FABRICATION OF YBACUO NONSUPERCONDUCTIVE-YBACUO/YBACUO COPLANAR JOSEPHSON-JUNCTION BY FOCUSED ION-BEAM

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Fabrication of YBaCuO/nonsuperconductive-YBaCuO/ YBaCuO co-planar Josephson Junction by Focused Ion Beam

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Abstract—**Thin film of $YBa_2Cu_3O_{7-\delta}$ grown on the MgO substrate damaged by a focused ion beam loses superconductivity due to an abnormal growth. We have fabricated a $YBa_2Cu_3O_{7-\delta}$ co-planar Josephson junction whose coupling region is a non-superconductive $YBa_2Cu_3O_{7-\delta}$ grown on an MgO substrate damaged locally by a scan of a focused ion beam. The I-V characteristic of the junction behaves like a flux flow type. At temperatures from 4.2K to 60K, Shapiro steps were observed for the junctions in which the length of the coupling region was from 0.2 μm to 1 μm . The highest IcRn product of the junction was 5.0mV. The critical current density decreased exponentially with the junction length. It is considered that nonsuperconductive $YBa_2Cu_3O_{7-\delta}$ grown on the damaged substrate works as a normal layer in an S-N-S junction. Also the junction responded to the magnetic field and behaved like asymmetric dc-SQUID.**

I. Introduction

Most of high-T_c Josephson junctions have lower I_cR_n products than gap voltage of low-T_c metallic Josephson junctions. To fabricate high-T_c Josephson junctions with higher I_cR_n product is important for implementing digital circuits. Regarding the implementation of integrated circuits, co-planar Josephson junction using c-axis oriented YBaCuO thin film is required due to the in-plane conduction of YBaCuO film. Thin films of $YBa_2Cu_3O_{7-\delta}$(YBaCuO) grown on an MgO substrate damaged by a focused ion beam(FIB) lose superconductivity due to an abnormal growth on the irregular crystal structure of MgO. We have fabricated a YBaCuO co-planar Josephson junction whose coupling region was a non-superconductive YBaCuO grown on an MgO substrate damaged locally by a scan of FIB [1]- [2]. The fabrication process of this junction is simple, since the deposition of YBaCuO on the substrate makes up most part of this junction. As damages by FIB can be placed freely on a chip, it gives much freedom to designing circuits.

In this paper, a co-planar Josephson junction is fabricated by changing the condition of damage and the size of the junction. Several characteristics of these junctions are measured, including the I-V characteristic, the critical current density, and the magnetic field modulation. Furthermore, we discuss how the current flows through the non-superconductive YBaCuO.

II. Experimental

First, we describe the fabrication process of a YBaCuO / non-superconductive YBaCuO / YBaCuO co-planar Josephson junction by FIB. A schematic drawing of the fabrication process of the junction is shown in Fig.1. The fabrication process is as follows:

(a) A protective layer of gold (Au) with 40nm thick was deposited on an MgO (100) substrate by a vacuum evaporation, to avoid the charging effect by FIB and to protect the surface of substrate except the damaging area.

(b) Local damage was performed on the substrate by a scan of FIB with $1.0\times10^{17} \sim 4.0\times10^{17}$ions/cm^2 doses. A high energy ion beam of 80KeV and 0.2 μm in diameter was used. The implanted ion was Ga^+.

The coupling region of a junction induced by the damage at the center of the substrate had a width of 50μm and a length of 0.2~1.0μm.

(c) After the scan of FIB, the protective layer of Au was removed by chemical etching using KI + I_2 solution. Contamination on the substrate was removed using a supersonic washing machine.

(d) C-axis oriented YBaCuO thin film was deposited on the whole substrate including the damaged region by rf-sputtering method with an rf-power of 150W in the mixed gas that consisted of Ar and O_2 in the ratio of 4:1 at 700 °C. The thickness of deposited YBaCuO was 300nm. The critical temperature of the thin film was 70K.

(e) Finally, by a standard photolithographic process, we patterned YBaCuO bridge with a width of 5~30μm and a length of 20μm over the locally damaged region by FIB, and obtained the junction containing the damaged portion. Au electrodes were deposited on YBaCuO thin film to measure the junction using the four-probe method. The YBaCuO / non-superconductive YBaCuO / YBaCuO co-planar Josephson junction was completed by the process mentioned above.

For these devices, we examined the characteristics of the junction in several aspects: I-V curve, Shapiro steps, the critical current density dependence on junction length, and the magnetic field modulation.

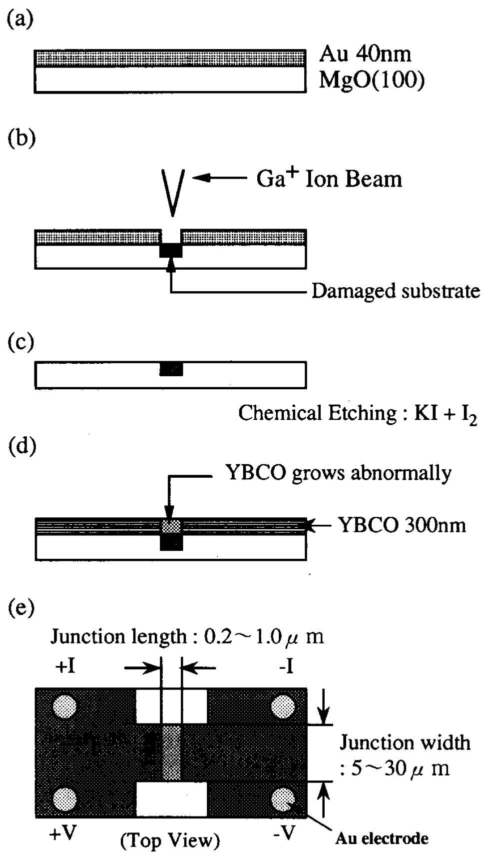

Fig. 1. Fabrication process of a YBaCuO co-planar junction using FIB. (a) Deposition of Au as a protection layer. (b)Damage to MgO substrate by FIB. (c)Removing of Au layer. (d)Deposition of YBaCuO thin film by rf-sputtering. (e)Patterning Josephson junction.

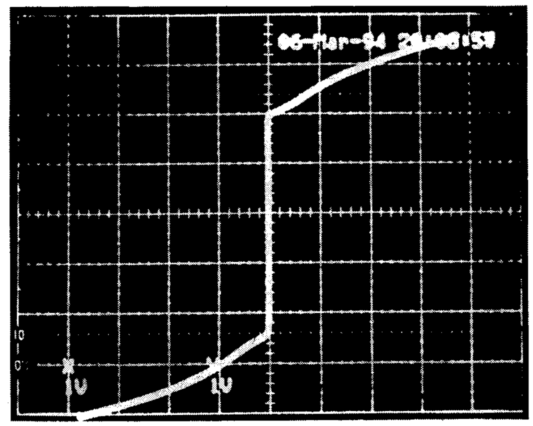

Fig. 2. The I-V characteristic of the junction with a length of 0.2 μm and a Ga^+ ion dose of $2 \times 10^{17}[ions/cm^2]$ at 4.2K. x-axis: voltage 0.2mV/Div; y-axis: current 1.0mA/Div.

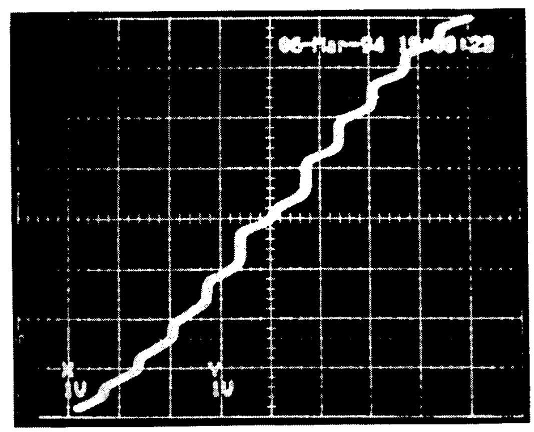

Fig. 3. The I-V characteristic when irradiated with microwave of 8.325GHz at 33K. x-axis: voltage 20μV/Div; y-axis: current 0.2mA/Div.

III. Results and Discussion

A. The I-V characteristic

The I-V characteristic is shown in Fig.2 for a junction length of 0.2 μm and a Ga^+ ion dose of 2×10^{17}[ions/cm^2] at 4.2K. The critical current is 2.2[mA]. The IcRn product of the junction is 1.1[mV]. The highest IcRn product of fabricated junctions is 5.0[mV] at 4.2K. We measured the normal resistance Rn of junction when irradiated with high power microwave.

B. The I-V characteristic when irradiated with microwave

Figure 3 illustrates the I-V characteristic when irradiated with microwave of 8.325GHz for the same junction shown in Fig.2.

Sharp Shapiro steps were observed as shown in Fig.3 for the wide range of temperature from 4.2K up to 60K. The frequency of irradiated microwave(f) was 8.325GHz. A step interval voltage (V_s) of 16.5μV is calculated from this frequency, and it corresponds well with the measured value of V_s in Fig.3. Up to the 16th step of Shapiro steps could be observed in this junction, and highest one corresponds to 133.2GHz.

Furthermore, the dependence of step heights on microwave power is shown in Fig.4. The supercurrent decreased in proportion to the microwave power. This dependence on microwave power is similar to the power characteristic of current source model of RSJ circuit [6].

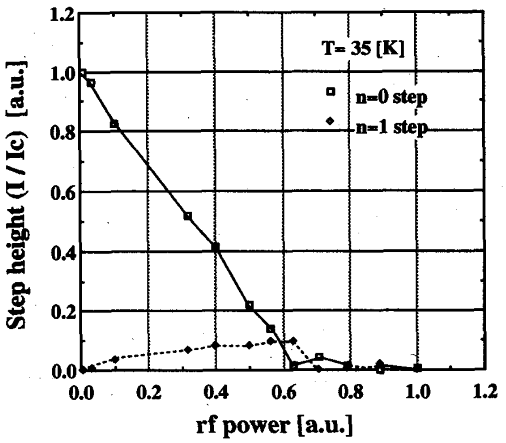

Fig. 4. Step heights versus microwave power at 35K. x-axis: microwave power a.u.; y-axis: current a.u. Frequency: 8.325GHz.

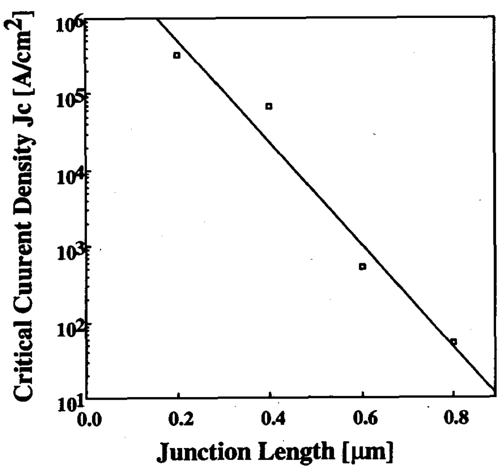

Fig. 5. Critical current density versus junction length.

C. *The critical current density dependence on junction length*

Using the same dose of Ga^+ ion, we fabricated junctions with different junction lengths between $0.2\mu m$ and $0.8\mu m$ and measured the characteristics of critical current density. The dependence of the critical current density on the junction length(Jc-L) is shown in Fig.5.

The critical current density decreased exponentially with the junction length. It is considered that nonsuperconductive YBaCuO grown on the damaged substrate works as a normal layer in an S-N-S junction with a proximity effect. On the other hand, the surface looks like the series of two steps in the SEM micrograph of the junction [2]. It is possible that the junction is the series of two step junctions.

However this Jc-L characteristic is in contrast to the case of the artificial grain boundary Josephson junction with a step-edged geometry that has been reported, where no decrease in the critical current density is observed with increasing the step length [7]-[9]. As a result, it is considered that a junction is not the series of two junctions but the junction whose coupling region is a non-superconductive YBaCuO.

D. *The characteristic of magnetic field modulation.*

We measured the dependence of the critical current on the magnetic field for the junction at 4.2K. The junction length is $0.6\mu m$ and the junction width is $30\mu m$. Figure 6 shows the magnetic field modulation of the critical current in the junction. This characteristic was similar to Fraunhofer-like diffraction pattern. The irradiated magnetic field was one hundred times as large as the magnetic field estimated from the fabricated junction area. Hence, it is considered that Josephson current flows in the narrow path across the coupling area.

We fabricated a junction with a width of 5 μm to obtain more uniform junction. Also, the critical current of the junction was measured for various temperatures. The magnetic field modulation dependence on temperature is shown in Fig.7. To avoid the thermal effect of the coil that induced magnetic field, the range of magnetic field was from -12[Gauss] to 12[Gauss].

This characteristic is similar to the magnetic field modulation of a dc-SQUID whose junction size is probably in the same scale as the superconductive loop. The cycle of the critical current oscillation is about 3[Gauss]. The estimated value of junction area is $8 \times 10^{-8}[cm^2]$. On the other hand, the value calculated from the ac-

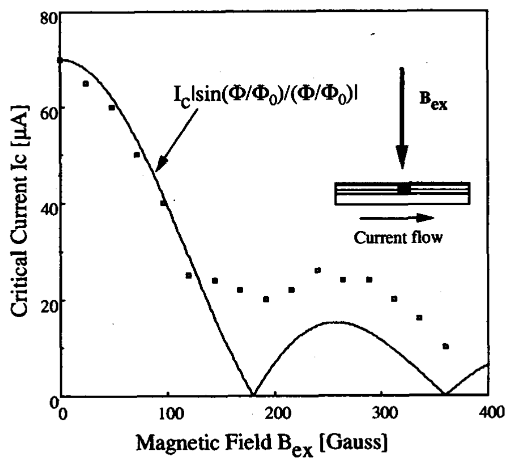

Fig. 6. The dependence of the critical current on the magnetic field at 4.2K.

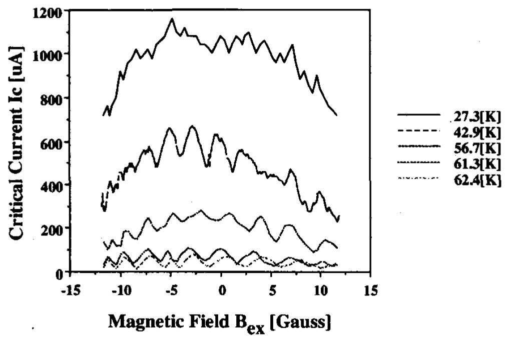

Fig. 7. The magnetic field modulation dependence on the temperature.

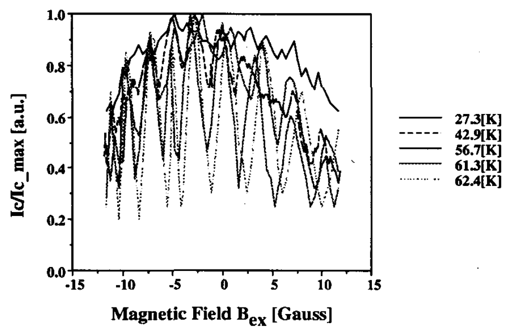

Fig. 8. The magnetic field modulation dependence on the temperature (the critical current is normalized).

tual junction size is $7 \times 10^{-8}[cm^2]$. These two values are probably the same. Also, it is expected that the critical current vanishes when the magnetic field is about ±20[Gauss]. The junction area estimated from this value was $1.2 \times 10^{-8}[cm^2]$. As a result, it is considered that the junction is the parallel of narrow junctions and behaves like dc-SQUID.

The magnetic field modulation of the critical current increased with the temperature(Fig.8).

In dc-SQUID, the magnetic modulation depends on the product of the loop inductance(L) and the circulate current(I_{cir}). When LI_{cir} is bigger than Φ_0 (quantum flux), the effect of self-magnetic field is big, and the magnetic field modulation is small. On the other hand, when LI_{cir} is much smaller than Φ_0 (quantum flux), the effect of self-magnetic field is small, and the magnetic field modulation is big. Since the critical current decreases with the temperature, the magnetic field modulation increases with temperature. Therefore, it is considered that abnormally grown YBaCuO consists of some narrow Josephson current paths and non-superconductive area. This junction behaves like non-symmetric dc-SQUID whose junction size is probably in the same scale as the superconductive loop.

IV Conclusion

We have fabricated a YBaCuO co-planar Josephson junction whose coupling region was a non-superconductive YBaCuO. The IcRn products of these junctions were from several hundreds μV to mV order (max. 5mV) at 4.2K.

At temperatures from 4.2K to 60K, Shapiro steps could be observed for the junctions in which the length of the coupling region was from 0.2 to 1 μm. The critical current density decreased exponentially with the junction length. It is considered that this junction is not two series of edge junction.

The magnetic modulation of the critical current behaves like non-symmetry dc-SQUID whose junction size is near the superconductive loop size. It is considered that the junction is the parallel of some junctions.

The magnetic field modulation of the critical current increased with the temperature. It is considered that the effect of self-magnetic field induced by a circulating current decrease with temperature.

Acknowledgment

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