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Magnetic Field Modulation of Critical Currents in YBaCuO Co-planar Josephson Junctions Using Focused Ion Beam

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Abstract—**The $YBa_2Cu_3O_{7-\delta}$ co-planar Josephson junctions by Focused Ion Beam were fabricated by changing the width and the thickness of a $YBa_2Cu_3O_{7-\delta}$ thin film. The magnetic properties of the junctions were measured at different temperatures. In the junction with 300 nm thickness, the magnetic field modulation of the critical current at 4.2K was not observed. Near the critical temperature of the junction, the magnetic modulation curve was similar to that of a dc-SQUID. From the SEM observation, some microshorts were observed on the junction. In the junction with 200 nm thickness, the I-V curve was changed from flux-flow junction type to RSJ type. The magnetic modulation curve of the 7 μm wide junction at 4.2 K was similar to a Fraunhofer pattern. Thus it is considered that the coupling region was changed from a microshort to weak coupling region, when the thickness of the YBaCuO film was decreased from 300 nm to 200 nm.**

I. Introduction

The magnetic properties of Josephson junction play an important role in the device application. The magnetic field modulation of the critical current is important for analyzing the distribution of Josephson current and the uniformity of the junction.

We have fabricated a $YBa_2Cu_3O_{7-\delta}$ (YBaCuO) co-planar Josephson junction by Focused Ion Beam (FIB) [1] - [6]. FIB was used to form a locally damaged region on the substrate before the deposition of a YBaCuO thin film. The shape of the damaged region was the line 0.2 μm wide. When the YBaCuO bridge across the damaged region was formed, the bridge had a weak link. The weak link was the YBaCuO thin film deposited on the damaged substrate.

In a previous paper [3], we have fabricated FIB co-planar Josephson junctions and measured the characteristics of the junctions in several aspects. The I-V curve of the junction was similar to that of a flux flow junction. The highest I_cR_n product was 5.0 mV at 4.2 K. The magnetic field modulation of the critical current was very small at 4.2 K.

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In this paper, the magnetic field properties of FIB junctions were measured at temperatures from 4.2 K to Tc of the junction. These junctions were fabricated by changing the width of a bridge and the thickness of a YBaCuO thin film. In addition, the uniformity of the junction was discussed from these results.

II. Experiments

Fabrication process of FIB Josephson junctions is described briefly in the following. The detail of this process was described in the previous report [3]. First, a scan of FIB does damage to the MgO (100) substrate that was covered by a 30 nm thick gold layer. The gold layer removes defocusing by the charging effect of the insulating MgO substrates. The irradiation fluence of Ga^+ ion was 1.0×10^{17} ions/cm^2. The damaged pattern was a line 0.2 μm wide and 50 μm long. The depths of the damaged lines were from 30 nm to 20 nm. These depths were ten times as small as the height of a step edge used for step edge junctions. Second, the gold layer was removed by chemical etching in KI + I_2 solution. C-axis oriented YBaCuO thin film was deposited by rf-magnetron sputtering method at 700 °C. The critical temperature of YBaCuO thin films were from 65 K to 70 K. After the deposition, YBaCuO bridges were patterned over the locally damaged area by a photolithography and chemical etching in 1% HNO_3 solution. The bridge length was 20 μm . Finally, gold electrodes were deposited on YBaCuO thin film by thermal evaporation at room temperature. Figure 1 shows a schematic illustration of a FIB junction.

In this experiment, the junctions were fabricated by changing the junction width (from 5 μm to 30 μm) and the thickness of a YBaCuO thin film (from 150 nm to 300 nm). The thickness of a YBaCuO thin film was measured

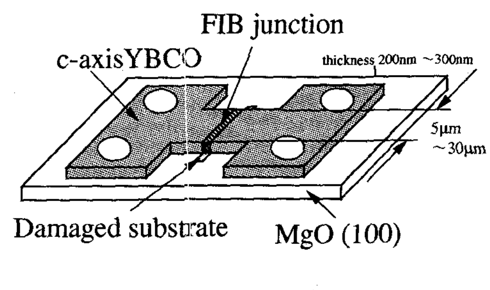

Fig. 1. Schematic illustration of YBaCuO co-planar Josephson junction using FIB

by a cross sectional analysis using Atomic Force Microscope. The electrical properties of the junction, I-V curve, the temperature dependence of I_c, and I_cR_n product, were measured by the conventional four-probe method. Furthermore, the magnetic field dependence of the critical current was measured at different temperatures from 4.2 K to T_c of the junction. The magnetic field was applied perpendicular to the substrate in order to irradiate the sample with the magnetic field effectively.

III. Results and Discussion

A. The magnetic field properties of the FIB junction with 300nm thickness

The FIB junctions were fabricated with the width of 30 μm, 20 μm, 15 μm, 10 μm, and 5 μm. In all samples, the width of the damaged line was 0.2 μm and the thickness of a YBaCuO film was 300 nm. At 4.2K, the 30 μm wide junctions had the critical currents from 2 mA to 5 mA and responded to the microwave. The I-V curve of the junction was close to that of a flux flow junction. However, these junctions did not respond to the magnetic field up to 100 G (Gauss) at temperatures from 4.2 K to 62 K (near Tc of the junction). If the Josephson current distributes in the whole junction, the magnetic field of about 3 G could modulate the critical current of the junction. It is considered that the junction area was very small.

The critical currents of the junctions at 4.2 K decreased with a decrease in the junction width. However, the junctions wider than 10 μm did not respond to the magnetic field .

In the junction of 5 μm width, the critical current at 4.2 K was suppressed to 80% when irradiated with the magnetic field of 100 G. However, the periodic modulation of the critical current was not observed. At temperatures above 30 K, the modulation was observed. Figure 2 shows the magnetic field modulation of the critical current at 62.4 K (Tc of the junction was 65 K.). This characteristic was similar to that of a dc-SQUID.

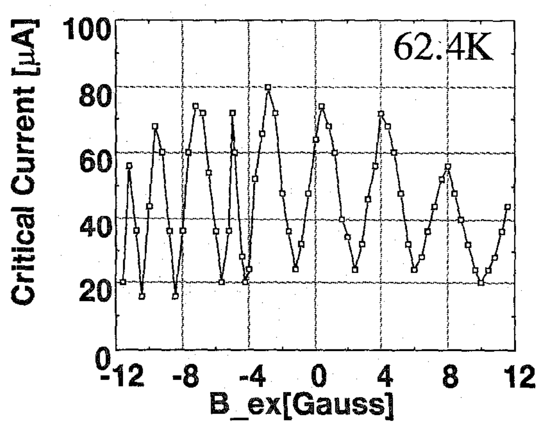

Fig. 2. The magnetic modulation of the critical current at 62.4 K for the junction 5 μm wide and 300 nm thick

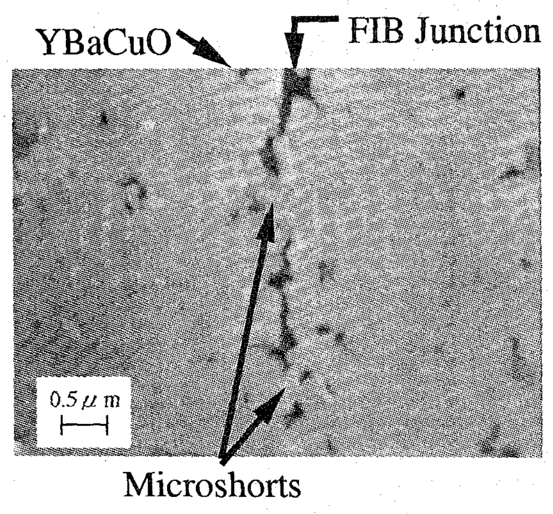

Fig. 3. The surface of the FIB junction by SEM photograph; Microshorts were observed on the junction.

Figure 3 shows the SEM photograph of the surface of the junction with 10 μm width and 300 nm thickness. The width of the damaged line was 0.2 μm. The regions covered by the YBaCuO thin film grown on the non-damaged substrate were observerd on the junction. If the covered region worked as a microshort, the current flowed mainly in the region and the coupling region was very small. The area of the microshorts were about ten times as small as the junction area. Hence, the high magnetic field of more than several hundred G was needed when the microshorts responded to the magnetic field. It is considered that the junction had some microshorts.

B. The changes of the magnetic field properties by decreasing film thickness

The thickness dependence of the FIB junctions was measured. The width of the junction was 10 μm and the width of the damaged line was 0.2 μm. The minimum thickness of a YBaCuO thin film was 150 nm, since the Josephson effect was very weak in the junctions less than 150 nm thick.

The characteristics of the FIB junctions were changed with decreasing film thickness. The two types of the junctions were fabricated. One had the same characteristics as that of the junction with 300nm thickness . In the other type junction, the I-V characteristic was close to the RSJ model. Figure 4 shows the I-V characteristics of the FIB junction with 10 μm wide and 200 nm thick at 4.8 K. The I_cR_n product was 0.12 mV at 4.8 K. Also Shapiro steps up to 16th step could be observed when irradiated with microwave of 8.05 GHz. The temperature dependence of the critical current is shown in Fig. 5. The T_c of the junction was 67 K. At temperatures above 40 K, the critical current (Ic) decreased as $(1 - T/T_c)^n$ (n=1.5).

Figure 6 shows the magnetic field modulation of the critical current at 4.2 K (Fig. 6(a)) and 52 K (Fig. 6(b)) for the same sample as in Fig. 4. At 4.2 K, the critical

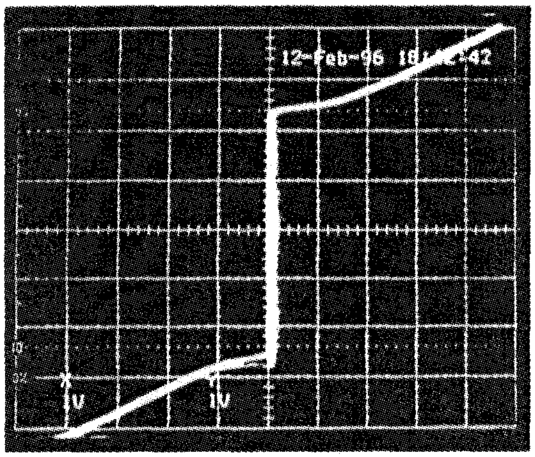

Fig. 4. The I-V characteristic of the junction 200 nm thick and 10 μm wide at 4.8 K. x-axis: 50 μV/div; y-axis: 0.2 mA/div

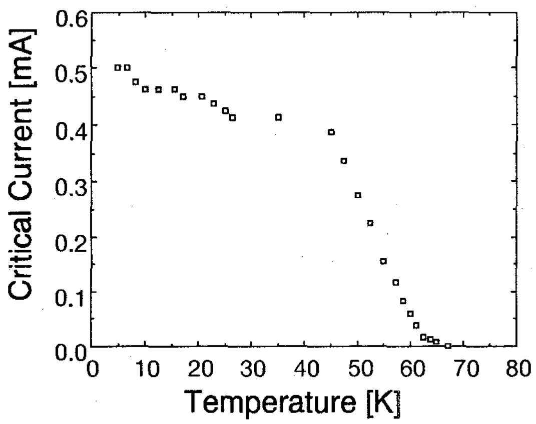

Fig. 5. The temperature dependence of the critical current of the junction. The junction is the same as in Fig.4.

current decreased with the applied magnetic field. However, the periodical modulation was not observed. At 52 K, the magnetic modulation curve with several minima was observed. The period (ΔB) of the magnetic modulation was 37 G. The period was estimated from the minima of the critical current in Fig. 6(b). The modulation curve at 52 K was similar to a Fraunhofer diffraction pattern.

Figure 7 shows the magnetic mudulation curve of the 7 μm wide and 200 nm thick junction at 4.2K. The I-V curve of this junction was close to the RSJ model. Solid line in Fig. 7 is a Fraunhofer like pattern. The period of the magnetic modulation was 40 G. The junction area calculated from the period of the magnetic modulation was 5.0×10^{-9} cm^2. The junction area calculated from the pattern size of the junction was 1.4×10^{-8} cm^2. The junction area included with the magnetic penetration depth (λ) at 4.2K was bigger than the pattern size of the junction. It is considered that the Josephson current flowed in a part of the junction.

In the junctions that showed RSJ like I-V characteristics, the ranges of the critical currents at 4.2 K were from

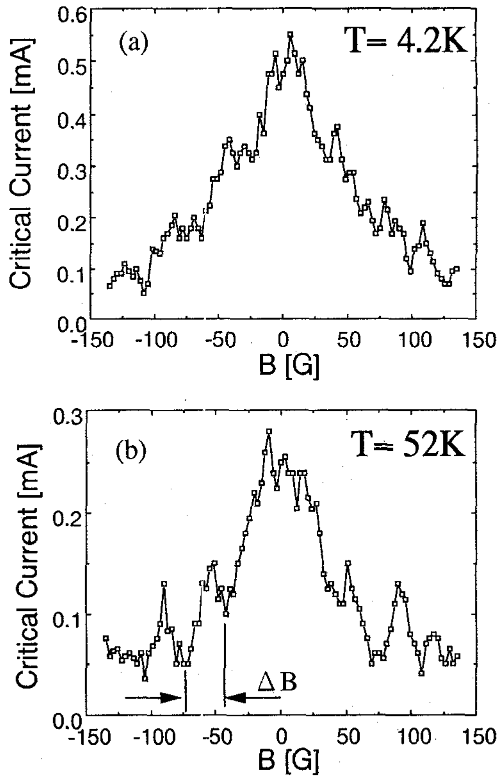

Fig. 6. The magnetic field modulation of the critical current for the junction of 10 μm width and 200 nm thickness at (a) 4.2 K and (b) 52 K.

490 μA to 50 μA . The I_cR_n products at 4.2 K were from 0.2 mV to 0.05 mV. Most of these junctions were fabricated using the thin film thinner than 200 nm. In some junctions with less than 200 nm thickness, the junctions had no response to the applied magnetic field. The junctions with more than 250nm thickness did not show RSJ like I-V characteristics. It is considered that the current distribution in the junction was changed with a decrease in the film thickness.

C. Discussion of the FIB junction

When the thickness of the junction was varied from 300nm to 200nm, I-V characteristics were changed from flux-flow type to RSJ type. Also, the magnetic properties were changed from SQUID like responses to the response of a single junction. These results indicated that the current distribution of the FIB junction were changed.

It is assumed that the junction 300 nm thick has a weak coupling region and microshorts. Since the critical currents of microshorts were bigger than that of a weak coupling region, the junction 300nm thick had big I_c of several mA and the current flowed mainly in the microshorts. Since the area of microshorts was very small, the junction did not respond to the magnetic field of 100 G at 4.2 K. In the junctions 200nm thick, the microshorts were not grown on the junction and the weak coupling region responded to the magnetic field at 4.2 K.

A YBaCuO thin film has grown abnormally on the

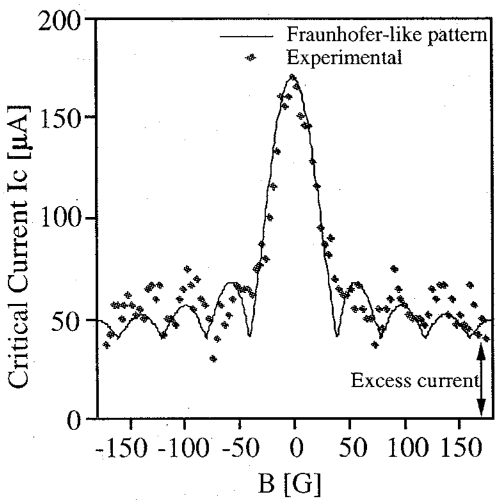

Fig. 7. The magnetic field modulation of the critical current for the junction of 7 μm width and 200 nm thickness at 4.2 K.

damaged MgO substrate. In the crystallinity, the abnormally grown YBaCuO were the mixed crystals of a polycrystal and an amorphous from Transmission Electron Diffraction (TED) [2] [4]. From the TEM observation, SRL-ISTEC group reported that a grain boundary was observed in the YBaCuO film on a damaged MgO substrate [9]. Thus it is considered that the coupling region was changed from a microshort to weak coupling of abnormally grown YBaCuO as shown in Fig. 8.

IV. Summary

The FIB junctions were fabricated by changing the width and the thickness of a YBaCuO thin film. The magnetic properties of the junctions were measured by changing the measurement temperature.

In the junctions 300nm thick, the magnetic field modulation of the critical current at 4.2 K was not observed. Near T_c of the junction, the magnetic field modulation of the critical current was similar to that of a dc-SQUID. From the SEM observation, some microshorts were observed on the junction.

When the film thickness was decresed from 300 nm to 200 nm, the I-V curve of the junction was changed from a flux flow junction type to a RSJ model type. In the junctions 200 nm thick and 7 mum wide , the magnetic field modulation of the critical current at 4.2K was similar to that of a Fraunhofer pattern.

Thus it is considered that the coupling region was changed from a microshort to weak coupling region of abnormally grown YBaCuO, when the thickness of the YBaCuO film was decreased from 300 nm to 200 nm.

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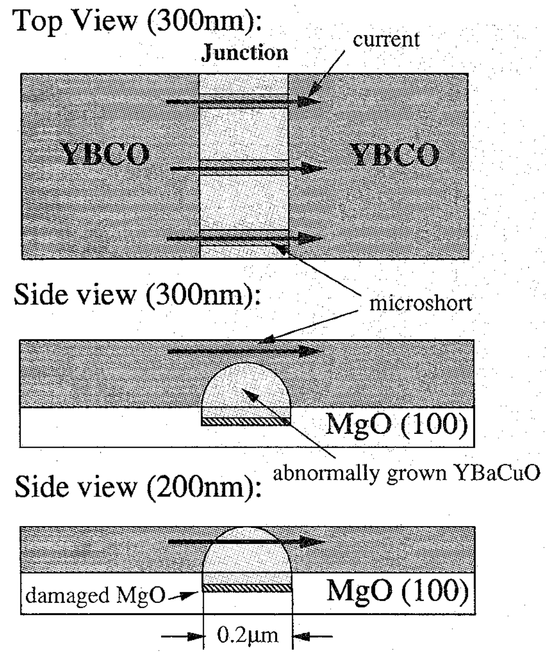

Fig. 8. The changes of the current in the FIB junctions of 300 nm thickness and 200 nm thickness

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