Fabrication of Ultra Low Capacitive High Temperature Superconducting Device Using Focused Ion Beam

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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).
In Bi-based single crystal whisker, the conducting CuO_2 planes (≈ 0.3 nm) are separated by insulating BiO−SrO layer (≈ 1.2 nm) [1]. This layered phenomenon gives high anisotropy to Bi-based single crystal whisker. Bi-based single crystal whisker is a naturally grown intrinsic Josephson junction (IJJ). These junctions are attractive because the current-voltage (*I-V*) property along the *c*-axis of the IJJs has anomalous nonlinear characteristics and a series of several hundred Josephson junctions can be easily obtained [2]. The junctions are considered to be a one-dimensional array of Josephson junctions in the stack. These junctions generate a Josephson plasma excitation with an extremely high frequency [3]. The IJJs can be expected as high frequency oscillator based on Josephson plasma frequency (10GHz to a few THz). In addition, the submicron junction can be used as electric field sensors and quantum current standards using the Coulomb blockade phenomenon where charging energy ($e^2/2C$) of submicron junction is higher than Josephson energy ($\varphi_0 J_c S/2\pi$) and thermal energy ($k_B T$), where C is capacitance of junction, φ_0 is flux quantum, J_c is critical current density, S is effective area, and k_B is Boltzmann's constant. The sub-micrometer junction can also be use in nano-electronics like single electron transistor (SET) [4]. The sub-micrometer tunneling characteristics in Bi−2212 have not yet been well studied. To study *c*-axis tunneling properties in sub-micrometer area, we have fabricated periodic IJJs array in single crystal whiskers by 3-D milling using the FIB method. We are attempting to describe the sub-micrometer junction characteristics fabricated on a Bi-2212 single crystal whisker.

2. Experimental Detail

We grew Bi-based superconductor (Bi−2212) whiskers by the solid state reaction method. High-purity commercial powders of Bi_2O_3, $SrCO_3$, CuO and TeO_2 were used to grow single crystal whisker. We fabricate a sub-micrometer stack which has ultra low capacitance in a Bi−2212 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 (Fig. 1 (a)). We tilt sample stage with 30º so that the *ab*-plane of sample is perpendicular to ion beam and mill along the *ab*-plane. Figure 1(c) shows the process for milling 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−2212 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 100 nm along the *c*-axis [5]. Figure 1(e) shows the FIB image of sub-micrometer stack in a Bi-2212 single crystal whisker.

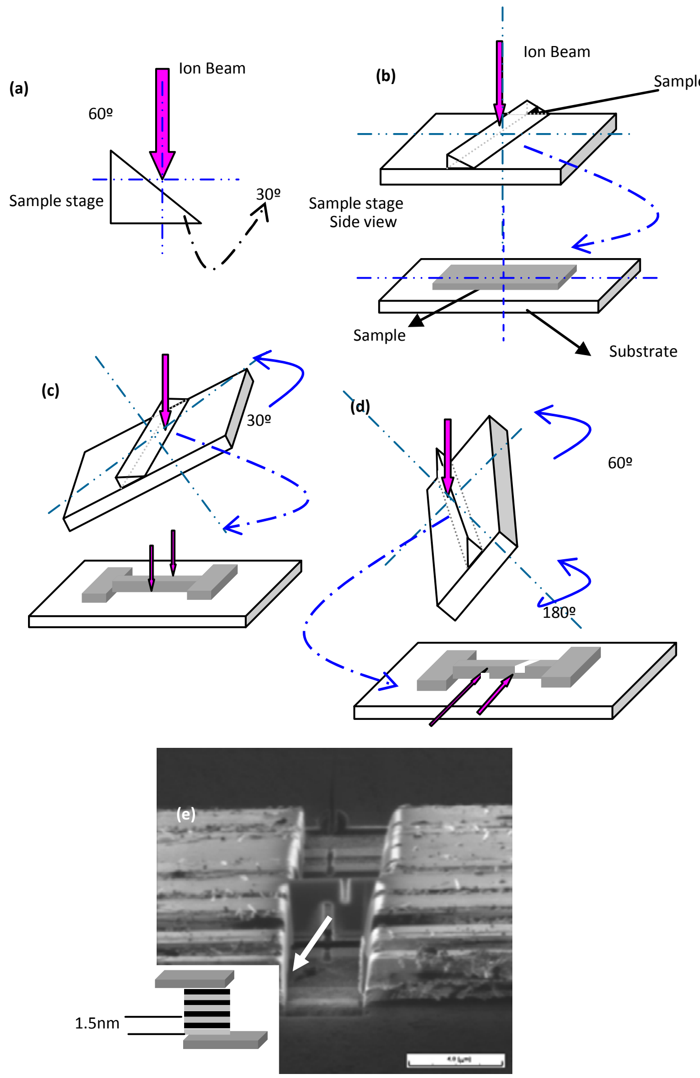

Fig. 1: (a) Scheme of the incline plane has an angle of 60º with ion beam (where we mount sample). (b) The initial orientation of sample and sample stage. (c) Sample stage titled by 30º anticlockwise with respect to ion beam and milling along *ab*-plane. (d) The sample stage rotated by an angle of 180º and also tilted by 60º anticlockwise with respect to ion beam and milled along the *c*-axis. (e) FIB image of the sub-micrometer stack fabricated on a Bi-2212 single crystal whisker along the *c*-axis height of 100 nm (scale bar of 4 μm). Inset shows the schematic diagram of stack fabrication along the *c*-axis.

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.

Table I: Junction parameters at 20 K.

Junction	Effective Area (μm^2)	Critical Current Density (A/cm^2)	Junction Capacitance (fF)	Charging Energy (meV)
J1 (0.5 μm x 0.5 μm x 200 nm)	0.25	176	0.1	0.2
J3(1 μm x 1 μm x 100 nm)	1	1.1×10^3	0.4	0.7
J2 (2 μm x 2 μm x 150 nm)	4	1.2×10^3	1.8	2.9

3. Experimental Results and Discussion

We evaluate *I-V* characteristics along the *c*-axis. Figure 2 shows *I-V* characteristics of a sub-micrometer junction in a Bi−2212 single crystal whisker at 20 K. A well-defined superconducting gap (V_g) of 0.6 V appears which indicates a number of elementary Josephson junctions. The inset shows low biasing region of *I-V* characteristics. It has a clear a few of branches, every branch belongs to an elementary Josephson junction. We estimate critical current density (J_c) about 176 A/cm^2. As shown in inset of Fig.2, we successfully observe a clear branch structure. The branched and uniform *I-V* characteristics indicate fine crystallinity of Bi-2212 single crystal whisker. The gap voltage spacing and critical current are gradually suppressed with increase in bias voltage. We consider this suppression to Joule heating due to self-biasing of junctions [6].

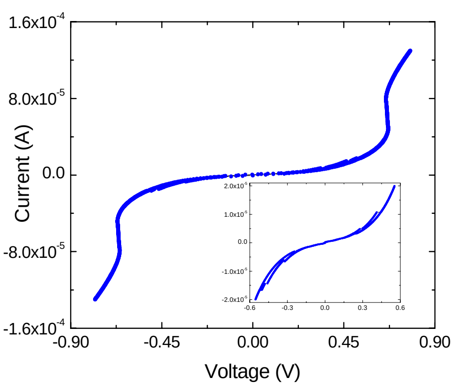

Fig. 2 *I-V* characteristics along the *c*-axis of a sub-micrometer junction (0.5 μm x 0.5 μm x 100 nm) in a Bi-2212 single crystal. Inset shows the low biasing region with a few of branches.

In Table I we summarized three different in-plane area junctions and calculated the critical current density, junction capacitance and charging energy. We notice there is a strong suppression in critical current as we decrease the junction size and also the capacitance is decreasing with increase in size. This decrease in capacitance increases the charging energy of junction. The junction can be used as a electronic device such as SET if its charging energy is higher.

From the *I-V* characteristics, we can deduce characteristics voltage V_c of 10-12 mV. These values are approximately close to the optimum value of 18 mV calculated from the zero temperature Ambegaokar-Baratoff relation $V_c \approx I_c R = \pi/2e\Delta$, with $\Delta = 1.75kT_c$ [7]. The spacing between the branches is decreasing with increase in temperature. The gap suppression can be possible due to the tunneling of quasiparticle between the layers [8]. At high voltage biasing, the *I-V* curves change in quasiparticle curve with a gap value of 0.6 V.

We plot the temperature dependence of *I-V* characteristics at low biasing region from 20 K up to 100 K in the interval of 10 K (see Fig. 3). We notice as the temperature increases the critical current and the gap between the branches decreases. The critical current is compressed because of the increase in charging energy or the milling process. During the milling process the Ga^+ ion can contaminate the junction. We further investigate the characteristics of temperature dependence of critical current (I_c-T) of IJJs of sub-micrometer junction in a Bi-2212 single crystal whisker as shown in the inset of Fig. 3. The I_c-T curves indicate towards SIS-type junction according to the Ambegaokar-Baratoff relation [7] and give rise to high anisotropy of sub-micrometer junction.

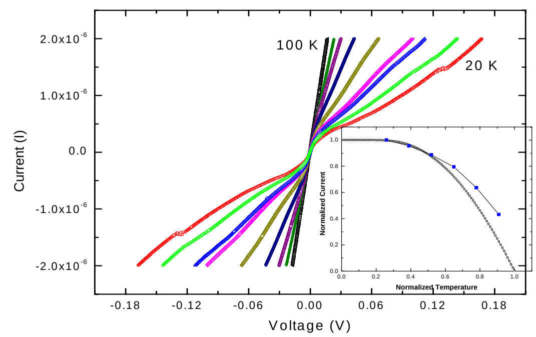

Fig. 3. *I-V* characteristics for low biasing region at different temperature from 20 K up to 100 K in the interval of 10 K. Inset shows Ic-*T* characteristics of a sub-micrometer junction fabricated on a Bi-2212 single crystal whisker compared with AB theory in open circle.

4. Conclusions

We have successfully fabricated a sub-micrometer stack with ultra low capacitance in a Bi-2212 single crystal whisker and investigated their detail characteristics. We fabricate 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 100 nm. The *I-V* characteristics indicate a well-defined superconducting gap (V_g) of approximately 0.6 V. We notice the clear branch structure of the *I-V* characteristics and the characteristics voltage (V_c) of about 10-12 mV. We estimate critical current density (J_c) about 176 A/cm^2 at 20 K and the experimental results give various ideas of application of sub-micrometer junctions.

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