Fabrication of YBaCuO Junctions by the Irradiation of Focused Ion Beam

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Abstract— **We have fabricated Josephson junctions in $YBa_2Cu_3O_{7-\delta}$ (YBaCuO) thin films by the irradiation of focused ion beam (FIB). We used Be^{2+} ions with the energy of 200 keV. When the fluence of Be^{2+} ions was 1.2×10^{16} ions/cm^2, the I–V characteristics of the junctions at 4.2 K showed RSJ-like characteristics with the excess current. The I_cR_n product of the junctions was 1.1 mV at 6.3 K. Shapiro steps up to 20th step could be observed by the irradiation of 8.47 GHz microwave at 6.3 K. The magnetic modulation curve of the junction at 4.2 K was similar to the Fraunhofer pattern. These characteristics remained unaltered after preservation in a desiccator for 6 months.**

I. INTRODUCTION

It is important for high-T_c Josephson junctions that the current flows in the a–b plane of the superconducting thin film. High-T_c Josephson junctions were fabricated using focused ion beam [1], [2], ion implantation combined with a lithography technique[3], [4], and direct writing electron beam damage[5]. In these junctions, the current flows in-plane.

We have fabricated Josephson junctions using a 200 keV focused Be^{2+} ion beam. We used Be^{2+} ions because they are smaller and have larger charges than Ga^+ ions, which make them reach deeper areas into the YBaCuO film. High energy Be^{2+} ions pass through the YBaCuO thin film, induce the defects in the film, and are embedded in the substrate. The ion damage profile is nearly uniform in depth. The lateral scattering of ion damage is small in the YBaCuO thin film.

The narrow damaged region was made across the YBaCuO bridge by the line-scan of FIB. This FIB process allows considerable flexibility in the location and orientation of the junctions. Other merit of the process is its ease of fabrication (only a single high-T_c thin film is required.)

In this paper, we report the fabrication of Josephson junctions with various conditions of ion damage, and the measurement of these junctions' several characteristics such as current-voltage (I–V), Shapiro steps, and magnetic field modulation.

Furthermore, we have investigated the junctions' stability to annealing and aging.

II. FABRICATION

The fabrication method of the FIB junctions is shown in Fig.1.

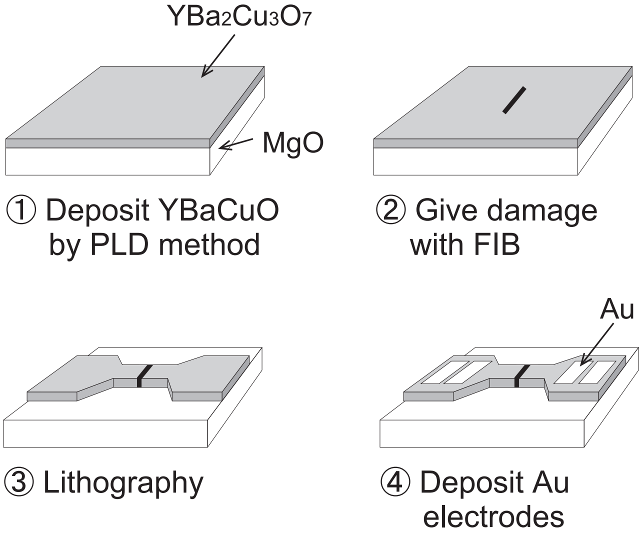

Fig. 1. The fabrication method of the FIB junctions.

1. Deposit YBaCuO on MgO substrate by pulsed laser deposition (PLD) method. The film thickness is about 100 nm.
2. Draw a line on the film with FIB apparatus using Be^{2+} ions. The YBaCuO crystal at the irradiated area is damaged and loses superconductivity.
3. Make bridge patterns by lithography, YBaCuO being removed by HNO_3 wet etching. The width of the bridge is 10 μm.
4. Deposit Au electrodes and measure the characteristics.

The deposition of YBaCuO film was performed with KrF eximer laser. The energy and the repetition rate were 230 mJ/shot and 2 Hz, respectively. The oxygen pressure during the deposition was 0.4 Torr. The temperature of the MgO substrate was 690∼730°C. T_c of the deposited film was about 80 K.

We used Be^{2+} ions as the ion source of the FIB. The acceleration voltage was 100 kV. The beam current and the diameter of the beam were 8 pA and 50 nm, respectively. We think the junction length is a little longer than this value, because the ion beam can not proceed straight in the film but is considered to be scattered.

III. CHARACTERISTICS

A. I–V characteristics

The I–V characteristics of the junction depend on the amount of the damage given by the irradiation of ion beam.

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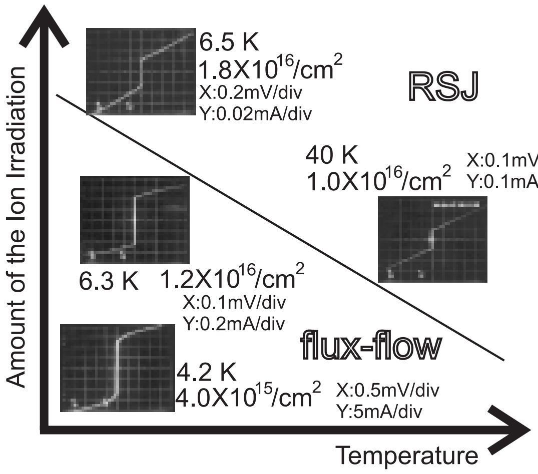

Fig. 2. The dependence of I–V characteristics on the fluence of the beam irradiation and the temperature.

The dependence of I–V characteristics on the fluence of the beam irradiation and the temperature is shown in Fig.2.

It is obvious from this figure that when the irradiation fluence is small, the I–V curve is flux-flow type regardless of the temperature. On the contrary, the curve is RSJ type when the irradiation fluence is large. If the irradiation fluence is medium, the junction shows RSJ type curve at high temperatures and flux-flow type curve at low temperatures.

The value of I_c decreases as the irradiation fluence increases, because the junction length increases along with the irradiation fluence, which is due to the Gaussian distribution of the beam intensity profile (detailed explanation is written in section IV-A.)

The I_cR_n product was 1.1mV when the irradiation fluence was 1.2×10^{16} ions/cm^2. R_n was determined by measuring the resistance of the junction at the point where I_c became zero by the irradiation of microwave.

Shapiro steps were observed by the irradiation of microwave. When the microwave of 8.47 GHz was irradiated to the junction at 6.3 K, Shapiro steps up to 20th step were observed.

B. The magnetic field modulation of the I_c

I_c modulation was observed when magnetic field was applied. The modulation pattern of the I_c is shown in Fig.3. The beam irradiation fluence was 1.0×10^{16} ions/cm^2. Fig.3–(a) and (b) are the patterns measured at 4.2 K and 60 K, respectively. The value of the I_c at 4.2 K is about 10 times larger than that measured at 60 K, but in Fig.3 they are normalized, the maximum peak amplitudes of each pattern being the same height, in order to simplify the comparison. These figures show that

- in Fig.3-(a), the modulation amplitude ratio is small, the excess current ratio is large, and the modulation pattern is Fraunhofer-like.
- in Fig.3-(b), the modulation amplitude ratio is large, the excess current ratio is small, and the modulation pattern is SQUID-like.

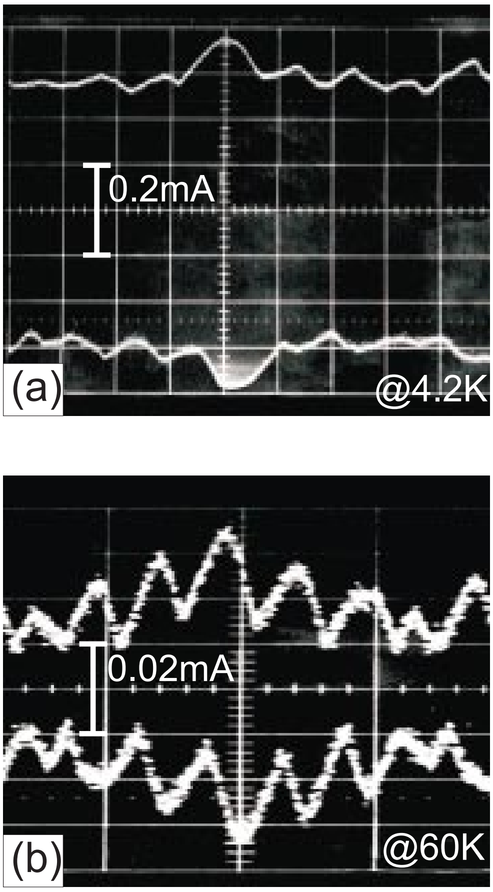

Fig. 3. I_c modulation pattern with the magnetic field. (a):4.2K, (b):60K.

C. stability

We have investigated the junctions' stability to low temperature annealing and aging.

C.1 stability to low temperature annealing

We put the junctions in a furnace and annealed. Then the I_c of the junction was measured. Annealing was done at room temperature, 100°C, 150°C, and 200°C in this order. Each time we kept the substrate at the indicated temperature for 2 hours in air atmosphere. A typical result is shown in Fig.4. The annealing at 150°C increased the I_c value by 7 %, but that at 200°C did not increase it any more. The damage given by FIB can not be recovered by annealings at up to 200°C. This proves that the damage is not only the lack of oxygen.

C.2 stability to aging

We preserved junctions in a desiccator (humidity was about 20 %) for 6 months. The magnetic field modulation patterns of the junction before and after the preservation is shown in Fig.5.

The patterns shown in Fig.5-(a) and (b) are almost identical. This means that the current path in the junction had not been changed during the period.

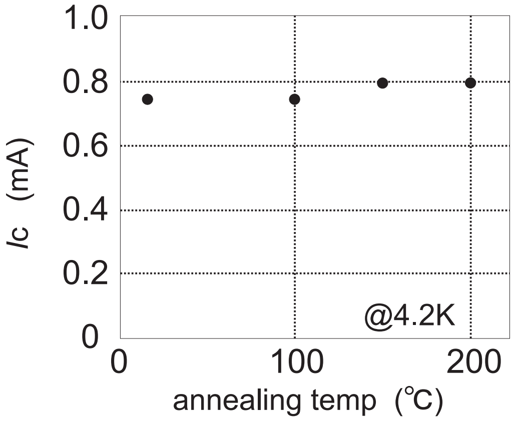

Fig. 4. The value of I_c after annealing.

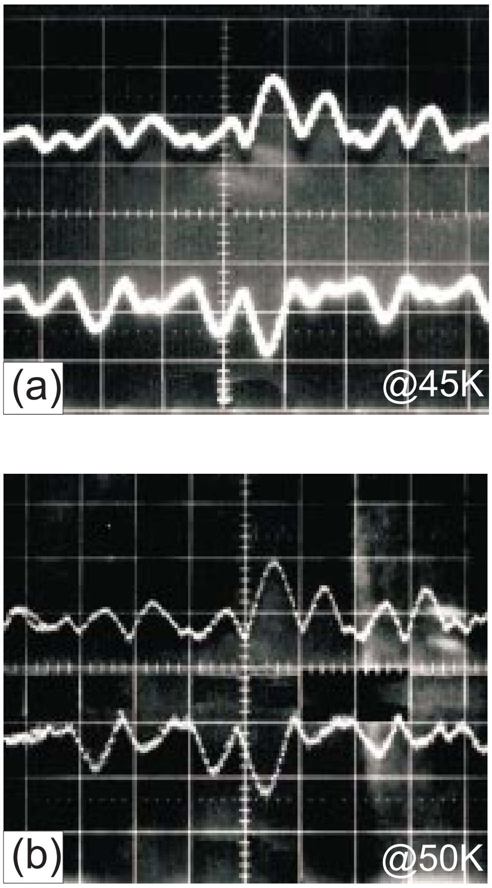

Fig. 5. The magnetic field modulation pattern.
(a):before preservation, (b):after 6 months preservation.

IV. Discussion

A. *junction length — variety of damage (longitudinal direction)*

The ion beam intensity profile is considered to be Gaussian distribution. In fabrication of FIB junctions, the beam is line-scanned on the YBaCuO film. Therefore, the damage given by the beam irradiation is largest at the center of the scanned line and it decreases as the distance from the center increases (Fig.6-(a)).

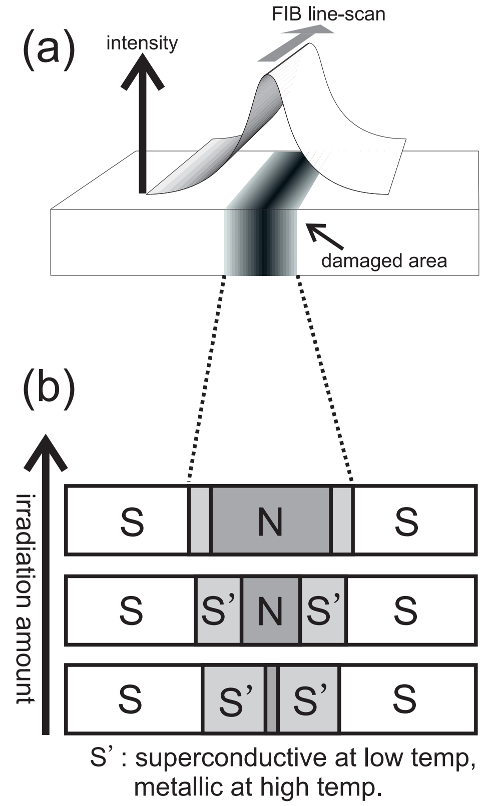

Fig. 6. Schematic models of the FIB junction.
(a):irradiation intensity profile, (b):the normal-metal area is broadened by increasing the irradiation fluence.

The strongly irradiated area shows normal-metal characteristics regardless of the temperature (abbreviated as N in the figure). On the other hand, the weakly irradiated area shows normal-metal characteristics at high temperatures and superconductive ones at low temperatures (abbreviated as S'). The T_c decreases with the increase of the irradiation fluence and when the fluence exceeds some threshold, the area totally loses superconductivity.

The cross-sectional views of the model of the FIB junction are shown in Fig.6-(b). When the irradiation fluence is small, only the narrow center part of the irradiated area becomes N and the both sides of the part becomes S'. However, if the irradiation fluence is large enough, wider area becomes N. Therefore the practical junction length becomes longer along with the irradiation fluence.

This is why the I_c of the FIB junction decreases as the irradiation fluence increases.

B. *micro-shorts — variety of damage (across the bridge)*

The existence of the excess current means that there are micro-shorts in the junction.

As described before, the excess current ratio is small at high temperatures (Fig.3). This phenomenon is explained as follows : when the temperature is low, most of S' area shows superconductive character. Therefore, the junction length is very short, especially when the irradiation fluence

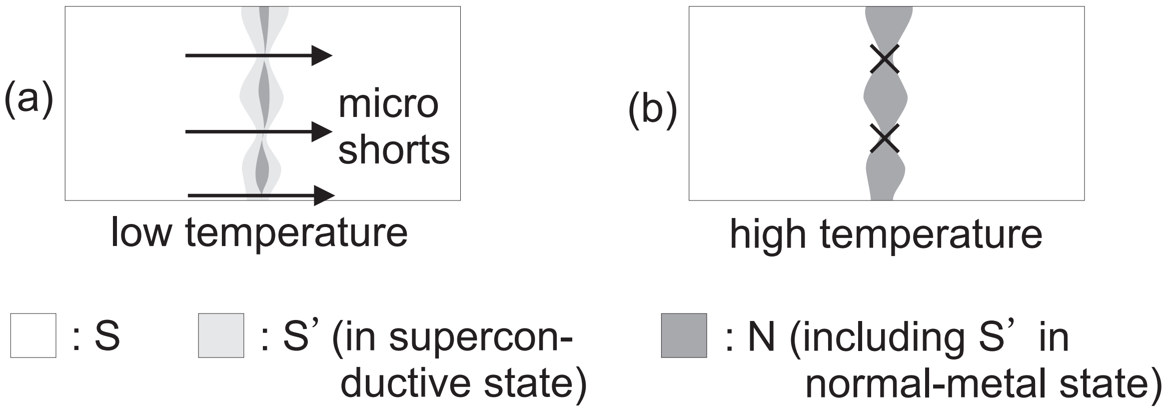

Fig. 7. (a):many micro-shorts, (b):SQUID-like.

is small (= the case drawn at the bottom of the three views in Fig.6-(b).) However, there are also position dependence of damage *across* the bridge because of the variety of the film thickness, etc. Many micro-shorts exist in a junction because of this position dependence (Fig.7-(a).) The excess current is larger at lower temperatures due to these micro shorts.

When the temperature is relatively high, most of S' area shows normal-metal character. This time, instead of micro shorts, there exist many junctions in parallel (Fig.7-(b)), and this forms a kind of SQUID. That is the reason why the pattern shown in Fig.3-(b) is SQUID-like.

V. Conclusions

We have fabricated Josephson junctions in the YBaCuO thin film by the irradiation of focused Be ion beam. When the irradiation was 1.2×10^{16} ions/cm^2, the $I_\mathrm{c}R_\mathrm{n}$ product of the junctions was 1.1 mV at 6.3 K. Fraunhofer-like pattern was observed when the magnetic field was applied and Shapiro steps up to 20th step were observed by the irradiation of 8.47 GHz microwave at 6.3 K. These characteristics remained unaltered after preservation in a desiccator for 6 months, or annealing at 200°C for 2 hours. From the characteristics of the junctions fabricated with different beam irradiation fluence, we proposed a model of the FIB junctions.

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