Y-Ba-Cu-O/Nb JOSEPHSON TUNNEL JUNCTIONS

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Abstract

We have fabricated Y-Ba-Cu-O/Au/AlO_x/Nb and Y-Ba-Cu-O/AlO_x/Nb Josephson tunnel junctions using electron-beam evaporation of Al and Nb films and natural oxidation. Sintered Y-Ba-Cu-O have been used as base electrode. Superconducting Josephson current and hysteresis of current-voltage characteristics, which are typical features of Josephson tunnel junctions, have been observed at 4.2 K. Rf-induced voltage steps at the voltage greater than 0.4 mV have been clearly observed and rf-induced subharmonic steps have also appeared. Moreover, the Superconducting Josephson current has been modulated by magnetic field.

Introduction

For digital and analog applications, superconducting materials with large gap voltage are attractive, because intrinsic switching speed of Josephson junctions is inversely proportional to the gap voltage. High-T_c materials such as Y-Ba-Cu-O are expected to have a large gap voltage, and are attractive as electrodes of Josephson junctions. Superconducting Josephson currents have been observed in point-contact junctions and weak links,[1-3] however, few experimental results have been reported on the characteristics of tunnel structure junctions.[4]

This paper reports that Y-Ba-Cu-O/Nb Josephson tunnel junctions have been fabricated. The junctions bad the structure of Y-Ba-Cu-O/Au/AlO_x/Nb or Y-Ba-Cu-O/AlO_x/Nb. Bulk Y-Ba-Cu-O was used as a base electrode, and Al and Nb thin films were deposited using an electron-gun (E-gun). The tunnel barrier was fabricated using natural oxidation of Al thin films. In these Y-Ba-Cu-O/Nb junctions, Superconducting Josephson current, hysteresis of current-voltage (I-V) curve, and rf-induced steps were clearly observed. Specially, in Y-Ba-Cu-O/AlO_x/Nb junctions, rf-induced voltage steps appeared at the voltage greater than 0.4 mV, and rf-induced subharmonic steps also appeared. Moreover, magnetic field dependence of the superconducting Josephson current was modulated by magnetic field. In the Y-Ba-Cu-O/Au/AlO_x/Nb junctions, Au was used as an interlayer to protect the reaction of Y-Ba-Cu-O and Al. In the Y-Ba-Cu-O/AlO_x/Nb tunnel structure, however, no interlayer at the Y-Ba-Cu-O/Al interface such as Au was used, and the reaction of Y-Ba-Cu-O and Al was kept down by the water-cooling of the substrate at the junction fabrication.

Preparation of Bulk Y-Ba-Cu-O

Bulk Y-Ba-Cu-O was used as a substrate. Sintered bulk Y-Ba-Cu-O was prepared as follows: mixing powder of Y_2O_3, $BaCO_3$ and CuO in ethanol and calcining the mixture at 900 C for 2 hours and pressing with the pressure of 7 ton/cm^2; then sintering at 900 C for 5 hours and cooling slowly at the rate of 1.6 C/min. The highest T_c of the bulk Y-Ba-Cu-O was 96 K.

Y-Ba-Cu-O/Au/AlOx/Nb Junctions

Fabrication of Y-Ba-Cu-O/Au/AlOx/Nb Junctions

Fabrication procedure of Y-Ba-Cu-O/Au/AlO_x/Nb junctions are as follows: First, the upper and lower surfaces of the sintered Y-Ba-Cu-O were polished with Al_2O_3 powder of 0.2 μm grain size. Next a thin Au film was deposited with resistive heating on the lower surface for an ohmic contact and on the upper surface for a protection layer against the reaction between Y-Ba-Cu-O and Al. Gold was expected to be inactive with oxide superconductors from the earlier study with the La-Sr-Cu-O system,[5] so that Au interlayer between Y-Ba-Cu-O and Al would kept down the reaction between Y-Ba-Cu-O and Al. The thickness and the deposition rate of Au interlayer deposited on the upper surface were 7 nm and 0.1 nm/s, respectively. Next, the sintered Y-Ba-Cu-O substrate was mounted upon the substrate holder of the high-vacuum oil-free system and an Al thin layer was evaporated using E-gun. No cleaning of the surface of the Y-Ba-Cu-O substrate such as rf-plasma sputtering was done before the deposition of the Al layer. Pure oxygen with pressure of 400 Pa was then introduced for 30 min in the chamber and tunnel barrier was formed by natural oxidation of the Al layer. After tunnel barrier formation, Nb counter-electrode was deposited using E-gun. The thickness of Al and Nb were 6 nm and 100 nm, respectively. The vacuum system used for the deposition of Al and Nb thin films and tunnel barrier formation was mainly pumped down with an ion pump, Ti sublimation pump and liquid nitrogen shroud, and its ultimate pressure was in the 10^{-7} Pa range. During the deposition of Al and Nb films and the natural oxidation, the Y-Ba-Cu-O substrate was water-cooled. Finally, Nb counter-electrode was reactively etched in CF_4(95%)+O_2(5%) plasma using photoresist mask.

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Characteristics of
Y-Ba-Cu-O/Au/AlOx/Nb junctions

From the current-voltage characteristics of Y-Ba-Cu-O/Au/AlO_x/Nb, superconducting current was observed. Its critical current was about 0.05 mA and the critical current density was 7 mA/cm^2 if tunnel current was assumed to flow uniformly in the junction area. A hysteresis of the I-V curve, which was typical feature of the tunnel type junction, was also observed.

Moreover, rf-induced voltage steps were observed when microwave was applied as shown in Fig. 1, i.e., rf-induced steps occurred at the voltages

$$V_s = n(h/2e)f, \qquad (1)$$

where n is 0, ±1, ±2, h is Plank's constant, e is the electron charge, and f is the frequency of the applied microwave (8.3 GHz).

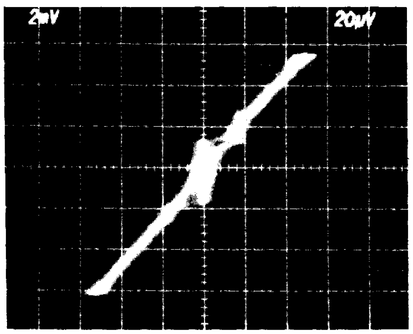


Fig. 1. Rf-induced voltage steps on the I-V characteristics of Y-Ba-Cu-O/Au/AlO_x/Nb Josephson tunnel junctions. Vertical scale: 20 μA/div, horizontal scale: 20 μV/div.

Y-Ba-Cu-O/AlOx/Nb Junctions

Fabrication of Y-Ba-Cu-O/AlOx/Nb Junctions

Fabrication procedure of Y-Ba-Cu-O/AlO_x/Nb junctions is shown in Fig. 2. First, a thin Au film was deposited with resistive heating for an ohmic contact upon the lower polished surface of the sintered Y-Ba-Cu-O through a metal mask at the 10^{-3}Pa range in a conventional vacuum system using an oil diffusion pump. An Al film was then deposited upon the upper surface through another metal mask using the E-gun. The thickness and the deposition rate were 6 nm and 0.5 nm/s, respectively. The surface of the Al layer was then naturally oxidized. Finally, the Nb counter-electrode was deposited using the E-gun through the metal mask. The thickness and the deposition rate were 100 nm and 1 nm/s, respectively.

Characteristics of Y-Ba-Cu-O/AlOx/Nb Junctions

Current-voltage characteristics of the

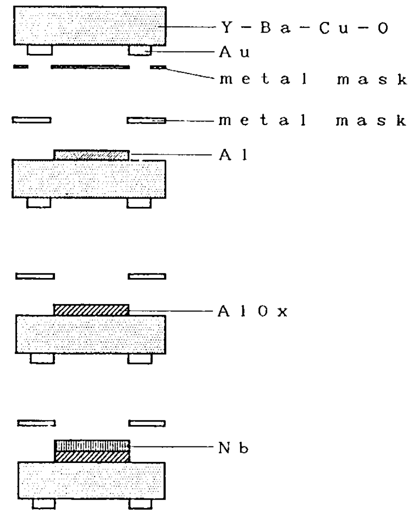
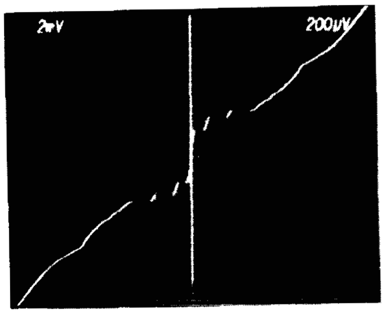


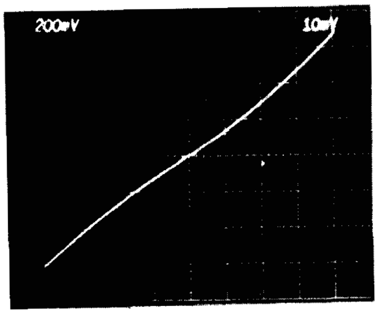
Fig. 2. Fabrication procedure of Y-Ba-Cu-O/AlO_x/Nb Josephson tunnel junctions. (a): The upper and lower surfaces of the bulk Y-Ba-Cu-O were polished and the Au was deposited for an ohmic contact upon the lower surface through a metal mask. (b): the Al was deposited upon the upper surface through another metal mask. (c): the surface of the Al layer was naturally oxidized. (d): the Nb counterelectrode was deposited through the metal mask.

Y-Ba-Cu-O/AlO_x/Nb junction are shown in Fig. 3. Superconducting Josephson current was observed and its critical value was 80 μA. The current density was 8 mA/cm^2 if we assumed the tunnel current flowed uniformly in the junction area. From Fig 3(a), quasiparticle characteristics cross the zero point; this feature is typical of tunnel-type junctions and has not been observed for point contact junctions and weak links. Self-resonant steps (Fiske steps) are also observed in Fig. 3(a), which are also distinctive to tunnel-type junctions. If we assume the London penetration depth of Y-Ba-Cu-O and Nb electrodes are 140 nm and 77 nm,[6] respectively, and the junction size is 1.0 mm defined by the metal mask, we find t/ε_r= 4.4 nm, where t and ε_r are the thickness and the relative dielectric constant of the tunnel oxide. If we assume the relative dielectric constant of AlO_x tunnel barrier to be 11, we find t = 48 nm. This value is one order larger than the expected value. This is because the substantial junction size would be much smaller than the junction size defined by the metal mask.

Rf-induced voltage steps are shown in Fig. 4. In (a), rf-induced voltage steps appear at the voltage greater than 0.4 mV. In (b), rf-induced subharmonic steps are clearly observed, i.e., rf-induced steps occur at the voltages of eq. (1), where n = 0, +1/2, +1, +3/2, +2, +5/2, +3, +7/2,···.



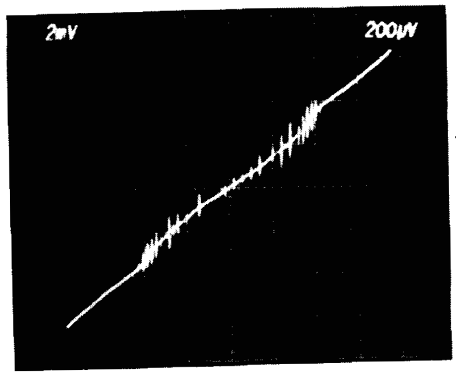
(a)



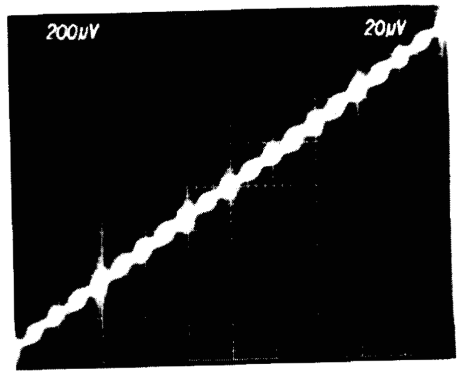
(b)

Fig. 3. I-V characteristics of the Y-Ba-Cu-O/AlO_x/Nb Josephson tunnel junction. T = 4.2 K. Junction No. 219. (a) Horizontal scale: 200 μV/div, vertical scale: 20 μA/div. (b) Horizontal scale: 10 mV/div, vertical scale: 2 mA/div.

The critical value I_c of superconducting current has been modulated by magnetic field as shown in Fig. 5. The modulated pattern is similar to the Fraunhofer diffraction pattern. If we assume the uniform current in the junction area of 1x1 mm^2, $\lambda_{Y-Ba-Cu-O}+\lambda_{Nb}+t$ is estimated to be 1.5 nm from this modulated pattern, where $\lambda_{Y-Ba-Cu-O}$ and λ_{Nb} are the London penetration depth of Y-Ba-Cu-O and Nb, respectively. This value is about two orders smaller than the expected value, therefore, substantial junction size would be about 1/100 of the junction size (1mm) defined by the metal mask. It is thought that the tunneling current would flow nonuniformly in the junction area, in other words, that there would be several small tunnel junctions and/or point contact junctions in the junction area of 1x1 mm^2. The sharp changes of I_c shown in the I_c-H characteristics of Fig. 5, which are similar to those of DC SQUID and three-junction SQUID, also support this assumption. This nonuniformity would be caused by polycrystallity of the Y-Ba-Cu-O substrate and nonuniformity of the AlO_x tunnel barrier.



(a)



(b)

Fig. 4. Rf-Induced voltage steps. The frequency of the applied microwave was 9.65 GHz. T = 4.2 K. Junction No. 219. (a) Horizontal scale: 200 μV/div, vertical scale: 20 μA/div. (b) Horizontal scale: 20 μV/div, vertical scale: 2 μA/div.

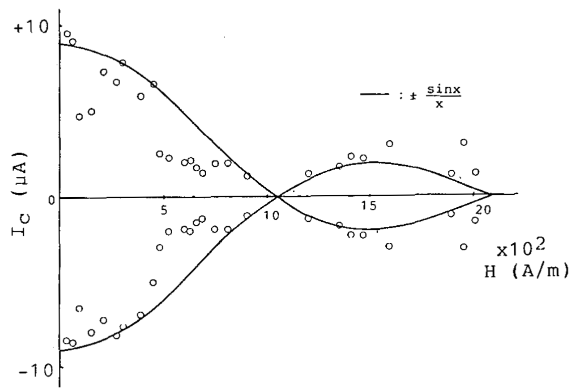


Fig. 5. Magnetic field dependence of the critical value of the superconducting Josephson current. T = 4.2 K. Junction No. 289. The curve of ±sinx/x is also shown.

Table I Comparison of the characteristics of the Y-Ba-Cu-O /Au/AlO_x/Nb, Y-Ba-Cu-O/AlO_x/Nb and Nb/Nb junctions.

Structure	Junction No.	Cooling*	Ic (μA)	Jc (mA/cm²)	Rnn (Ω)**	IcRnn (mV)	RnnS (Ωcm²)***	Vstep (mV)****
Y-Ba-Cu-O/Au/AlOx/Nb	105	Yes	50	7	0.8	0.040	0.0056	0.04
Y-Ba-Cu-O/AlOx/Nb	186	No	0	0	160	0	1.6	–
	219	Yes	80	8	7.6	0.61	0.076	0.43
	289	Yes	9	0.9	4.1	0.037	0.041	0.32
Nb/AlOx/Nb	N325	Yes	1300	2.6×10^5	1.0	1.3	5.2×10^{-6}	~ 1

*Cooling: the water-cooling of the substrate when the junction was fabricated. "No" means without water-cooling, and "Yes" means with water-cooling. **Rnn: the linear resistance at 1mV of the I-V curve of the junction except the Nb/AlO_x/Nb junction (4mV). ***S: the junction area. ****V_{step}: the maximum voltage where the rf-induced steps were observed.

Comparison of Y-Ba-Cu-O/Nb and Nb/Nb Junctions

Characteristics of Y-Ba-Cu-O/Au/AlO_x/Nb, Y-Ba-Cu-O/AlO_x/Nb and Nb/Nb junctions are compared in Table I. In the Y-Ba-Cu-O/AlO_x/Nb junctions, whenever the substrate was not water-cooled in tunnel barrier formation and deposition of counter-electrode, the superconducting Josephson current was not observed and $R_{nn}S$ product became more than two orders larger than that of the junctions fabricated with water-cooling (see Junction No. 186, 219 and 289 in Table I). It is thought that if the substrate was not water-cooled, the widths of Y-Ba-Cu-O/tunnel-oxide and tunnel-oxide/Nb interfaces became large because of the interdiffusion. The maximum voltage where the rf-induced steps were observed in the I-V curve(V_{step}) of Y-Ba-Cu-O/AlO_x/Nb junctions was higher than that of Y-Ba-Cu-O/Au/AlO_x/Nb junctions and was almost as high as that of Nb/AlO_x/Nb junctions. The current density J_c of Y-Ba-Cu-O/Nb junctions was much smaller than that of Nb/Nb junctions,[6] owing to the nonuniformity of the tunnel-oxide and/or the broad Y-Ba-Cu-O/tunnel-oxide interface of the Y-Ba-Cu-O/Nb junctions.

Conclusions

In conclusion, Y-Ba-Cu-O/Au/AlO_x/Nb and Y-Ba-Cu-O/AlO_x/Nb tunnel-type Josephson junctions were fabricated. Sintered Y-Ba-Cu-O was used as base electrode, and Nb counter-electrode and Al film was electron-beam evaporated. Superconducting Josephson current, and hysteresis of I-V curve were observed, which were typical features of tunnel-type Josephson junctions. The superconducting Josephson current was modulated by magnetic field, and rf-induced steps appeared at the voltage greater than 0.4 mV; i.e. DC and AC Josephson effect was observed. Moreover, rf-induced subharmonic steps were clearly observed. From the magnetic field dependence of I_c, it was thought that the superconducting Josephson current would flow nonuniformly in the junction area.

References

[1] T.Yamashita, A.Kawakami, T.Nishihara, M.Takata and K.Kishio,"Rf Power Dependence of AC Josephson Current in Point-Contacts of BaY(Tm)CuO Ceramics," Jpn. J. Appl. Phys. vol.26, pp.L671-L672, May 1987.

[2] T.Nishino, H.Hasegawa, H.Nakane, Y.Ito, K.Takagi and U.Kawabe,"Josephson Point Contact Using High-Critical-Temperature Oxide-Superconductors," Jpn. J. Appl. Phys. vol.26, pp.L674-L675, May 1987.

[3] J.S.Tsai, Y.Kubo and J.Tabuchi,"All-Ceramics Josephson Junctions Operativ up to 90 K," Jpn. J. Appl. Phys. vol.26, pp.L701-L703, May 1987.

[4] I.Iguchi, H.Watanabe, Y.Kasai, T.Mochiku, A.Sugishita and E.Yamaka,"Tunneling Spectroscopy of Y-Ba-Cu-O Compound," Jpn. J. Appl. Phys. vol.26, pp.L645-L646, May 1987.

[5] K.Takeuchi, Y.Okabe, M.Kawasaki and H.Koinuma,"Electrical Properties of La-Sr-Cu-O/Al Contact," Jpn. J. Appl. Phys. vol.26, pp.L1017-L1018, June 1987.

[6] A.Nakayama, A.Inoue and Y.Okabe, "NIOBIUM/ALUMINUM-OXIDE/NIOBIUM JOSEPHSON TUNNEL JUNCTIONS FABRICATED USING ELECTRON-BEAM EVAPORATION," Extended Abstracts of 1987 International Superconductivity Electronics Conference (The Japan Society of Applied Physics, Tokyo, 1987) pp.301-304.

[7] A.Inoue, K.Takeuchi, H.Ito, A.Nakayama, Y.Okabe, M.Kawasaki and H.Koinuma,"Y-Ba-Cu-O/Nb Tunnel Type Josephson Junctions," Jpn. J. Appl. Phys. vol.26, pp.L1443-L1444, September 1987.

[8] A.Nakayama, A.Inoue, K.Takeuchi and Y.Okabe,"Y-Ba-Cu-O/AlO_x/Nb Josephson Tunnel Junctions," Jpn. J. Appl.Phys. vol.26, pp.L2055-L2058, December 1987.