Easy fabrication of mesa-type Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ intrinsic Josephson junction using cross-whisker junction

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Abstract. An easy and inexpensive method to fabricate mesa-type intrinsic Josephson junctions (IJJs) is presented. After fabricating a cross-whisker junction (CWJ) of Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$, the CWJ was milled by argon ion beam. No special mask is necessary because the upper whisker plays a role of mask in the milling process. The milled CWJ exhibits typical multi-branch structures in current-voltage characteristics, similar to the one seen in mesa-type and s-shaped small IJJs of Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$.

1. Introduction
There have been much attention to the intrinsic Josephson effect in high temperature superconductor since Kleiner et al. and Oya et al. discovered them in Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ (Bi2212) single crystal [1, 2]. Recently, c-axis transport properties in small intrinsic Josephson junctions (IJJs), which are mesa-type or s-shaped junctions, have been examined due to its interesting phenomena such as macroscopic quantum tunneling [3, 4, 5] and potential for application for high frequency device [6, 7]. The mesa-type IJJs have been fabricated by photolithography or argon ion milling [8], while the s-shaped IJJs have been fabricated by double-side cleaving [9, 10] or focused ion beam (FIB) etching [11]. These techniques include, however, difficult and complicated processes [8, 9, 10] Moreover, expensive devices for FIB, photolithography, and electron beam lithography are necessary to fabricate such peculiar and small shape [1, 8, 9, 10, 11].

In this paper, we present an easy and inexpensive method to fabricate mesa-type small IJJs using a cross-whisker junction [13, 14] (CWJ) of Bi2212. After the CWJ was fabricated, argon ion milling was carried out. At the time the CWJ was being milled by argon ion beam, the upper whisker played a role of mask to protect the bottom whisker. As a result, a mesa-structure IJJs were developed under the upper whisker. The c-axis feature in both temperature dependences of resistance and current-voltage (IV) characteristics were enhanced with increasing times of milling.
2. Experimental

Bi2212 single crystalline whiskers were grown by tellurium-doped method [12]. The CWJ was fabricated by annealing of two Bi2212 whiskers crossed each other on the magnesium dioxide substrate at 840 - 850 °C with an atmosphere of oxygen [13, 14]. Then four electrodes of silver-epoxy were contacted to the end of the whiskers by hand. A schematic of the CWJ is shown in Fig. 1 (a), (b), and an optical microscope image of the CWJ is also shown in Fig. 1 (c). In conventional mesa-type small IJJs, electrodes of normal metals are directly contacted on the top of the mesa [8, 5]. Thus the effective temperature of IJJs may increase by Joule heating of the lead metal or the contact part. In contrast, the electrodes are separated from the mesa part in the CWJ. These two parts are connected each other by the superconducting whiskers. Therefore in contrast to the case in the conventional mesa, the heating effect could be neglected in the CWJ. Moreover, we can easily glue the electrodes by hand without complicated and time-consuming process such as vacuum evaporation, photolithography, and electron-beam lithography. The size of the junction area is about 150 × 147 μm².

A mesa-structure was fabricated by means of argon ion milling. We show the fabrication process in Fig. 2. Argon ion beam was showered onto the CWJ to gradually mill the surfaces of the two whiskers (Fig. 2 (b)). The upper whisker plays a role of mask in this process. As a consequence, small mesa-shaped IJJs are fabricated below the overlapped area (Fig. 2 (c)). The irradiation conditions are following: ion current was 10 mA and acceleration voltage was 500 V. We performed electrical transport measurements after each milling to investigate how the milled CWJ changes by the ion milling process. The size of the mesa IJJs can be controlled by choosing whiskers having proper widths. (The width of Bi2212 whiskers is typically 5 - 200 μm.) Moreover, we can control the number of the layers of IJJs in this method by changing the milling time with a considerable accuracy within 10 layers. A layer-by-layer control of Bi2212 IJJs has been already reported by You et al. [10].

Transport properties were measured by four probe method in the temperature range of 5 -
Figure 2. A schematic of the ion milling process to fabricate mesa-structure inside the cross-whisker junction. (a): A cross-sectional view of the cross junction part before milling. (b): A schematic in the milling process; the upper whisker plays a role of mask to protect the junction area. (c): The small mesa IJJs are fabricated inside the cross-whisker junction after milling.

300 K using a physical property measurement system (PPMS, Quantum Design) or a helium-free refrigerator (Janis research). The bias voltage was generated by an analog function generator (NF, FG-163). The voltages across the CWJ and the series resistance were amplified by differential amplifiers (Stanford Reseach Sys. SR560). The voltage across the series resistance was measured to monitor the current. The output voltages from the amplifiers were measured by both an analog and a digital oscilloscopes (IWATSU SS-7804/02 and YOKOGAWA DL750).

3. Results and Discussion

The temperature dependences of the resistance of the CWJ are shown in Fig. 3 (a). Three curves were measured after each milling process. After two minutes milling, the resistance becomes much larger than that of before milling in the normal state. The thickness of the mesa-structure should be developed by the ion milling, resulting in increasing of the resistance. From 110 K down to 82 K, superconducting transition occurs with three steps. The two steps at 110 K and 100 K are attributed to the intergrowth of the $\text{Bi}_2\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_{10+\delta}$ as reported in ref. [12, 13]. The resistance becomes further larger after the milling of two minutes more, while the shape of the $R - T$ curve is unchanged. It is worth noting that the critical temperature $T_c$ before and after milling is almost unchanged. This fact strongly suggests that the sample is not seriously damaged in the argon ion milling process, although the reason of the sudden peak of the resistance at 110 K is unclear.

Current-voltage ($IV$) characteristics of the CWJ measured at 5 K is presented in Fig. 3 (b). It is found that the critical currents are suppressed after ion milling. Moreover, the shapes of the IV curves obtained before and after milling are obviously different. The IV characteristic obtained before milling exhibits a series of small voltage jumps, but are similar to characteristics of overdamped resistively shunted junction. The gaps are reflected in the structure of intrinsic Josephson junctions of the CWJ, although the gap value 4 mV is much smaller than that of the well-known value, 20 mV, of $\text{Bi}_2\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_{10+\delta}$. Actually, the as-grown CWJ tends to behave as an overdamped resistively shunted junction [13, 14]. The edges of the cross-junction part may be in the normal state because of partial melting during the high temperature annealing process, and act as shunt resistors. After first and second milling, in contrast, the IV characteristics exhibit an unshunted underdamped junction behavior. The partially melted part in the edges
which worked as a shunt resistor before milling will be removed in the argon milling process. These two IV characteristics are similar to a typical multi-branch structure seen in the mesa-type \cite{8} and s-shaped \cite{9,10,11} small IJJs of Bi2212. This result suggests that masa-type small IJJs were fabricated in the cross-junction part of the CWJ.

4. Conclusion
We fabricated the mesa-type small intrinsic Josephson junctions using the cross-whisker junction by means of argon ion milling. The transport properties of the small mesa IJJs were examined before and after each milling process. As a result, the changes of the temperature dependences of the resistance and the current-voltage characteristics were found. The milled cross-whisker junction exhibited a typical multi-branch structure seen in the mesa-type and s-shaped small IJJs of Bi2212. This method enables us to fabricate micron sized small IJJs without expensive devices specialized to microfabrications.

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Figure 3. (a): Temperature dependences of the resistance of the cross-whisker junction after each milling process. (b): Current-voltage characteristics of the cross-whisker junction at 5 K before and after ion milling.
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