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CHARACTERISTICS OF Y-Ba-Cu-O/Nb AND Bi-Sr-Ca-Cu-O/Nb TUNNEL-TYPE JOSEPHSON JUNCTIONS

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Abstract

We have fabricated Y-Ba-Cu-O/Nb and Bi-Sr-Ca-Cu-O/Nb tunnel-type Junctions and observed the DC and AC Josephson effects. Gold thin films were deposited for an inter-layer to protect the reaction between the base electrode and the tunnel oxide before the tunnel barrier formation. In Y-Ba-Cu-O/Au/MgO_x/Nb junctions, superconducting current, hysteresis of current-voltage characteristics and the rf-induced voltage steps at the voltage as high as 0.13 mV in the current-voltage characteristics were observed. Moreover, the superconducting current has been modulated by the magnetic field. In Bi-Sr-Ca-Cu-O/Au/MgO_x/Nb junctions, superconducting current and the rf-induced voltage steps at the voltage as high as 0.15 mV were also observed.

Introduction

The technology of tunnel-type Josephson junctions such as niobium/aluminum-oxide/niobium hetero-structure has enhanced the superconducting electronics. The intrinsic switching time of Josephson junctions made of the low-temperature superconductors would, however, be limited to about one pico second, and the electronic circuits of the two terminal devices such as Josephson junctions are more complex than that of the three terminal devices. Hence, we expect that from the Cu-oxide compounds such as Y-Ba-Cu-O and Bi-Sr-Ca-Cu-O, new devices will be made and the new effects will be found out in these materials, although no one can clearly tell the reason why these Cu-oxide compounds show superconductivity, yet. The first step to make such new devices is making the tunnel-structure junctions with high-temperature oxides. Up to now, a number of papers were reported about the tunnel-type[1-10] and bridge-type[11-14] devices with high-temperature oxides. In the latter type, only grain boundary junctions exhibited the Josephson behavior, hence, the reproducibility of the electrical characteristics would be rather poor. In the tunnel-type junctions, no junctions have shown both the clear gap structure and the high Josephson current density, simultaneously.

In our group, both high-Tc /low-Tc type[1-3] and all-high-Tc type[4,5] junctions have been fabricated. This paper reports that Y-Ba-Cu-O/Nb and Bi-Sr-Ca-Cu-O/Nb tunnel-type Josephson junctions have been fabricated and superconducting currents and DC and AC effects have been observed. Before the tunnel barrier formation, the surface of the base electrode was treated by oxygen plasma, and Au thin films were deposited for an inter-layer to protect the reaction of the tunnel oxide with the base electrode of the high temperature oxide. In Y-Ba-Cu-O/Nb junctions with Y-Ba-Cu-O thin film prepared by rf-magnetron sputtering method, the superconducting Josephson current and the hysteresis of current-voltage characteristics were observed. Rf-induced voltage steps at the voltage as high as 0.13 mV have been clearly observed. Moreover, the superconducting Josephson current has been modulated by the magnetic field. Also in Bi-Sr-Ca-Cu-O/Nb junctions with bulk Bi-Sr-Ca-Cu-O, superconducting current and rf-induced voltage steps at the voltage as high as 0.15 mV have been observed.

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Preparation of Films

We prepared Y-Ba-Cu-O thin films by rf magnetron sputtering. As the substrates, MgO (100) and $SrTiO_3$ (100), (110) were used. Substrate temperature was 650 C and the rf power was 300 W. During sputtering, the gas ratio of Ar : O_2 was typically 1:1. In order to compensate Ba and Cu, target compositions were $Y_1Ba_{2.6}Cu_6$. As-sputtered films showed the zero resistance at 70 K and 65 K on MgO (100) and $SrTiO_3$ (110) substrates, respectively. We also prepared Bi-Sr-Ca-Cu-O thin films by rf magnetron sputtering. The films on MgO (100) substrates showed the zero resistance at about 75 K after annealing at 880 C.

Fabrication of Tunnel Junctions

The tunnel barriers and the counter-electrodes were deposited in a vacuum system with an electron-gun. When the system was pumped down by turbo molecular pump, Ti getter pump, ion pump and liquid nitrogen shroud surrounding the rf-cathode, the ultimate pressure was 10^{-6} Pa. Fabrication process of Y-Ba-Cu-O/Au/MgO_x/Nb is shown in Fig. 1. After mounting the substrates with high temperature film on the rf-cathode of the vacuum

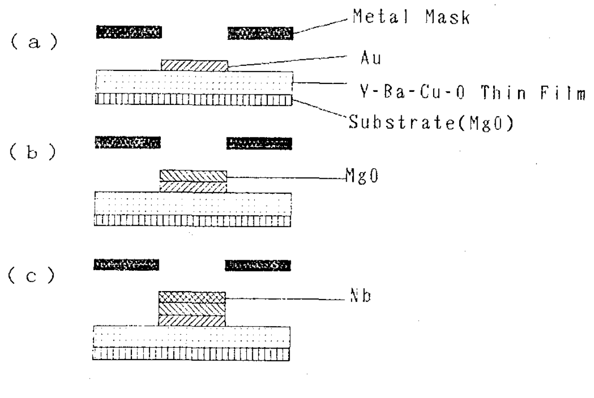

Figure 1. Fabrication process of the Y-Ba-Cu-O/Au/MgO_x/Nb junctions.

system, the surface of the Y-Ba-Cu-O film was treated by oxygen plasma for 30 min. In order to reduce the reaction of the tunnel barrier with the base electrode, gold thin layer was deposited, because from our earlier studies[1-2] Au was expected to be inactive with oxygen, which was also confirmed by Auger electron spectroscopy. The thickness and the deposition rate were 7 - 10 nm and 0.1 nm/s. For the tunnel barrier, AlO_x and MgO_x were used.

In the case of Al-oxide, the Al film was deposited at about 0.1 nm/s to 7 nm thickness. The Al film was, then, partially oxidized to form the tunnel barrier by admitting pure oxygen to the vacuum chamber. In the case of MgO_x barrier, MgO was deposited by the E-gun at the rate of 0.1 nm/s to 7 - 10 nm thickness. The Nb films were deposited at the rate of 0.3 -1.0 nm/s, at the back ground pressure of 2 - 5 x 10^{-5} Pa, with the film thickness of 100 - 200 nm for the counter-electrode.

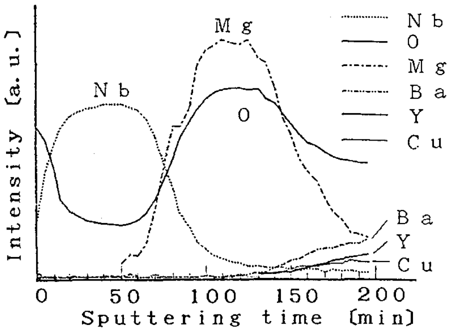

Figure 2. Depth profile of Y-Ba-Cu-O/MgO_x/Nb junction by Auger electron spectroscopy. This junction has no Au layer between the base electrode and the tunnel barrier of MgO_x.

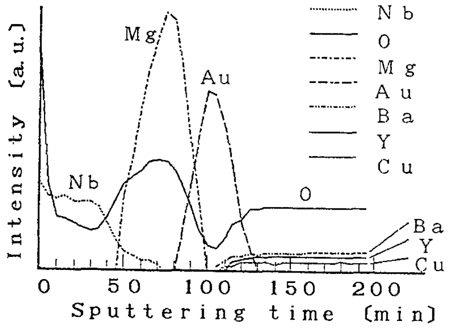

Figure 3. Depth profile of Y-Ba-Cu-O/Au/MgO_x/Nb junction by Auger electron spectroscopy. The Au layer separates the tunnel barrier of MgO_x from the base electrode .

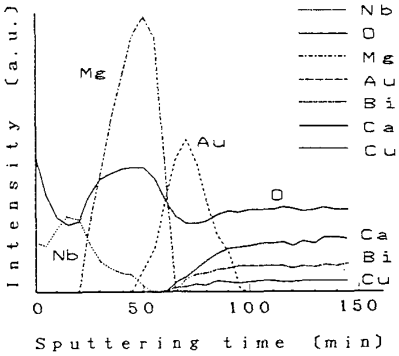

Figure 4. Depth profile of Bi-Sr-Ca-Cu-O/Au/MgO_x/Nb junction by Auger electron spectroscopy. This junction has Au layer, which separates the MgO_x layer from the Bi-Sr-Ca-Cu-O.

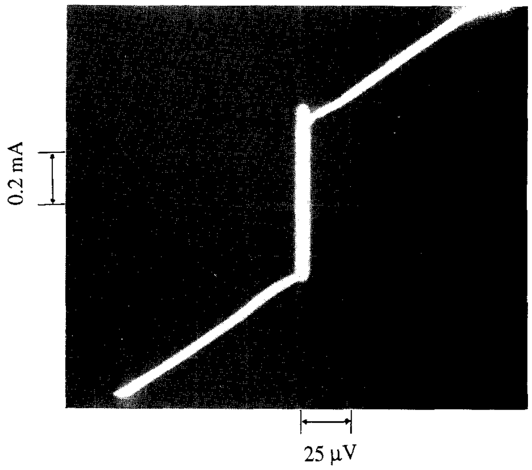

Figure 5. Current-voltage characteristics of Y-Ba-Cu-O/Au MgO_x/Nb junctions at 4.2 K. Superconducting Josephson current was observed.

Results and Discussions

Depth Profile by Auger Electron Spectroscopy Analysis

We analyzed the depth profile of the tunnel structure junction by Auger electron spectroscopy. Depth profile was analyzed by etching the samples with ion -gun of 2.0 kV. The samples have the thinner (10-20 nm thickness) counter-electrode than the real junctions so that the the effect of ion bombardment during analysis might be as small as possible.

Comparing the profiles without and with Au inter-layer as shown in Figs. 2 and 3, the tunnel barrier region was separated from the base electrode superconductor by the Au inter-layer deposited before the tunnel barrier formation. Without the Au inter-layer the depth profile of Mg and that of the base electrode partially overlapped. Also in Bi-Sr-Ca-Cu-O/Nb junctions gold layer separated the tunnel oxide from the base electrode, as shown in Fig. 4.

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

Figure 5 shows the current -voltage characteristics of Y-Ba-Cu-O/Au/MgO$_X$/Nb junction at 4.2 K. Superconducting Josephson current was observed and its current density was about 10 mA/cm^2, assuming the uniform current flow in the junction area. A hysteresis of the current -voltage characteristics was also observed. As shown in Fig. 6, when microwave was induced into the junction, voltage steps (Shapiro steps) were clearly observed as high as 0.13 mV. Moreover, as shown in Fig. 7, rf-induced subharmonic steps were observed, i.e. , the steps were observed at the voltages:

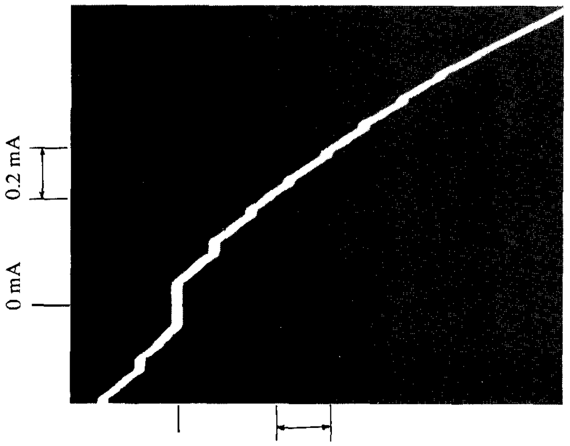

Figure 6. Rf-induced voltage steps of Y-Ba-Cu-O/Au/MgO$_X$/Nb junctions at 4.2 K . Input microwave frequency was 8.15 GHz. The steps were observed as high as 0.13 mV.

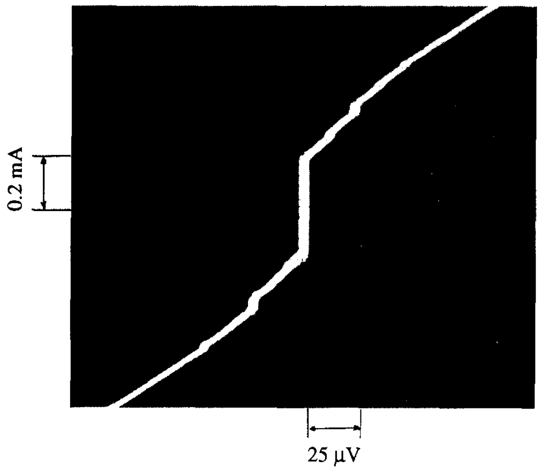

Figure 7. Sub-harmonic voltage steps of Y-Ba-Cu-O /Au/MgO$_X$ /Nb junctions. Input microwave frequency was 9.4 GHz.

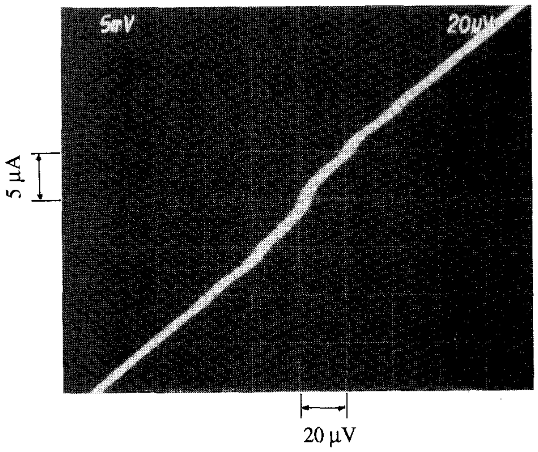

Figure 8. Rf-induced voltage steps of Bi-Sr-Ca-Cu-O/Au/MgO$_X$ /Nb junctions at 4.2 K . Input microwave frequency was 8.15 GHz.

$$V_{\mathrm{step}} = n\,hf/2e\,, \tag{1}$$

where $n = 0, \pm 1/2, \pm 1, \pm 3/2, \pm 2, ..$ h is Planck's constant, e is the absolute value of the electron charge and f is the applied microwave frequency. When the magnetic field was applied to the junction, the dc current was modulated. From this modulation pattern, the sum of $\lambda_{\mathrm{Y\text{-}Ba\text{-}Cu\text{-}O}}$ and λ_{Nb} was calculated about two orders smaller than that of the expected value, where $\lambda_{\mathrm{Y\text{-}Ba\text{-}Cu\text{-}O}}$ and λ_{Nb} were the London penetration depth of Y-Ba-Cu-O and Nb, respectively. Hence the current didn't flow uniformly in the junction area.

Characteristics of Bi-Sr-Ca-Cu-O/Nb Junctions

Superconducting current was observed in the current-voltage characteristics of Bi-Sr-Ca-Cu-O/Au/MgO$_X$/Nb junctions with bulk Bi-Sr-Ca-Cu-O. Superconducting current was 3 µA, and the current density was about 50 µA/cm^2 at 4.2 K. This value was much smaller than that of the ordinary tunnel junctions such as Nb/Nb junctions. This is probably because of the nonuniform current flow in the junction area and worse superconducting property of the surface of the Bi-Sr-Ca-Cu-O base electrode and the interface between the base electrode and the tunnel barrier. Shapiro steps were observed as shown in Fig. 8, and these steps were observed at the voltages as high as 0.15 mV. Bi-Sr-Ca-Cu-O/Nb junction with thin film Bi-Sr-Ca-Cu-O is currently studied.

Tunnel Barrier Formation by Plasma Treatment

The surface morphology of the barrier deposited on the Y-Ba-Cu-O films was studied by scanning electron microscopy. The deposited MgO$_X$ and SrTiO$_X$ thin film showed island structures even though the thicknesses were as much as 0.1 µm. So we also made the barrier by plasma treatment with CF$_4$ and CCl$_2$F$_2$ gas. By the depth profile with Auger electron spectroscopy, the barrier layer could not be made with CF$_4$ gas, but the chloride layer was made with CCl$_2$F$_2$ gas. Moreover, with CCl$_2$F$_2$ gas treatment, the junction resistance depended exponentially on the treatment time.

Conclusions

We fabricated Y-Ba-Cu-O/Nb and Bi-Sr-Ca-Cu-O/Nb Tunnel-type Junctions. Before the tunnel barrier formation, Au thin films were deposited for an inter-layer to protect the reaction between the base electrode and the tunnel oxide. In all thin film Y-Ba-Cu-O/Au/MgOx/Nb junctions, superconducting current and Shapiro steps at the voltage as high as 0.13 mV were observed at 4.2 K. Moreover, the superconducting current was modulated by the magnetic field. In Bi-Sr-Ca-Cu-O/Au/MgOx/Nb junctions with bulk Bi-Sr-Ca-Cu-O, superconducting current and Shapiro steps at the voltage as high as 0.15 mV were also observed at 4.2 K

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