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Suppression of critical current in submicron intrinsic Josephson junction fabricated in a $Bi_2Sr_2Ca_2Cu_3O_{10+\delta}$ (Bi-2223) Single Crystal Whisker

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1. Introduction

A single crystal whisker can be used in the fabrication of nano-electronic devices with the application of intrinsic Josephson junction effects and related phenomenon. Growth and characterization of high temperature superconducting single crystal whiskers have long been in focus of researchers because of perfect crystalline structure and the ability to study in small cross sections (when width and thickness are less than the magnetic field penetration depth). There are three compounds in the Bi-family high temperature superconductors, differing in the type of planar CuO_2 layers; single-layered $Bi_2Sr_2CuO_{6+\delta}$ (Bi-2201), double-layered $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi-2212), and triple-layered $Bi_2Sr_2Ca_2Cu_3O_{10+\delta}$ (Bi-2223) single crystals. The Bi-2223 single crystal has the highest transition temperature in this family at about 110 K and indicates conducting CuO_2 planes are one of the promoters for superconductivity [1]-[4].

The spacing of consecutive copper oxide planes in the anisotropic cuprate superconductors is greater than the coherence length in the out-of-plane *c*-axis. When a current flows along *c*-axis, it therefore flows through intrinsic Josephson junctions [5]. We are reporting the experimental results on submicron intrinsic Josephson junctions fabricated on Bi-2223 using focused ion beam (FIB) 3D etching technique. We fabricate junction on Bi-2223 with different cross sectional area (S) and notice remarkable suppression in critical current. We notice when S < 1 μm^2, there is a strong suppression in critical current. We believe the suppression occurs when the normal resistance of junction belongs in the range of quantum resistance ($R_Q=h/4e^2$; where *h* is Planck's constant and *e* is electron charge) range.

2. Experimental Details

We grow single crystal whiskers by solid state reaction method. A high-purity commercial powder of Bi_2O_3, $SrCO_3$, CuO and TeO_2 was used to grow a single crystal whisker. These powders were mixed in the proportional ratio of $Bi_2Sr_2Ca_2Cu_{2.5}Te_{0.5}O_x$ [6]. The whiskers were grown on the surface of pellet, being of various dimensions in length (0.5 to 3 mm), width (10 to 30 μm) and thickness (0.5 μm to 3 μm).

We attempt to fabricate a sub-micrometer stack in a Bi−2223 single crystal whisker using the FIB etching method. The stack has an array of Josephson junctions and all elementary junctions have arranged in the series. In the FIB we have freedom for tilled up to 60º and rotation up to 360º. We use sample stage that is itself 60º incline with Ion beam. We tilt sample stage with 30º so that the *ab*-plane of sample is perpendicular to ion beam and mill along the *ab*-plane. We turn back sample stage in the initial orientation and give the rotation of 180º so that the incline plane is making 60º with ion beam. We tilt sample stage by 60º so that the *c*-axis of sample is perpendicular to ion beam and mill along the *c*-axis in this orientation. Bi−2223 single crystal whisker has been etched along the *ab*-plane with size of 0.5 μm x 0.5 μm and with the height of 200 nm along the *c*-axis [7]. We also fabricate junction called J2 with the size of 2 μm x 2 μm x 100 nm. For transport characterization, we performed resistance-temperature (*R-T*) characteristics and current-voltage (*I-V*) characteristics using four probe technique. We used low pass filter on signal line to reduce the external noise.

3. Results and Discussion

We evaluate *I-V* characteristics along the *c*-axis for junction J1 and notice a well-defined superconducting gap (V_g) of 2 V which belongs to the number of elementary Josephson junctions along the *c*-axis. The critical current appears 25A/cm^2 along the *c*-axis. In contrast we measure junction J2 and find critical current 500 A/cm^2. The suppression in critical current occurs due to suppression in the junction size. As we reduce the size of the junction, the normal resistance of junction decreases and belongs to quantum resistance. Fig. 1 shows the comparative study of *I-V* characteristics of both junctions at 30 K.

We also attempt to calculate Josephson plasma frequency, which is directly proportional to $(J_c)^{1/2}$, so J_c is one of the important junction parameters for the realization of high-frequency device applications using IJJs. The J_c of IJJs in other high temperature superconductor materials depends on their carrier density [8]. We estimate the Josephson plasma frequency (f_{pl}):

$$f_{pl}= (1/2\pi)(2eJ_cd/ \hbar\varepsilon_b\varepsilon_o)^{1/2}$$

(Where: *d* is inter layer separation (1.8nm), *h* is plank's constant, ε_b is the dielectric constant (12 for Bi-2223), ε_o is the dielectric constant of vacuum)

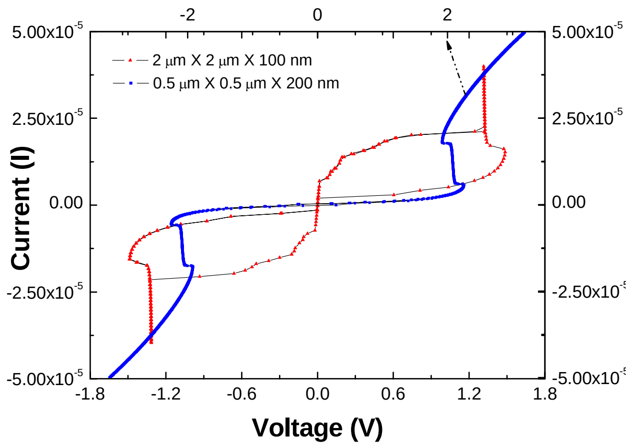

Fig. 1 *I-V* characteristics along the *c*-axis of junction J1 (0.5 µm x 0.5 µm x 200 nm) and J2 (2 µm x 2 µm x 100 nm) of Bi-2223 single crystal. It shows a well defined voltage gap of 2 V for J1 and 1.5 V for J2. (Scale is different for both junctions)

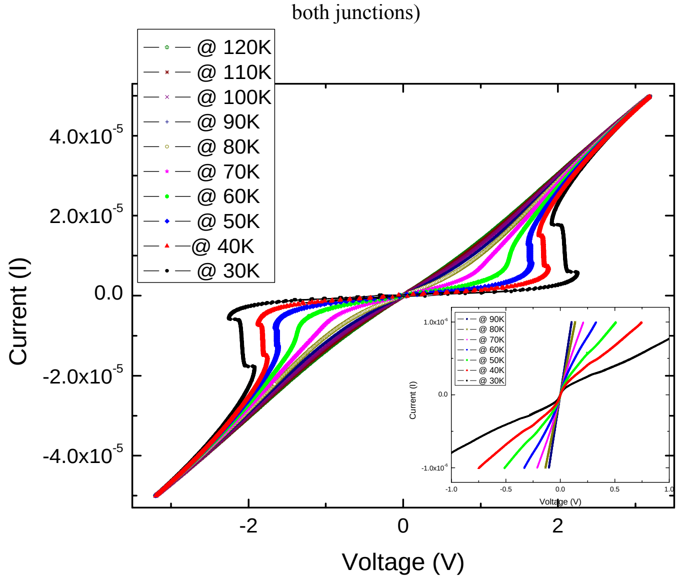

Fig.2 *I-V* characteristics for junction J1 at different temperature from 30 K up to 120 K in the interval of 10 K. Inset shows low biasing region near the zero voltage.

The Josephson plasma frequency lies in the range of GHz to THz. A high frequency device can be possible by the application of Josephson plasma frequency. Usually large junctions are used as a high frequency device. We have calculated Josephson plasma frequency for junction J1 and estimated about 7 GHz at 30 K. We compared this value with junction J2 and find 35 GHz. Junction J1 can be prospective candidate for low frequency detection, which can excite Josephson plasma.

We plot the temperature dependence of *I-V* characteristics from 30 K up to 120 K in the interval of 10 K (see Fig. 2). We notice as the temperature increases the critical current and the gap between the branches decreases. At high voltage at any temperature, the *I-V* curve approaches the straight line. This behavior is a consequence of usual tunneling theory. The normal tunneling resistance is defined as the static resistance at high voltage where *I-V* curve sufficiently approaches the straight line and cross the origin. Fig. 2 is also following the same phenomenon at high voltage biasing at any temperature. Inset shows the low biasing region near the zero voltage; it indicates the change in critical current with temperature difference.

We believe as we reduce the size of junction its normal resistance belongs in quantum resistance and the quantum fluctuation across a single Josephson junction become significant when $E_J/E_C < 1$ (where $E_C = (2e)^2/(2C)$ is the coulomb energy for Cooper pairs and e is electronic charge). In arrays of junction the charging energy is enhanced due to inter-junction coulomb interaction. In a finite array of N junctions, the soliton length is clearly limited to N junctions, so the charging energy is enhanced by a factor min (N, $(C/C_0)^{1/2}$)[9].

4. Conclusions

We have successfully fabricated a sub-micrometer stack in a Bi-2223 single crystal whisker and investigated their detail characteristics. We fabricated the sub-micrometer junction by tilting and rotating an incline stage with respect to ion beam in FIB. The sub-micrometer stack has a nano scale array of Josephson junction with an area of 0.5 µm x 0.5 µm and height of about 200 nm.

The *I-V* characteristics indicate a well-defined superconducting gap (V_g) of approximately 2 V and 1.5 V for J1 and J2 respectively. We estimate critical current density (J_c) about 25 A/cm^2 at 30 K. The suppression in critical current occurs when the normal resistance of junction belongs in the range of quantum resistance range. The experimental results give various ideas of application of sub-micrometer junctions.

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