Fabrications of Small and High-quality Intrinsic Josephson Junctions by Combinatorial Method of Ar-ion and Focused Ga-ion Etchings

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Abstract. We present a study on the fabrication of the intrinsic Josephson junctions (IJJs), which are made of Bi$_2$Sr$_2$CaCu$_2$O$_y$ (Bi2212) single crystals, by using the focused Ga-ion etching and the Ar-ion etching. We made sure that the current-voltage ($I$-$V$) characteristics of small IJJs was never influenced by the direction of a Ga-ion beam in the focused ion beam (FIB) etchings. In addition, it was found that Ar-ion etching after FIB process is quite useful to improve the performance of the $I$-$V$ curves of IJJs. By using a substrate with a small hole, we succeeded in employing the double-side Ar-ion etching after the FIB microfabrication. These results strongly support that the combinatorial method of FIB and Ar-ion etchings is very important to fabricate the small and high-quality IJJs.

1. Introduction

The discovery of the intrinsic Josephson junctions (IJJs) of high-$T_c$ cuprate superconductors have stimulated many studies on the macroscopic quantum tunneling (MQT) observed for the phase switches from the zero voltage state [1,2] and finite voltage state [3-5], and those on the interlayer tunnel spectroscopy probing the superconducting gap and the pseudogap [6-8]. For such studies, the fabrication of small and high-quality IJJs is crucially important. The previous study on ultrasmall IJJs (a lateral area was 0.3 $\mu$m$^2$), which were fabricated from Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ (Bi2212) by the focused ion beam (FIB) etching, suggested that the current-voltage ($I$-$V$) characteristics of small IJJs was degraded by the damage generated in the FIB etching processes [9]. Another study on the submicron IJJ stacks made of La$_{2-x}$Sr$_x$CuO$_y$ (La214) reported that an argon ion etching after FIB etching was useful to control the thickness of IJJs [10]. Recently, the transmission electron microscope (TEM) study of Bi2212-IJJs suggested that the amorphous damage produced by FIB etchings was successfully removed by an additional argon ion etching [11]. Thus, the appropriate combination of FIB and Ar ion etching techniques is expected to improve the performance of small stacked IJJs.

Here, we present a study on the fabrication of Bi2212-IJJs by using FIB and Ar-ion etchings. First of all, we confirmed that the $I$-$V$ characteristics of the bridge-type IJJs, where IJJs were sandwiched by two slits fabricated on the side wall of a microbridge (See also Fig. 1), was never influenced by the direction of a Ga-ion beam in the FIB etching processes. This shows a good agreement with the recent report that the thickness of FIB damage is independent of the direction of the Ga ion beam [11]. We also demonstrate that Ar ion etching after FIB process is quite useful to improve the $I$-$V$ characteristics
of IJJs. Furthermore, we succeeded in employing the double-side etching by the irradiation of Ar ions after the FIB fabrication, by using a substrate with a micro-hole. These results strongly support the importance of the combinatorial method of FIB and Ar-ion etchings for the fabrication of small and high-quality IJJs.

![Diagram](image)

**Figure 1.** (Color online) Schematic of the FIB or Ar-ion etching processes to fabricate the bridge-type Bi2212-IJJs in (a) Method 1, (b) Method 2, (c) Method 3, and (d) Method 4.

### 2. Experiments

Bi2212 single crystals were grown by the floating zone method and annealed to be optimal doped. We fabricated the bridge-type Bi2212-IJJs by using the following four methods. Method 1 is the conventional FIB method where two slits nearby IJJs are fabricated after the fabrication of the microbridge, as illustrated in Fig. 1(a). Details of this method are described in elsewhere [11]. Method 2 is similar to a method investigated by Matsumoto *et al* [9]. In this method, as shown in Fig. 1(b), the finishing fabrication of the microbridge is done after the fabrication of two slits, in contrast to Method 1. Method 3 is a combinatorial method of FIB and Ar ion etchings, which was proposed by Kubo *et al* [10]. In this method, one of slits is finished by Ar ion etching after FIB etching, as shown in Fig. 1(c). Method 4 was newly developed in this work, based on the achievement of Method 3. In this method, both slits are finished by the additional Ar ion etchings, as shown in Fig. 1(d). Instead of a usual sapphire substrate, we use a silicon substrate with a square hole (50×50 μm²), which has often been prepared as a nanopore to detect DNA molecules [12].
The FIB and Ar ion etchings were performed by using a JEOL JEM-9310FIB at 30 kV and an ELIONIX EIS-200ER at 1100 V, respectively.

3. Results and discussion
In this work, we measured the $I$-$V$ curves of 22 devices fabricated by 4 methods shown in Fig. 1. Figure 2 shows the typical $I$-$V$ characteristics of the IJJs (the lateral area is 1.2x0.98 $\mu$m$^2$), fabricated by using Method 1. We estimated the magnitude of the switching current $I_{SW}$ and of the voltage jump $V_{jump}$ for the first and the maximum-ordered switching events, as shown in Fig. 2. We compared the results obtained for Method 1 with those for Method 2. Figures 3(a) and 3(b) show the plots of the switching current density $j_{SW}$, which is the switching current for a unit junction area, for the 1st and the maximum-ordered switches as a function of the lateral area $S$, respectively. Figures 3(c) and 3(d) show the plots of $V_{jump}$ versus $S$ for the 1st and the maximum-ordered switches, respectively. These data were obtained in a low temperature region ($T/T_c$ ~ 0.05 to 0.1), where the temperature dependence of $j_{SW}$ and $V_{jump}$ was found to be negligibly small. We also found that there was a distribution in the measured values of $T_c$ for the IJJ devices, determined by the onset temperature of the superconducting transition in the dc resistance, as shown in Fig. 3(e) [13]. This indicates that the FIB etching processes give the damage degrading the superconducting properties to the IJJ devices. However, in contrast to the previous report by Matsumoto et al. [9], we did not observe any advantage of Method 2.

Independent of the difference between Method 1 and Method 2, our results show a common feature that the magnitude of $j_{SW}$ and $V_{jump}$ is decreased with decreasing $S$, except for $j_{SW}$ for the maximum-ordered switches ($j_{SW}^{max}$). We found that the magnitude of $j_{SW}^{max}$ was not decreased very well even for IJJs with small $S$. These results strongly suggest that the $I$-$V$ characteristics of the bridge-type IJJs is never influenced by the direction of a Ga-ion beam in the FIB etching processes. It shows a good agreement with our resent TEM observations that the thickness of FIB damage (~30 nm for a beam emitted at 50 pA and 30 kV) is independent of the incident direction of the Ga-ion beam [11].

![Figure 2. $I$-$V$ characteristics of the IJJs (the lateral area is 1.2x0.98 $\mu$m$^2$), which were fabricated by Method 1.](image-url)
Next, we performed similar estimations of the \( I-V \) characteristics for 5 IJJ devices, which were fabricated by using Method 3. Although this method has originally been developed to control the junction number involved in the La214-IJJs [10], we applied it to the removal of the damage region produced in the FIB processes. Figures 4(a) and 4(b) show the plots of \( j_\text{SW} \) and \( V_{\text{jump}} \) as a function of the total irradiation time of Ar-ion etching, respectively. They were obtained in the low temperature region (\( T/T_c \sim 0.05 \) to 0.1). We confirmed that both of \( j_\text{SW} \) and \( V_{\text{jump}} \) roughly showed the increasing behavior with increasing the Ar-ion irradiation time, although there was a wide range in the data obtained at the same irradiation time. The difference between data obtained at the same irradiation time is considered to be due to the difference in the influences of FIB damages before Ar-ion etching, as suggested by the plots of \( T_c \) shown in Fig. 4(c). The recent TEM study also indicates that the additional Ar-ion etching after the FIB process successfully trims the FIB-induced damage [11]. Thus, it is concluded that the additional Ar-ion etching after the FIB etching plays an important role to improve the performance of the \( I-V \) curves of the bridge-type IJJs.

![Figure 3.](image)

**Figure 3.** (Color online) Comparison between Method 1 (solid circles) and Method 2 (open circles). Symbols with the same color represent the data for the same device. (a) Plots of \( j_\text{SW}^{1\text{st}} \) versus \( S \). (b) Plots of \( j_\text{SW}^{\max} \) versus \( S \). (c) Plots of \( V_{\text{jump}}^{1\text{st}} \) versus \( S \). (d) Plots of \( V_{\text{jump}}^{\max} \) versus \( S \). (e) Plots of \( T_{c_{\text{onset}}} \) versus \( S \).

Finally, based on the experimental results obtained by Method 3, we tried to develop the new fabrication method (Method 4), which pursued the additional Ar-ion etching after the FIB processes in order to remove the FIB damage more completely. In Method 4, both slits are additionally etched by Ar-ion irradiation, while only one of slits is additionally etched in Method 3.
Figure 4. (Color online) (a) $j_{SW}^{1st}$ and $j_{SW}^{max}$ for 5 IJJs fabricated by Method 3 as a function of the irradiation time of Ar-ion etching. (b) Similar plots of $V_{jump}^{1st}$ and $V_{jump}^{max}$. (c) Similar plots of $T_{c}^{onset}$. Note that symbols with the same color represent the data for the same device.

Figure 5. (Color online) (a) $I$-$V$ characteristics of the IJJs (the lateral area is $1.3 \times 1.1 \ \mu m^2$), which were fabricated by Method 4. The total irradiation time of the Ar-ion etching was 5 min for each slit. (b) Plots of $j_{SW}^{1st}$ and $j_{SW}^{max}$ for 4 IJJs fabricated by Method 4 as a function of the irradiation time of Ar-ion etching for each slit.

Figure 5(a) shows the $I$-$V$ characteristics of the IJJs (the lateral area is $1.3 \times 1.1 \ \mu m^2$), fabricated by Method 4. The total irradiation time of the Ar-ion etching was 5 min for each slit, which was the same as the maximum value in Method 3. As shown in Fig. 5(b), we confirmed that $j_{SW}^{1st}$ was monotonously increased with increasing the irradiation time of the Ar-ion beam, although the magnitude of $j_{SW}^{1st}$ was not as largely enhanced as that shown in Fig. 4(a). More systematic investigation is needed to demonstrate the advantage of Method 4.
4. Conclusion
We present the detailed comparison between the characteristics of Bi2212-IJJs fabricated by four different methods. From the results obtained by Methods 1 and 2, we concluded that the incident Ga-ion beam direction in the FIB processes did not influence to the $I$-$V$ characteristics. We also demonstrated that the additional Ar-ion etching after the FIB processes, which was applied in Methods 3 and 4, was quite useful to improve the performance of the $I$-$V$ characteristics measured for the bridge-type IJJs. This effect is probably because the damage region due to the FIB etching processes is successfully removed by the Ar-ion etching. Thus, the combinatorial method using both the Ar-ion and the focused Ga-ion beams has a beneficial effect on the fabrication of the high quality IJJs.

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