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Intrinsic Josephson Junctions in BiSrCaCuO-2212: Recent Progress

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SUMMARY In this paper, we review the progress in BiSrCaCuO-2212 Intrinsic Josephson junctions (IJJs) by summarizing our recent results in fabrication and high frequency experiments. Using a double-side fabrication process, a well defined number of intrinsic Josephson junctions in a well defined geometry can be fabricated. The junctions in the stack are quite homogeneous, and the power distribution of external irradiation among the junctions is even. Shapiro steps are clearly observed up to 2.5 THz, and the general condition for the occurrence of Shapiro steps at frequency f_{rf} is that it should be much greater than the plasma frequency f_{pl}. Under certain conditions the Shapiro steps are zero-crossing, making some applications possible, such as quantum voltage standard etc.

key words: *intrinsic Josephson effects, terahertz response, zero-crossing steps, double-side process*

1. Introduction

The pioneering work of Kleiner et al. [1] and Oya et al. [2] on the intrinsic Josephson effects (IJEs) in high T_C superconductors has opened a new research area where there are many chances as well as challenges. As a system consisting of closely coupled Josephson junctions, this is a rich treasury of nonlinear problems in which scientists from many circles are interested. From the practical point of view, such a system of Josephson junctions in series is also very promising because, being intrinsic, the junctions should be rather homogeneous; the array of junctions should show a rather high resistance, making it less difficult to get matched to external circuits than with a single junction; and operation at terahertz or even higher frequencies should be possible due to the high energy gap; etc. [3]–[5]. In our attempts to fully explore these possibilities, we have developed a double-side fabrication process enabling ourselves to fabricate a well-defined number of intrinsic Josephson junctions (IJJs) in a well-defined structure; the samples show clear Shapiro steps with irradiation up to 2.5 THz, making many electronic applications possible; in particular, under certain conditions the Shapiro steps are zero-crossing, and can thus be utilized in systems such as quantum voltage standards. In this paper we are going to review in detail our recent work, stressing the above mentioned points.

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2. A Novel Double-Side Process for Fabricating IJJs

To fabricate IJJs, different structures on different materials have been used. Kleiner et al. first used bulk $Bi_2Sr_2CaCu_2O_{8+x}$ (BSCCO) single crystals as IJJs which had typical dimensions of $30\,\mu m \times 30\,\mu m$ in an a-b plane and $3\,\mu m$ along a c-axis, involving about 2000 junctions inside [1]. IJJs fabricated on BSCCO single crystal whiskers made it possible to use a four-terminal measurement method [6]. In addition to fabricating stacked IJJs in BSCCO films [7], IJJs were successfully fabricated in c-axis Tl-Ba-Ca-Cu-O and oxygen-deficient Y-Ba-Cu-O films crossing substrate steps [8], [9]. Lateral type IJJs were patterned using a-axis oriented grains in YBCO film and (110) needle-like grains in BSCCO film [10]. Although these experiments were quite successful to various extent, there were still quite some remaining problems such as the junction number in a stack was not well controlled; in a stack of junctions the outmost one was often considerably degraded; etc. The basic idea of our double-side fabrication is to single out, from inside a BSCCO single crystal, a slice 200 nm thick in which there are a stack of intrinsic Josephson junctions plus something integrated to it such as a bow-tie antenna, chokes, etc. Thus any surface degradation during fabrication can be avoided and all the junctions involved are really intrinsic. So far the number of junctions inside a stack can be controlled down to a few.

In the double-side fabrication process [11], a BSCCO single crystal (typically with a T_C of about 88 K) is photolithographically patterned into the bow-tie shape on its surface, and etched by argon ion milling for 200 nm, leaving a mesa sitting on the BSCCO pedestal (Fig. 1). The central part of the bow-tie antenna is a micro-bridge a few micron wide. Then, using photolithography and ion milling, a vertical step is fab-

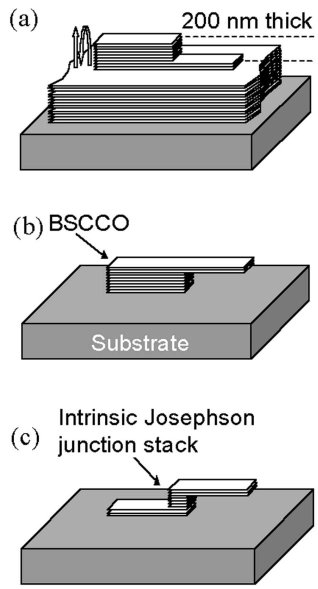

Fig. 1 A schematic description of the major steps involved in the double-side fabrication process.

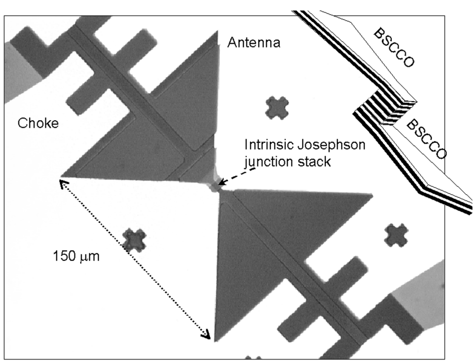

Fig. 2 Structure in details of a sample fabricated on MgO substrate (taken through an optical microscope with back-side illumination, where the schematic view is shown in inset).

ricated mid-way between the bow-tie center and one of the banks. The patterned single crystal was glued on either a silicon or a MgO substrate with its freshly cleaved side facing upwards. The cleaved single crystal looks like a thin film of about 200 nm thick on a substrate, with a step underneath. Finally, starting from the top surface, another step on the opposite side from the bow-tie center is made, followed by deposition of gold electrodes for current-voltage measurements. The cleaved single crystal is quite thin, then it is possible for us to observe the structure of the samples fabricated on transparent substrates like MgO. Shown in Fig. 2 is an IJJs stack integrated with a bow-tie antenna and rf choke filters on MgO substrate (taken through an optical microscope with back-side illumination, where the schematic view is shown in the inset.

The junctions in the fabricated stack are very uniform, and the number of junctions involved is rather

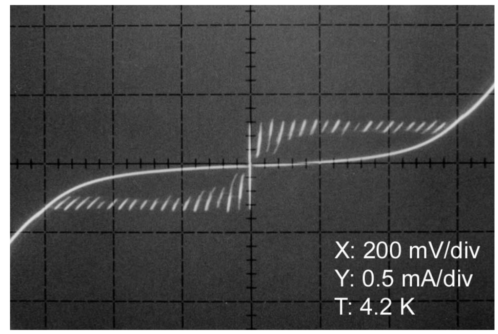

Fig. 3 Typical current-voltage (I-V) curves of a stack of intrinsic Josephson junctions with a-b plane sizes of $4 \times 2.5\,\mu m^2$.

controllable. Potentially it will be possible to use this method to fabricate integrated circuits based on intrinsic Josephson junctions in high T_C superconductors.

3. dc Current-Voltage Characteristics of IJJs

In our experiments, the samples are mounted in a liquid helium cryostat. Shown in Fig. 3 are the typical dc current-voltage (I-V) curves of our stack of IJJs. The critical currents and the voltage jumps (about 30 mV) of all junctions in the stack are almost the same, demonstrating that the stack can be regarded as an array of almost identical junctions. This is in sharp contrast to the case of conventional mesa structure where the critical current of the outermost junction is much lower than those of the others due to superconductivity degradation of the surface junction.

4. Terahertz Responses of IJJs

As a very important step towards the understanding of the physical mechanism in IJJs as well as towards the possible electronic applications, we show here the observation of Shapiro steps at high frequencies [12]. In our experiments, a far infrared (FIR) laser optically pumped by a CO_2 laser is used as the signal source [13]. Irradiation is fed to the samples from the substrate side. The planar bow-tie antenna, the silicon substrate and an extended hyperhemispherical silicon lens form a quasi-optical system. Shown in Fig. 4 are the I-V curves of a sample (with the a-b plane sizes of 4 microns by 4 microns and 17 junctions in the stack) exposed to the irradiation at 1.6 THz. Clear Shapiro steps are observed at voltages of $Nhf_{FIR}/2e$ satisfying the Josephson frequency-voltage relation, i.e., 3.4 mV for 1.6 THz. As we have point out in Ref. [12], N is the number of junctions biased at voltage states in the stack, but not the order of the steps caused by a single junction. Thus, in the stack, the applied radiation is quite evenly distributed among the junctions which are almost identical to each other. These junctions respond to the applied irradiation synchronously. Similar results have also been achieved with irradiation up to

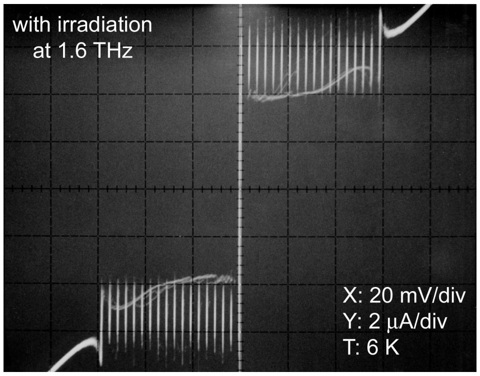

Fig. 4 Close-up of a typical *I-V* curve (with a stack of 17 junctions and the lateral sizes of 4 microns by 4 microns) under 1.6 THz irradiation where Shapiro steps at $Nhf_{FIR}/2e$ are apparent with N ranging from 1 to 17.

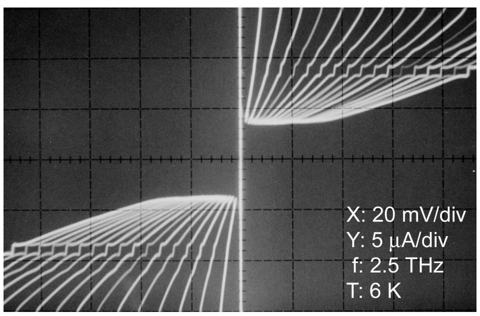

Fig. 5 Shapiro steps observed in IJJs under irradiation at 2.5 THz.

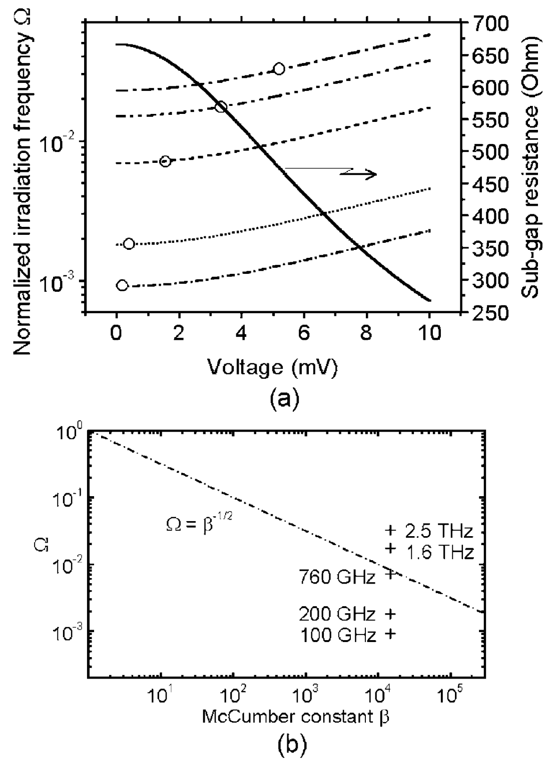

Fig. 6 (a) Voltage dependence of the sub-gap resistance and the normalized irradiation frequencies of 100 GHz, 200 GHz, 760 GHz, 1.6 THz, and 2.5 THz (from bottom to top), where open circles mark the points where the first order Shapiro steps may appear. (b) $\beta - \Omega$ plane divided by the line $\beta^{-1/2} = \Omega$, where experimental points are marked with crosses.

2.5 THz (Fig. 5).

5. Conditions for Observation of Shapiro Steps

With intrinsic Josephson junctions, we have found the conditions for the occurrence of Shapiro steps and onset of chaos on the $\beta - \Omega$ plane, where $\beta(=4\pi e I_C R^2 C/h)$is the McCumber constant and Ω $(=f_{rf}h/(2eI_C R))$ is the normalized frequency. In the expression of normalized frequency, R should be sub-gap resistance rather than normal resistance; it can be calculated by fitting the resistive branch of a single junction with $i(v) = a(v+bv^3)$, taking into account that for $v < 10$ mV $a = 1.5$ $(\mathrm{k}\Omega)^{-1}$ and $b = 5 \times 10^{-3}$ $(\mathrm{mV})^{-2}$gives the best fitting. The results are shown in Fig. 6(a). The McCumber constant is estimated to be about 1.5×10^4 [14]; while Ω for 100 GHz, 200 GHz, 760 GHz, 1.6 THz, and 2.5 THz irradiations are 9.1×10^{-4}, 1.8×10^{-3}, 7.1×10^{-3}, 1.7×10^{-2}, and 3.2×10^{-2}, respectively. In the $\beta - \Omega$ plane (Fig. 6(b)), which is divided by the line $\Omega = \beta^{-1/2}$ into two regions with the upper one having $\Omega > \beta^{-1/2}$ while the lower one having $\Omega < \beta^{-1/2}$, the points for 760 GHz, 1.6 THz and 2.5 THz are very close to or well above the line $\beta^{-1/2} = \Omega$, in very good agreement with our observation of Shapiro steps; the points for 100 GHz and 200 GHz, however, are in the region where chaos could often occur. Indeed, in the *I-V* characteristics of our samples under irradiation at frequencies of 100 GHz and 200 GHz, although plenty of power is available to suppress the zero voltage critical current greatly, no Shapiro steps were observable. These results for IJJs are similar to those for Nb tunneling junctions, strongly supporting the argument that Shapiro steps are observable only when $f_{pl} << f_{rf}$ is satisfied in heavily underdamped IJJs [4], [15].

6. Potential Applications of IJJs

It is important to notice that our junctions satisfy the conditions for achieving stable zero-crossing steps at terahertz region [16], [17], i.e., $\Omega < 0.58$ and $\Omega^2\beta >> 1$. Experimentally, with sufficiently good coupling between IJJs and high frequency signal, we did observe zero-crossing Shapiro steps as shown in Fig. 7 for signal source at 760 GHz. Such zero-crossing steps, which are observable at temperatures up to 50 K, provide us with a good chance to use the IJJs for applications such as quantum voltage standards.

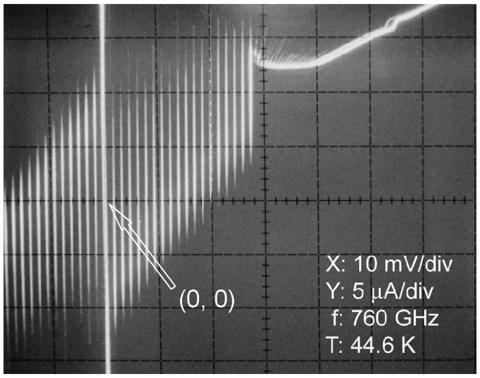

Fig. 7 Zero-crossing Shapiro steps observed in IJJs under terahertz irradiation at temperature up to 44.6 K.

7. Conclusions

To conclude, we have developed a double-side fabrication process so that a well defined number of intrinsic Josephson junctions in a well defined geometry can be fabricated. This new fabrication process seems helpful in making integrated circuits based on intrinsic Josephson junctions in high T_C superconductors. Using samples fabricated in such a way we are able to observe Shapiro steps with irradiation at terahertz region, convincingly showing that the junctions in the stack are quite homogeneous, and that the power distribution of external irradiation among the junctions is even. To observe Shapiro steps at frequency f_{rf}, the plasma frequency f_{pl} should be made much smaller than f_{rf}. Under certain conditions the Shapiro steps are zero-crossing, making some applications possible, such as quantum voltage standard etc.

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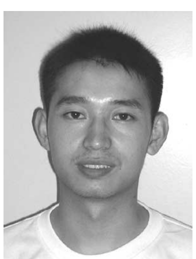

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