Microwave response of $YBa_2Cu_3O_{7-x}$ grain boundary junction

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$YBa_2Cu_3O_{7-x}$ superconductor thin films were deposited on $LaAlO_3(100)$ single crystal substrates using a metalorganic chemical vapor deposition method. These films showed a critical temperature of about 90 K and a critical current density of over 10^5 A/cm^2 at 77 K. These films showed granular structure with 0.5–1.5 μm grains. Bridge-type junctions, 6 μm in width and 6 μm in length, were fabricated using photolithography and Ar ion milling techniques. Current-voltage (I-V) characteristics of these junctions with microwave irradiation at 77 K were studied. The critical current densities decreased as the irradiated microwave power increased. When microwaves are irradiated on the bridge at 77 K, the I-V characteristics showed constant voltage steps (Shapiro steps) at $\Delta V = nh\nu/2e$, but subharmonic steps. © *1995 American Institute of Physics.*

In 1962, Brian D. Josephson theoretically predicted Josephson effects. If a dc voltage on which is superimposed an ac voltage of frequency ν is applied, the dc characteristic has a zero slope resistance part at $2eV/\text{h} = n\nu$, where n is an integer.[1] An ac supercurrent was detected in 1963 by Shapiro by observing constant voltage steps.[2] The effective length, l, of the junction should satisfy the condition of $l \leqslant 3–5\xi$ to observe Josephson effects, where ξ is the coherence length.[3] As the coherent lengths of the low T_c superconductors are about several hundreds to several thousands of angstroms, Josephson junctions can be fabricated without much difficulty using many methods. After the discovery of superconductivity above 77 K, the possibility of fabricating a high T_c Josephson junction has stimulated much research. But the coherent lengths of the high T_c superconductors are a few angstroms and thus it is difficult to fabricate Josephson junctions with high T_c superconductors, which has an insulating tunneling barrier. According to Hauser and Gijs, Josephson junctions have been successfully fabricated using natural grain boundaries, but only Gijs reported the subharmonic steps in I-V characteristics of the junctions.

The objective of this study is to fabricate a bridge-type Josephson junction of $YBa_2Cu_3O_{7-x}$ superconductor thin film deposited using the metalorganic chemical vapor deposition (MOCVD) method, and to investigate the I-V behavior of the junction. In order to reach the objective, the following research was carried out in this study: (1) deposition of $YBa_2Cu_3O_{7-x}$ superconductor thin films using the MOCVD method, (2) photolithography and etching of the films using an Ar ion milling system to fabricate the bridge, (3) verifying Josephson junction by observing Shapiro steps with microwave irradiation on the bridge, and (4) studying the I-V characteristics of bridge with and without microwave irradiation. The details of the film deposition procedure were reported in a previous paper.[4]

Figure 1 shows an x-ray diffraction (XRD) pattern of a thin film deposited on a $LaAlO_3(100)$ single crystal substrate. The XRD pattern consists of mainly (00l), some (h00) and small other peaks, which indicate that the a-b planes of the dominant superconductor grains in this film are parallel to the $LaAlO_3$ substrate. The films showing only (00l) peaks in their XRD patterns were also successfully deposited on the $LaAlO_3$ substrate, but Shapiro steps in I-V curves were detected for the films showing some misorientation rather than the films showing only (00l) peaks. This observation may indicate that the weak link in grain boundaries was originated from the misorientation between the grains.

Figure 2 shows a bridge fabricated with a thin film on a $LaAlO_3(100)$ substrate using the photolithography and the Ar ion milling techniques. The size of the bridge is 6 μm in width and 6 μm in length. As shown in Fig. 2, the diameter of grains on the bridge region is in the range of 0.5–1.5 μm.

Figure 3 shows the resistance versus temperature curve of the films deposited on the $LaAlO_3(100)$ single crystal substrate. The films had a T_c of about 90 K and small tails. The film showing only (00l) peaks in their XRD patterns showed a T_c of above 90 K and the transition width was within 0.5 K without tail. The critical current density (J_c) of the films on the $LaAlO_3$ substrate at 77 K was over 10^5 A/cm^2 which was one order lower than that of the films showing only (00l) peaks in their XRD patterns.

Figure 4 shows the I-V characteristics of the bridge made of the superconductor film on the $LaAlO_3(100)$ substrate with and without microwave irradiation at 77 K (whose XRD pattern and microstructure are shown in Figs. 1 and 2, respectively). The I-V curves showed flux flow type behavior. But without the microwave irradiation, constant current steps which can be the proof of the flux flow type junction were not observed.[5] Neither the subharmonic steps in the I-V curve were observed which also can be the proof of the flux flow type junction.[6,7] With the irradiation, critical current decreased and constant voltage steps which are consistent with the frequency of microwave were observed.

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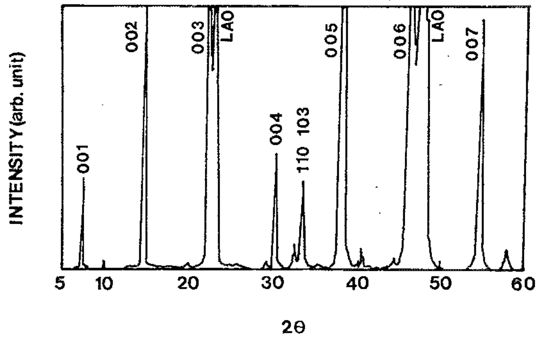

FIG. 1. An x-ray diffraction pattern of the $YBa_2Cu_3O_{7-x}$ thin film deposited on a $LaAlO_3(100)$ single crystal substrate.

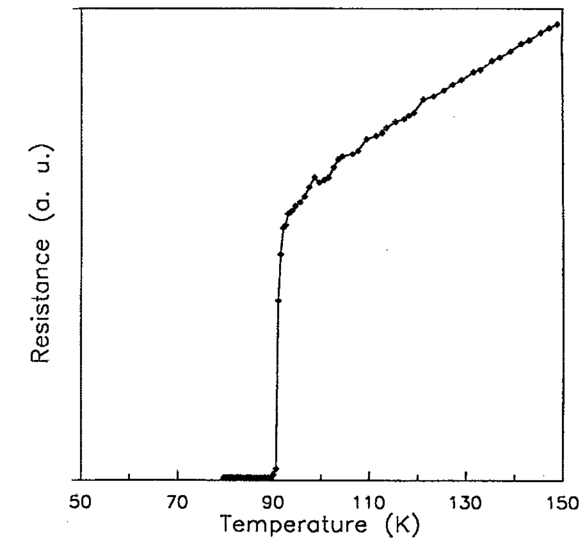

FIG. 3. Resistance vs temperature curve of the film deposited on a $LaAlO_3(100)$ single crystal substrate.

Figure 5 shows the I-V characteristics of the bridge when microwaves were irradiated at 77 K. Constant voltage steps are observed at the voltage intervals of about 20.6 and 16.2 μV when the microwave frequencies are 9.95 and 7.83 GHz, respectively. The arrows indicate the constant voltage steps. These values are consistent with the step voltages calculated using the relationship: $\Delta V = hf/2e$, where h is the Planck constant, e is the electric charge of electron, f is the frequency of the microwave, and n is an integer. If there are several junctions in a series in a bridge, we may observe enhanced voltage steps in the voltage spacings, $\Delta V = nhf/2e$.[8] The observed voltage steps suggest that only one Josephson junction is effective in the bridge region. The reason for only one effective Josephson junction in the relatively long and wide bridge (about 6 μm) in this study is not clear at the moment.

Figure 6 shows the I-V characteristics of the bridge with 9.95 GHz microwave irradiation having different microwave power levels at 77 K. As the microwave power increased, the width of the constant voltage step at $n=0$ decreased to zero, but that at $n=1$ increased for relatively low microwave power levels and then decreased to zero for relatively high microwave power levels. It has been known that the width of the constant voltage steps depends on the value of normalized frequency.[9] The normalized frequency, Ω, is defined as $\Omega = h\nu/2eI_cR_N$, where I_c is the critical current of the bridge, and R_N is the normal resistance of the bridge. For a relatively high Ω, the width of the steps is large and more steps can be observed. As the Ω value decreases, the width of the steps decreases and the step finally disappears at $\Omega=0$ for a limiting case. The Ω value of the film deposited on the $LaAlO_3$ substrate was 0.064 (where $f=9.95$ GHz, $I_c=8$ mA, and $R_N=40$ mΩ) which is about 10^{-3} orders lower than the value reported in other studies.[9,10] The relatively small width of the constant voltage steps observed in this study is consistent with the Russer's prediction in which a low value of normalized frequency produces a small width of voltage steps.[9]

FIG. 2. SEM photolithograph of the 6 μm bridge fabricated on the superconductor film deposited on a $LaAlO_3(100)$ single crystal substrate.

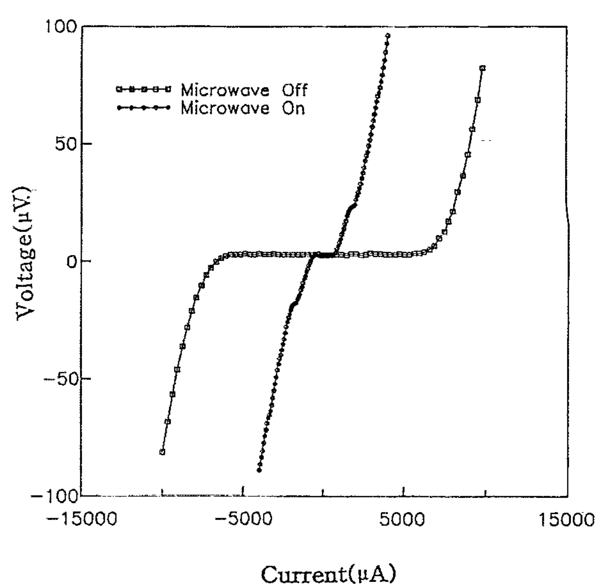

FIG. 4. I-V characteristics of the bridge fabricated on the superconductor film with and without a microwave irradiation at 77 K.

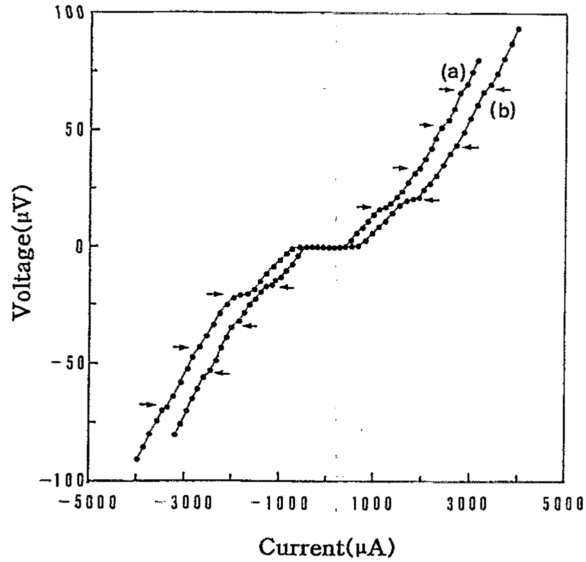

FIG. 5. *I-V* characteristics of the bridge fabricated on the superconductor film with microwave of (a) 7.83 GHz and (b) 9.95 GHz irradiations at 77 K. The arrows indicate the constant voltage steps.

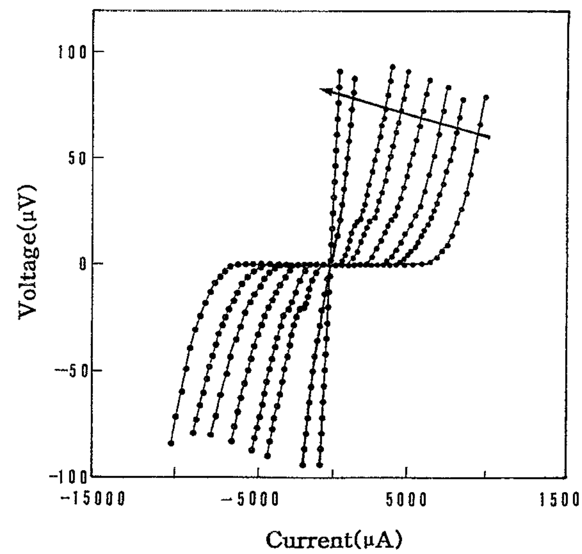

FIG. 6. *I-V* characteristics of the bridge fabricated on the superconductor film irradiated at 9.95 GHz microwave having different microwave power levels the arrow indicates the increase in the microwave power at 77 K.

In conclusion, we studied the Josephson junction fabricated on a $YBa_2Cu_3O_{7-x}$ superconductor thin film deposited by a MOCVD method. Microbridges, which are 6 μm in width and 6 μm in length, were fabricated using the photolithography and the Ar ion milling. The establishment of the bridge-type Josephson junction was verified by observing Shapiro steps. The constant voltage steps corresponding to the Josephson frequency were observed when the microwave was irradiated on the bridge. Even though the bridge included many grain boundaries, subharmonic steps did not appear on the *I-V* characteristics, and only one Josephson junction was effective in the bridge region. Because Ω was very small for the bridge, the width of the constant voltage step was relatively small. The critical current of bridge-type natural grain boundary Josephson junction decreased with increasing microwave power, and it showed the possibility of microwave detection.

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