Fabrication of Submicron Sized Josephson Junctions Array in a High-T_C Superconductor using Focused Ion Beam

S.Saini[1], *#김상재[1]

S. Saini[1], *#S.-J. Kim[1] (kimsangj@cheju.ac.kr)

[1]Nano Materials and System Lab, Dept of Mechanical System Engineering, Cheju National University

Key words Focused Ion Beam (FIB), Single Crystal Whiskers, Submicron junction, Intrinsic Josephson Junction, Superconducting gap

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) [1-4]. $Bi_2Sr_2CaCu_2O_{8+x}$ (Bi-2212) crystal is a naturally grown Josephson junction. Conducting CuO_2 bilayer plane (≈ 0.3 nm) is separated by an insulator BiO-SrO layer (≈ 1.2 nm). This layered phenomenon gives highly anisotropy to Bi-2212 single crystal whiskers (comparable properties in *ab*- plane and *c*-axis). To study *c*-axis properties, we fabricated submicron sized intrinsic Josephson junction array in high-T_C superconducting single crystal whisker by 3D etching through focused ion beam (FIB).

We are reporting submicron sized stack fabrication to study interlayer characteristics in high temperature superconducting single crystal whisker through FIB. We fabricated a stack area of 0.5 μm x 0.5 μm and height of approximately 100 nm using FIB etching, which have several hundred of elementary Josephson junctions in *c*-axis. This stack has fabricated by rotation and tilt of sample stage in FIB. We measured resistance (R) - temperature (T) characteristics found transition temperature (T_c) of 77 K, which indicates good quality of Bi-2212 single crystal whisker. We also measured current (I) - voltage (V) characteristics, which gives a well defined voltage gap ($V_g \approx 1$ V).

2. Growth and fabrication of sample

We prepared our sample from solid state reaction. We used 99.9% pure powder of Bi_2O_3, $SrCO_3$, CuO, and TeO_2. Te is used to enhance the growth of whiskers. We mixed these powders in the proportional ratio of $Bi_2Sr_2Ca_2Cu_{2.5}Te_{0.5}O_x$. The mixture was ground and put for calcination at 760°C for two times and at 820°C for one time only in presence of air. The calcinated powder pressed into a pellet at 60 kN. The pellet was 10 mm in diameter and 2~3 mm in thickness. The pellet kept in a pure alumina boat and annealed at 880°C for 100 hours. During the process we used oxygen atmosphere with constant flow of 150 ml/min [5]. The whiskers were grown on the surface of pellet. We found whiskers 0.5~3 mm in length and 10 to 30 μm in width.

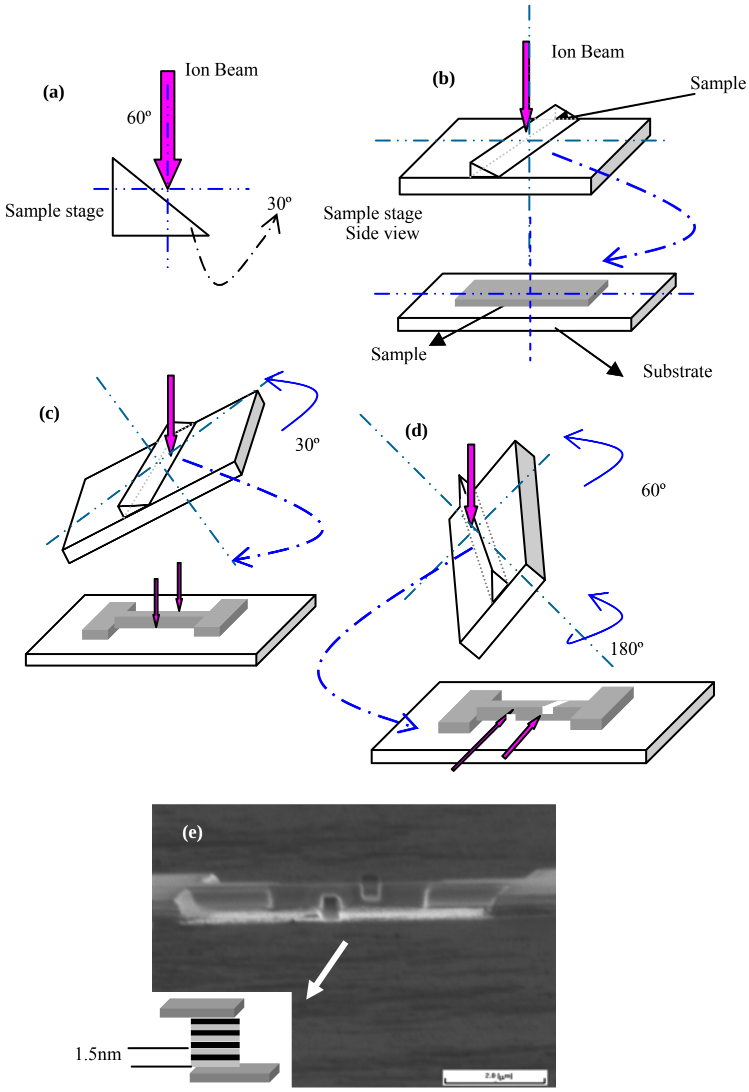

Fig. 1: (a) Scheme of the incline plane has an angle of 60° with ion beam (where we mount sample). (b) The initial orientation of sample and sample stage. (c) Sample stage titled by 30° anticlockwise with respect to ion beam and milling along *ab*-plane. (d) The sample stage rotated by an angle of 180° and also tilted by 60° 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 2 μm). Inset shows the schematic diagram of stack fabrication along the *c*-axis.

We fabricated stack junctions in Bi-2212 single crystal whisker through FIB. In the FIB we have freedom for tilled up to 60° and rotation up to 360°. We use sample stage that is itself 60° incline with Ion beam (Fig. 1 (a)). We tilt sample stage with 30° 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 [6]. Figure 1(e) shows the FIB image of sub-micrometer stack in a Bi-2212 single crystal whisker.

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. Experimental results

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 [7].

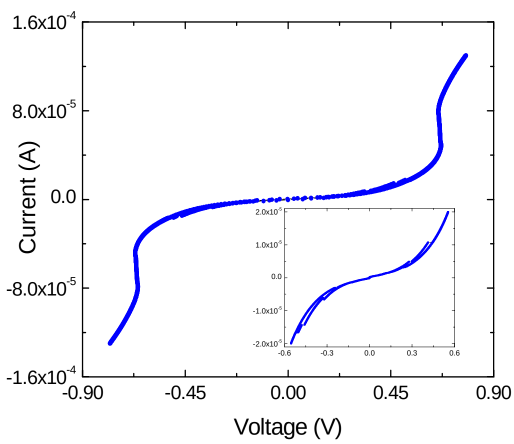

Fig. 2 *I-V* characteristics along the *c*-axis of a sub-micrometer junction (0.5 μm x 0.5 μm x 100 nm) in a Bi-2212 single crystal. Inset shows the low biasing region with a few of branches.

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 [8] and give rise to high anisotropy of sub-micrometer junction.

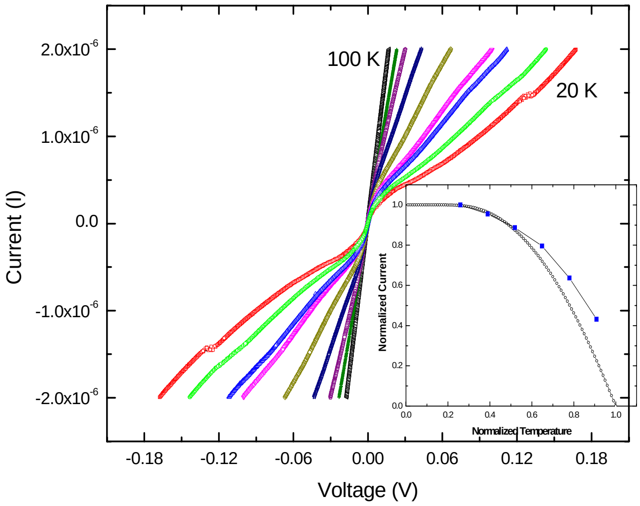

Fig. 3 *I-V* characteristics for low biasing region at different temperature from 20 K up to 100 K in the interval of 10 K. Inset shows Ic-*T* characteristics of a sub-micrometer junction fabricated on a Bi-2212 single crystal whisker compared with AB theory in open circle.

4. Summary

We have successfully fabricated a sub-micrometer sized Josephson junction array 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.

REFERENCES

1. J.Appel and D. Fay, Phys. Rev. B **41**,873 (1990).
2. R. Kleiner, F. Steinmeyer, G. Kunkel, and P. Muller, Phys. Rev. Lett. **68**, 2394 (1992).
3. G. Oya, N. Aoyama, A. Irie, S. Kishida, and H. Tokutaka, Jap. J. Appl. Phys., Part 2 31, L829 (1992).
4. R. Kleiner and P. Muller, Phys. Rev. B **49**, 1327(1994).
5. M. Nagao, M. Sato, H. Maeda, S. -J. Kim and T. Yamashita, Appl. Phs. Lett. **79**, 2612(2001).
6. S.-J. Kim, I. Yu. Latyshev, T. Yamashita, Supercond. Sci. Technol. **12**, 729 (1999).
7. H.B. Wang, P.H. Wu, J. Chen, K. Maeda and T. Yamashita: Appl. Phys. Lett. **80,** 1604 (2002).
8. V. Ambegaokar and A. Baratoff: Phys. Rev. Lett. **10** 486 (1963).