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# Intrinsic Josephson junctions in mesas and ultrathin BSCCO single crystals: Ultimate control of shape and dimensions

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**Abstract**

We describe experiments which are only possible through an ultimate control of sample shape and dimensions down to nanometer scale whereby transport measurements can be done in various restricted geometries. We use photolithography patterning together with a flip–chip technique to isolate very thin ($d \sim 100$ nm) pieces of $Bi_2Sr_2CaCu_2O_{8+\delta}$ (BSCCO) single crystals. Ar-ion milling allows us to further thin these crystals down to a few nanometers in a controlled way. With decreasing thickness below two to three unit cells, the superconducting transition temperature gradually decreases to zero and the in-plane resistivity increases to large values indicating the existence of a superconductor–insulator transition in these ultrathin single crystals. In a refined technique, a precise control of the etching depth from both sides of the crystal makes it possible to form stacks of intrinsic Josephson junctions (IJJs) inside the ultrathin single crystals. The stacks can be tailor-made to any microscopic height (0–9 nm < $d$), i.e. enclosing a specific number of IJJs (0–6). In certain geometries, by feeding current into the topmost $Cu_2O_4$-layer of a mesa on the surface of a BSCCO single crystal, we measured the critical value of this current by detecting a sharp upturn or break in the current–voltage characteristics. From this, we estimate the sheet critical current density of a single $Cu_2O_4$ plane to be ~0.3–0.7 A/cm at 4.5 K, corresponding to a bulk current density of ~2–5 MA/cm$^2$. These values are among the largest ever reported for BSCCO single crystals, thin-films and tapes.


*Keywords:* Intrinsic Josephson junctions; Critical current; Superconducting gap

## 1. Introduction

Intrinsic Josephson junctions (IJJs) [1] have proved to be useful in both basic studies on high-temperature superconductors (HTS) and have shown characteristics that are promising for future applications [2,3]. The intrinsic Josephson effect naturally exists in highly anisotropic layered HTS single crystals, like $Bi_2Sr_2CaCu_2O_{8+\delta}$ (BSCCO). The electric transport perpendicular to the well-conducting (and superconducting) $Cu_2O_4$ layers in such materials occurs via the sequential tunneling of quasi-particles (and Cooper pairs) through insulating Bi–O and Sr–O layers. A BSCCO single crystal in the $c$-axis direction can thus be viewed as a one-dimensional array of superconductor–insulator– superconductor (SIS) Josephson junctions. This is perhaps the first known example of Josephson junctions that are entirely made of single-crystalline media and is also the only reliable way to obtain HTS SIS junctions.[1]

Here, we review our recent experiments on stacks of IJJs both on surfaces of single crystals and also imbedded in tiny-thin pieces of single crystals. A refined flip–chip technique involving calibrated low-energy and current Ar-ion etching intermitted by complete $I$–$V$ characterization of the samples allow tailor-making stacks enclosing any low number of IJJs, down to one. The precise control of sample shape and dimensions down to nanometer scale made it possible to measure superconducting properties of a single IJJ or a single $Cu_2O_4$ plane therefore significantly reducing adverse effects of self-heating or crystal-lattice defects.

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[1] Another example is epitaxial NbN/MgO/NbN Josephson junctions, see Ref. [4].

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## 2. Samples

### 2.1. Simple mesas

Shortly, our fabrication process is as follows. First, we deposit a gold layer on a freshly-cleaved BSCCO single crystal glued to a substrate by polyimide or epoxy. Mesas from a few-up to several tens of μm large can be formed by conventional photolithography and Ar-ion milling. An insulating layer of $CaF_2$ or $SiO_x$ is then deposited on the etched surfaces around the mesas. After that, thin-film metallic electrodes reaching from the contact pads of the substrate to the top of the mesas are made. The height of the mesas (and the number of the junctions $N$ in them) is controlled by the timing of the Ar-ion etching.

After a simple mesa is fabricated, a slit can be made in the middle of the mesa by conventional photolithography dividing the top gold layer and a few junctions below into two parts, thus forming a U-shaped mesa (see Fig. 1). Only the junctions below the slit in the mesa will be seen in the four-probe measurements as all the IJJs in the arms of the U-shaped mesa can be considered as parts of the electrodes. The slit can be made deeper until a single IJJ is left under the slit. More details of the fabrication process can be found elsewhere [5].

### 2.2. Zigzag structures

Our method is a refined flip–chip technique introduced earlier [6]. The sample processing starts with fabrication of a bow-tie-shaped "simple" mesa with a micro-bridge in the center. The thickness of this mesa $d$ is about 100 nm. Then, a 40-nm-deep slit is made across the bridge (slit 1 in Fig. 2). In the next step, we flip the sample and glue it to another substrate, sandwiching the single crystal between the two substrates. Separation of the substrates cleaves the single crystal into two pieces, one with the mesa being glued upside down to the second substrate. With the aid of Scotch tape, we remove excess parts of the crystal that might also stick to the second substrate and be on top of the flipped mesa. A new gold layer is then deposited and patterned immediately after that to make four electrodes attached to this small piece of single crystal. Finally, a $CaF_2$ protection layer with an open window placed across the bridge is formed. Further Ar-ion etching will incise a second slit into the bridge through that window. When the slits overlap, a stack of IJJs appear in the middle which becomes gradually higher with further Ar-ion etching [7].

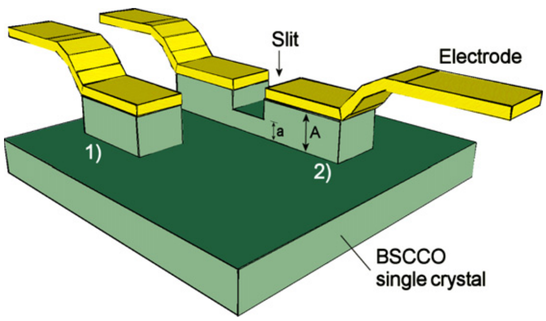


Fig. 1. Schematic sketch of a simple mesa (1) and a U-shaped mesa (2). Note that only junctions underneath the slit are seen in the four-probe measurements on a U-mesa (two more contacts on the base crystal are not shown).

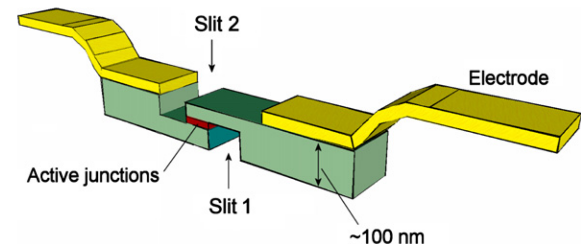


Fig. 2. Schematic sketch of a zigzag-type structure with an active stack of IJJs in the middle of all-superconducting material.

## 3. Results and discussion

It should be emphasized that despite the apparent simplicity, the fabrication techniques guarantee very high accuracy (1 nm) in controlling the stack heights and in tailor-making samples with any low number of IJJs, down to one.

### 3.1. The in-plane critical current

There is a large inconsistency regarding the data on the in-plane critical current density $j_{ab}$ for BSCCO which is a common material for superconducting power cables. Values from 0.01 to 5 $MA/cm^2$ have been reported for single crystals and thin-films (see Ref. [8] and references therein). The disparity is much likely due to hidden experimental parameters, like crystal defects or unknown current distribution in the sample. Using the well-controlled geometry of our virtually defect-free stacks of IJJs, decisive measurements of the critical current of a single $Cu_2O_4$ plane could be done [8], setting up the upper limit of $j_{ab}$ for a single-crystalline BSCCO.

The idea is to inject the current through the topmost $Cu_2O_4$-layer, say from one top electrode of a U-mesa to another one (see Fig. 3). The actual current which is needed to reach the large expected $j_{ab}$ in a single plane is rather small. When the current exceeds its superconducting critical value, a break in $I$–$V$s can be clearly seen (see Fig. 4). In the U-mesas with a single junction below the slit, this transition is even more pronounced. From the current of the break, we can calculate the sheet critical current density of a single $Cu_2O_4$ plane to be ~0.3–0.7 A/cm at 4.5 K, corresponding to $j_{ab} \sim 2$–5 $MA/cm^2$. These values are among the largest ever measured for BSCCO single crystals, thin-films and tapes [8].