a) the junctions’ structure is sketched. (c) Simulation of a 2 facets junction with α=0.2 using eq. (1) in normalized units (as explained in the text).

A possible strategy to realize more predictable structures could be the reduction of the junctions’ size. The facets in the GB line, for example, are known to be long hundreds of nanometers; therefore a junction with width in the same range will likely include a few facets, aiming to single facet structures. To realize this simple idea is not easy. Nanotechnology applied to HTS devices has to face many problems related to the sensitivity of the materials, to oxygen desorption, to their complex structure and to far from perfect films (when compared to metals for which these technologies were developed). Indeed, in the literature only few examples of sub-micron HTS junctions are present [11, 12]

In this work we present sub-micron off-axis biepitaxial junctions. We will briefly review the fabrication process, and then focus on the transport properties.

2. Junctions’ structure and fabrication

The structure of the off-axis biepitaxial junctions is showed in the inset of Fig.1a. The junctions are characterized by an off-axis electrode realized with a (103) oriented YBa$_2$Cu$_3$O$_{6+x}$ (YBCO) film grown on (110) SrTiO$_3$ (STO) substrate, while the other electrode is a (001) YBCO film grown on (110) CeO$_2$ seed layer. Patterning the seed layer it is possible to change the reciprocal orientation of the electrodes spanning the whole coupling range between the two order parameters. In Fig. 1a two misorientations are showed, 0° and 90° (tilt and twist respectively). An important feature is also the 45° tilt around the c-axis the (001) YBCO film undergoes. This feature allows a better “use” of the d-wave symmetry.

The fabrication procedure involves a first patterning step to shape the seed layer and a second to define the junctions’ bridge. These steps were carried out using e-beam lithography and a carbon mask technique [11]. The fabrication of the carbon mask and more details about the whole process will be reported elsewhere. Junctions of width going form 0.6 to 1.5µm were realized, also with different thickness of the YBCO film.

The transport properties of the junctions were measured down to 0.3K using a standard four probe technique. During the measurements the samples were magnetically shielded using two superconducting screens and a cryoperm screen. Noise reduction was obtained thanks to RC filters and two stages of low-pass copper-powder filters. The magnetic behavior of the devices was also studied applying a magnetic field in the plane of the junction.

3. Results

The junctions have maximum critical current density $J_c$ and product $I_cR_N$ in the range of $10^3$ A/cm$^2$ and 1mV respectively. These values correspond to the lobe versus lobe configuration (for misorientations of 50°-60°), in agreement with the theory and previous works [8, 9] and are
and the flux quantum), lengths \( l = 10 \) the critical current and \( \gamma \) is a coefficient related to the current distribution and is \( \approx 10 \) the Stewart-McCumber parameter), these features lead to the classification of the steps as Fiske resonances [13]. The mechanism (with \( \beta \), is larger than one. In the case of the junctions showed in Fig. 1, \( \beta \) times are normalized to zero bias (taking into account also the junction’s dissipation):

\[
\varphi_{xx} - \varphi_{tt} + \alpha \varphi_t + \epsilon(x) \sin \varphi = \gamma
\]

with boundary conditions: \( \varphi(0,t) = \varphi(l,t) = \eta \). In this equation times are normalized to zero bias plasma frequency \( \omega_0 = \sqrt{2\pi I_0 / C\Phi_0} \) (with \( I_0 \) the critical current and \( \Phi_0 \) the flux quantum), lengths to the Josephson penetration depth \( \lambda_J \), \( \eta = (2\pi \mu_0 \lambda_J / \Phi_0)B \) is the normalized magnetic field, \( \alpha = 1 / \eta = 1 / \sqrt{\beta} \) is the normalized normal conductance (with \( \beta \) the Stewart-McCumber parameter), \( \gamma = I_b / I_c \) is the normalized bias current, \( \epsilon(x) \) is a coefficient related to the current distribution and is positive for conventional facets and negative for \( \pi \) ones. An example of an \( I-V \) characteristic calculated using eq. (1) is presented, in normalized units, in panel Fig. 1c. This simulation was obtained for a junction with 2 equal facets and dissipation \( \alpha = 0.2 \). There is a very good qualitative agreement with the \( I-V \) plots measured for our junctions. It is important to stress that the investigation of semifluxons in HTS Josephson junctions has never been possible up to now due to the high dissipation of the structures and to the large number of facets, with uncontrolled structure.

The high quality of the junctions is testified also by their magnetic behavior. In figure 2a the critical current vs. applied magnetic filed pattern of device 11c is showed (black dots). The pattern has comparable with data available in the literature for other types of GB junctions [9]. This result is per se very positive, since it means that the submicron fabrication procedure did not damage the HTS film transport properties. All the realized junctions show steps in their \( I-V \) characteristics (measured in zero applied field). Examples are shown in panels (a) and (b) of Figure 1. The voltage position of these steps is between 100 and 600\( \mu \)V. The junctions, moreover, belong to the “long” type. A Josephson junction is called “long” when its normalized length \( l \), that is the ratio between the width \( L \) and the Josephson penetration depth \( \lambda_J \), is larger than one. In the case of the junctions showed in Fig. 1, \( l \geq 3 \). These features lead to the classification of the steps as Fiske resonances [13]. The mechanism responsible for the formation of the steps in the \( I-V \) curve is, from a phenomenological point of view, the following: the current injected in the junction promotes the creation of fluxons at the two edges of the junction’s bridge. These start to travel along the GB towards opposite ends. If the junctions is composed of two facets, with a spontaneous semifluxon sitting at the central corner, when the fluxons reach the center interact with the semifluxon. This results in the flipping of the semifluxon polarity and in the reflecting of the fluxons at the facets boundary.

This dynamics can be simulated calculating the Sine-Gordon equation for the phase difference \( \varphi(x,t) \) (taking into account also the junction’s dissipation):

\[
\varphi_{xx} - \varphi_{tt} + \alpha \varphi_t + \epsilon(x) \sin \varphi = \gamma
\]

A) magnetic pattern of device 11c measured at 0.3K (black dots) compared with the pattern simulated for a 2 asymmetric facets junction. Panel (b) shows a comparison between our data and HTS junctions properties available in literature.

Figure 2. Panels (a): magnetic pattern of device 11c measured at 0.3K (black dots) compared with the pattern simulated for a 2 asymmetric facets junction. Panel (b) shows a comparison between our data and HTS junctions properties available in literature.
a Fraunhofer-like shape, with an absolute maximum of the \( I_c \) at zero magnetic field. The multiple and irregular lateral lobes often observed in GB junctions [4] are missing. These are hints of a clean barrier structure. Indeed, we compare the data with the simulated magnetic pattern of a 2 (asymmetric facet junction, showed in red in Fig. 2a, with a good agreement.

Finally, in Fig. 2b we present a comparison between the main transport parameters of the sub-micron biepitaxial junctions and data available in literature for other types of HTS junctions [4, 5, 12, 13]. The junctions presented in this work have properties that are comparable even to micron-size junctions; therefore we can affirm that the nanofabrication procedure did not harm the junctions’ transport. Moreover, as was shown in this section, this new fabrication procedure allowed to realize junction with a more controllable structure.

4. Conclusions

From the transport properties of the sub-micron biepitaxial junctions presented, we can conclude that the nanotechnology route is a feasible one for the realization of higher quality HTS junctions. We showed that a careful processing technology does not damage the transport properties of the devices. Moreover, the junctions realized show relative low dissipation. This, together with a more ordered GB structure involving only two facets, allows the study of semifluxions dynamics. This study is not only a tool to investigate the junctions’ properties but could also bring to a better understanding of how to manipulate semifluxions in the view of possible electronics applications.

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