

Characterization of YBCO/STO/YBCO and YBCO/Au/YBCO Junctions

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Abstract

We have made YBCO/STO/YBCO edge junctions and YBCO/Au/YBCO step edge junctions by pulsed laser ablation using an all *in-situ* technique. The working junctions showed T_{co} between 80 K and 90 K and J_c (77 K) in the range of $10 - 10^4$ A/cm². Clear Shapiro steps were observed at temperatures up to 85 K. The normal resistances of these junctions with SrTiO₃ barriers were much lower than one would naively expect and the resistances of the junctions with Au barriers were much higher than one would naively expect. In both cases the junction resistance was approximately $1 \Omega\text{-}\mu\text{m}^2$. This value for the resistance is similar to that reported by other groups who have made high T_c junctions using a variety of barriers.¹ In this paper we show that this resistance comes close to the minimum resistance allowed by quantum mechanics.

Introduction

Many materials systems have been studied in order to find one which allows for the reproducible fabrication of high quality high T_c junctions. These studies have yielded a number of puzzling results concerning YBCO junctions. One of these puzzles is that the Josephson coupling is much stronger in the planes than perpendicular to the planes. This cannot be simply explained by the well-known anisotropy in this material.² Another puzzle is that no true tunnel junctions have been made even when the coupling is along the planes. When one attempts to make an SIS junction using YBCO electrodes, the resistance is typically lower than one would expect judging from the measured resistivity of the barrier material. Junctions with SrTiO₃ and PBCO barriers fall in this category. On the other hand, when one attempts to make an SNS junction using YBCO electrodes, the resistivity is higher than one would expect from the resistivity of the normal metal. The junctions made with high resistivity barriers and those coupled with low resistivity materials share a few common features. When one optimizes the junctions for a reasonably low critical current density, fairly reproducible, RSJ-like junctions result. When one strives for high critical current densities, the results are less reproducible and there are indications that the critical current densities are not uniform in the junctions. Nevertheless, there are occasionally tantalizing indications that if the high current density junctions could be made controllably, that junctions could be made with an $I_c R_N$ product of about 10 mV at 77 K. In the high critical current density limit, the lowest resistances measured for the junctions are about $0.1 \Omega\text{-}\mu\text{m}^2$ for all sorts of junctions. A major point of this paper is to show that there is a minimum junction resistance allowed by quantum mechanics and that the measured value of the resistance in all sorts of high current density junctions are very close to this limit.

Fabrication

Junctions using a high resistance barrier material, YBCO/STO/YBCO edge junctions, and junctions using a low resistance metallic coupling, YBCO/Au/YBCO step edge junctions, were both made by

pulsed laser ablation using an all *in-situ* technique. Briefly, the YBCO/STO/YBCO junctions³ were made by depositing a c-axis oriented YBCO/SrTiO₃ bilayer onto half of a [100] SrTiO₃ substrate, while the other half of substrate was covered by a 0.12 mm thick SrTiO₃ mask. The SrTiO₃ mask was then removed and a thin barrier layer of SrTiO₃ and a top electrode of YBCO were deposited. The typical thickness of the base YBCO electrode was 400 - 600 nm, the top YBCO electrode was 200 - 300 nm, the SrTiO₃ insulating layer was 300 - 400 nm, and the SrTiO₃ barrier was 0 - 20 nm. A schematic drawing of these junctions is shown in Fig. 1a.

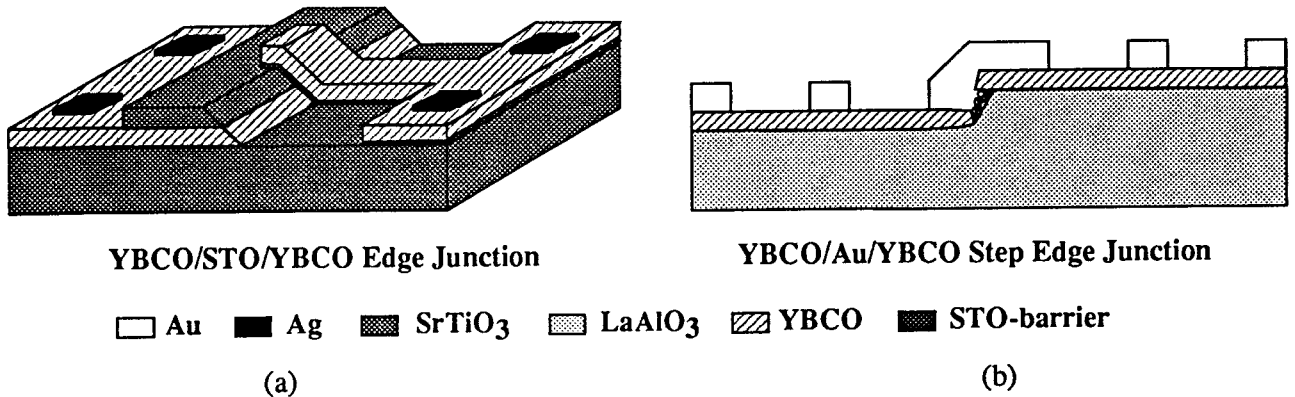
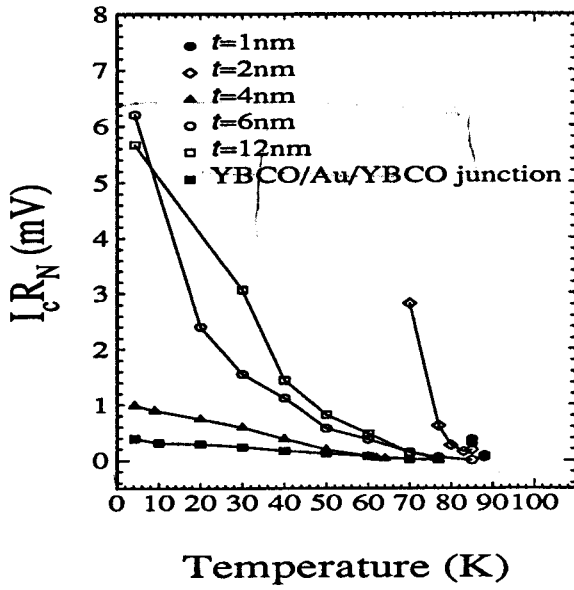


Fig. 1. Schematic drawings of the multilayer YBCO/STO/YBCO edge junction (a) and the step edge YBCO/Au/YBCO junction (b). The "boulders" in (b) at step are copper oxides.

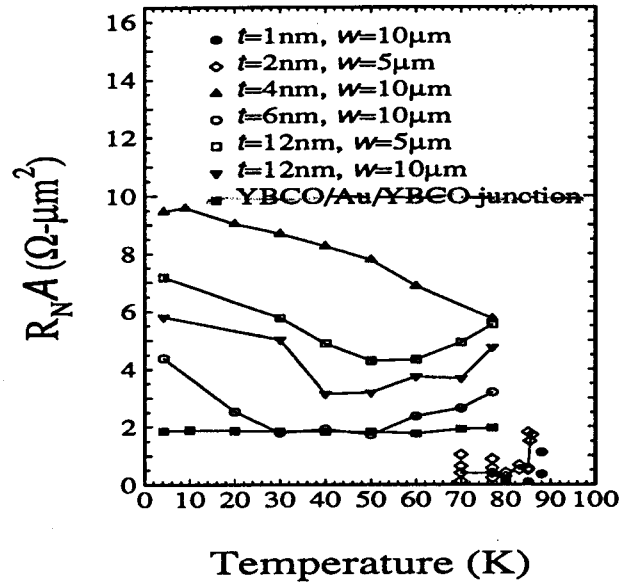
The YBCO/Au/YBCO junctions were also made by an entirely *in-situ* technique. First steps, 300 - 400 nm deep were etched in an [001] LaAlO₃ substrate by Ar ion milling using a metal mask. The YBCO was then ablated at an angle so that a shadow gap was formed at the step. The thickness of the YBCO layer was typically half that of the step. The cross-sectional transmission electron micrographs (TEM), local energy dispersive x-ray (EDAX) and the electrical measurements all showed that there was no YBCO film connection over the steps. There were, however, copper oxides in the gap between the two regions of YBCO. Finally, a 200 nm thick Au film was ablated at another angle on top of YBCO in the same vacuum cycle. This resulted in the YBCO/Au/YBCO structure shown in Fig. 1b.

Six SQUIDS and fourteen junctions with widths of 3 μm , 5 μm , 10 μm , 15 μm , 20 μm , 30 μm , and 50 μm were defined on each chip by means of conventional wet etching. Typically, the YBCO electrodes had zero-resistance transition temperature, T_{co} , around 88 - 92 K and critical current density at 77 K, $J_c(77\text{ K})$, of 10^6 A/cm^2 . The total time to fabricate these high- T_c junctions using the *in-situ* technique was several hours and the yield of working junctions was above 50 %. The working junctions usually showed T_{co} between 80 K and 88 K for YBCO/STO/YBCO edge junctions and between 86 K and 90 K for YBCO/Au/YBCO step edge junctions. The dc SQUIDS showed magnetic field modulation at temperatures from 4.2 to 82K. The critical current densities could be varied in the range $J_c(77\text{ K}) \sim 10 - 10^4\text{ A/cm}^2$. For the high current density junctions the lowest resistances that were reached both for the YBCO/STO/YBCO and the YBCO/Au/YBCO junctions were $0.1\ \Omega\text{-}\mu\text{m}^2$. The reason these two types of junctions have the same resistances is explained in the next section.

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(a)



(b)

Fig. 2. (a) The $I_c R_N$ product as a function of temperature (b) The resistance of several junctions as a function of temperature. For YBCO/STO/YBCO edge junctions, the thickness of the barriers, t , and the width of the junctions, w , is given in the legend.

Sharvin resistance

The standard expression for resistance is, $R = \rho \ell / A$, where R is the resistance, ρ is the resistivity, ℓ is the length of the sample and A is the cross sectional area. In this formula the resistance goes to zero as ℓ goes to zero. In 1965 Sharvin⁴ showed that the resistance does not go to zero for as $\ell \rightarrow 0$. In this limit the resistance becomes independent of length and inversely proportional to the area. Sharvin gave a the following formula for the resistance of short constrictions,

$$R = \frac{h}{2e^2} \frac{4\pi}{k_F^2 A}$$

Here $h/(2e^2) \approx 13 \text{ k}\Omega$ is the resistance quantum, and k_F is the Fermi wavevector. The application of this formula is a bit problematic for YBCO since one cannot say that there is a clearly defined Fermi wavevector in this material. If one ignores this complication and calculates the Fermi wavevector from the carrier density one finds that minimum resistance for a junction with YBCO electrodes is roughly $0.02 \text{ }\Omega\text{-}\mu\text{m}^2$. This minimum allowed resistance is independent of the barrier material of the junctions; it is a property of the electrodes. Comparing this to the lowest measured resistance of $0.1 \text{ }\Omega\text{-}\mu\text{m}^2$ and allowing for the fact that the conduction is not uniform in these junctions, one sees that the measured resistance comes quite close to the estimate for the Sharvin resistance. Note that the Sharvin resistance for junctions with YBCO electrodes is higher than the Sharvin resistance for most metals since YBCO has a low carrier density.

Sharvin was considering the case where there is no scattering in the constriction. Thus if one is using a high resistance barrier material in an attempt to make an SIS junction and the resistivity

comes within an order of magnitude of the Sharvin resistance then the junction is not just leaky; it is shorted. Any description in terms of tunnelling would fail. For SNS junctions there has been some speculation that since the junction resistance is much higher than what is expected from the resistivity of the normal metal, there must be some large resistance at the SN interface. Certainly boundary resistances can play a role but if junctions can be made with resistances on the order of $0.02 \Omega\text{-}\mu\text{m}^2$ then it must be the Sharvin resistance which dominates the junction resistance.

Figure 2a shows the $I_c R_N$ product as a function of temperature. Low current density junctions of any kind typically have a mildly temperature dependent $I_c R_N$ product which is much lower than the optimal $I_c R_N$ product that can be calculated from the presumed gap of YBCO. Note that the $I_c R_N$ product of the high current density junctions rise quickly with decreasing temperature. Since the resistance of these junctions is approaching the Sharvin resistance, one must conclude that YBCO shorts are responsible for conduction through these junctions. This view is supported by the magnetic diffraction patterns which indicate that the critical current density is not uniform throughout the junctions. In Fig. 2b, the resistance is plotted as a function of temperature. The resistance is largely temperature independent as it would be for a quantum process such as tunnelling. However, the resistance does not increase exponentially with barrier thickness as it should for tunnelling. Again this suggests that conduction takes place through a collection of shorts. If a method can be found to make a controllable array of YBCO shorts, junctions with high $I_c R_N$ products might be obtained.

Conclusions

We have fabricated and measured both YBCO/STO/YBCO and YBCO/Au/YBCO junctions. In the limit of high critical current density we find that both kinds of junctions have a resistance lower limit of about $0.1 \Omega\text{-}\mu\text{m}^2$. This resistance is on the order of the Sharvin resistance which is the lowest resistance for the junctions that is allowed by quantum mechanics. If the resistance of a nominally SIS junction is on the order of the Sharvin resistance one can eliminate the possibility that conduction occurs via tunnelling. The Sharvin resistance can also play a role in SNS junctions where it results in higher than expected resistances. Junctions with YBCO electrodes have a higher Sharvin resistance than junctions composed of most other metals because of the low carrier density in YBCO.

References

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