Tunneling between Dissimilar High-T_c Oxide Superconductors

T. Imaizumi, T. Kawai, T. Uchiyama, and I. Iguchi

Department of Physics and CREST-JST, Tokyo Institute of Technology, 2-12-1 O-okayama, Meguro-ku, Tokyo 152-8551, Japan

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We report the first successful fabrication and measurement of high-T_c heterojunctions with different oxide electrodes, $YBa_2Cu_3O_{7-y}$ and $Bi_2Sr_2CaCu_2O_y$. Different kinds of junction characteristics are observable according to the magnitude of the tunnel resistance. With higher tunnel resistance, gap structures corresponding to two gaps are clearly observed, ensuring that the conventional tunneling scheme is also valid for this geometry. Peculiar behavior for the zero bias conductance peak is also observable. Josephson current is found to flow between these dissimilar superconductors.

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Josephson and quasiparticle tunneling between superconducting electrodes made of identical material, such as $YBa_2Cu_3O_{7-y}$ (YBCO) and $Bi_2Sr_2CaCu_2O_y$ (Bi2212), has been widely studied for the past few years. There are many reports on bicrystal, ramp-edge, and step-edge junctions using identical electrode material [1–8]. Recently, it was demonstrated that the Josephson current and tunnel current observed between the same YBCO electrodes was found to behave like anisotropic d-wave superconductors [9–12]. In contrast, no report is available on the measurement of junctions with different high-T_c oxide electrodes because the growth conditions for the two oxide films are quite different and it is hard to find the optimal conditions that would make two different superconducting oxide films on the same substrate. The study of such a heterojunction is quite important because it provides more detailed information for understanding the essential nature of anisotropic d-wave high-T_c oxide superconductors [13–18] and their tunneling scheme. Concerning high-T_c oxide superconductors, although their pairing symmetry is d wave, their transport properties are sometimes quite different. For example, the gap characteristics observed by scanning tunneling microscopy or tunnel junctions are qualitatively different between YBCO and Bi2212. No evidence of a Josephson current flow between these two materials has been provided. It is interesting to see how they appear in the heterojunctions, and the validity of the semiconductor-tunneling scheme should be addressed.

This Letter describes the first successful fabrication of YBCO/Bi2212 ramp-edge-type junctions, which allow tunneling between the ab planes of two different oxide superconductors. It was confirmed that the Josephson current flowed between YBCO and Bi2212 d-wave superconductors. With a junction with larger resistance, the quasiparticle tunnel current was also observable. The gap structures corresponding to the sum and difference of YBCO and Bi2212 were observable, showing that the semiconductor model for the tunneling scheme also applies to high-T_c heterojunctions.

For the fabrication of a ramp-edge junction, a YBCO thin film 200 nm thick was first deposited onto an $SrTiO_3(100)$ substrate at 860 °C under 0.2 Torr oxygen pressure; then, an $SrTiO_3$ insulating layer of 100 nm was subsequently deposited at 800 °C using a pulsed-laser deposition method. The ramp edge was formed by photolithography and with an Ar ion-milling technique. Thereafter, a 200-nm-thick Bi2212 thin film was deposited, and, if necessary, an artificial barrier layer of $PrBa_2Cu_3O_{7-y}$ (PBCO) with a few nm thickness. Thereafter, the Ar ion milling was done again to pattern out the upper Bi2212 electrode. Finally, the fabricated sample was postannealed at 830 °C in oxygen gas of 0.4 Torr. Both films were c axis oriented, and the measurement on x-ray pole figures indicated that the CuO_2 planes (ab plane) of the YBCO and Bi2212 films were parallel to each other. The junction width was 40 μm. The schematic of a fabricated ramp-edge junction is shown in Fig. 1(A).

The junction resistance of various magnitudes was obtained according to the treatment of the ramp-edge surface. With a PBCO artificial barrier of a few nm, the junction resistance appeared to be remarkably large. The junction barrier with low tunnel resistance was natively formed by directly depositing a Bi2212 film onto a YBCO film. When the junction resistance was low (0.1–1 Ω), a supercurrent of up to about 1 mA was observed in the current-voltage characteristics. With a larger junction resistance, a quasiparticle tunneling behavior was observable. In Fig. 1(B), the temperature dependence of the junction resistance of various magnitudes is shown. While junction (a) had a PBCO barrier of 2 nm, junctions (b) and (c) had only native barriers. For all samples, a two-step-like structure corresponding to the superconducting transition of YBCO and Bi2212 films was observable. The zero-resistance transition temperatures, T_{c0} (YBCO) and T_{c0} (Bi2212), for each junction were found to be 90 and 68 K for (a), 92 and 63 K for (b), and 90 and 67 K for (c), respectively. While the transition for YBCO films was sharp, the transition for Bi2212 films appeared rather broad and was 80–90 K at the onset of the Bi2212 film. Below the zero-resistance transition temperature of the two films, the resistance vs temperature curves reflected those of the junction resistance itself. With a smaller junction resistance [(b) and (c)], it appeared to be almost constant or zero. The same

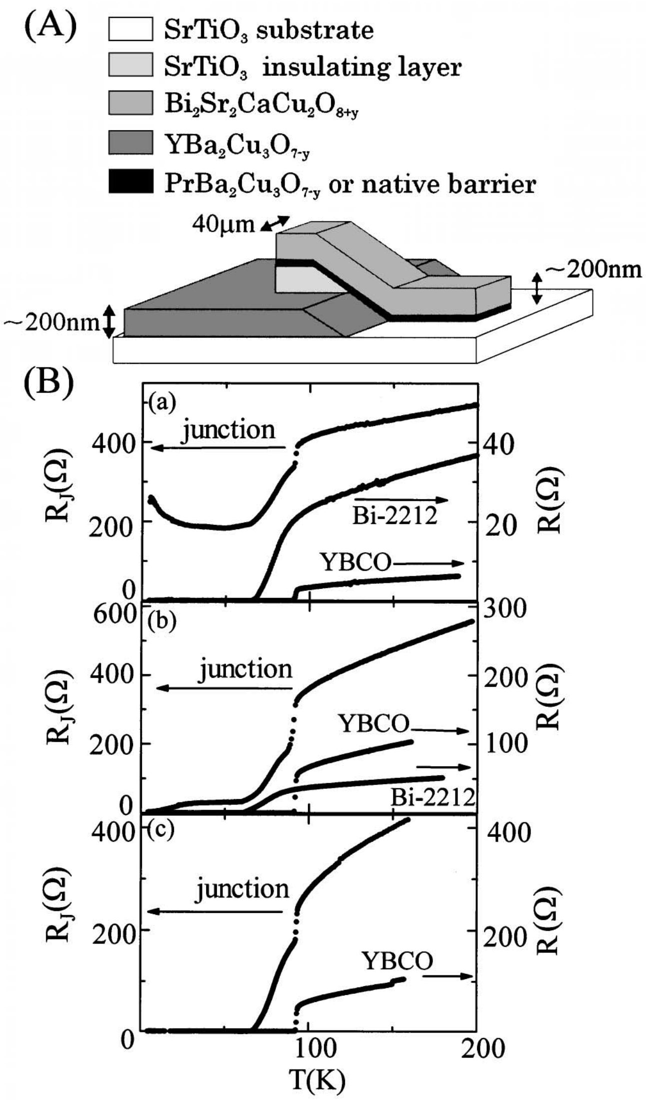

FIG. 1. (A) Schematic of a fabricated ramp-edge junction. (B) Temperature dependence of the junction resistance (R_J) and the film resistance (R) for Bi2212/YBCO ramp-edge junctions fabricated under different conditions. While junctions (b) and (c) have a native barrier formed between YBCO and Bi2212, junction (a) has an artificial PBCO barrier of 2 nm.

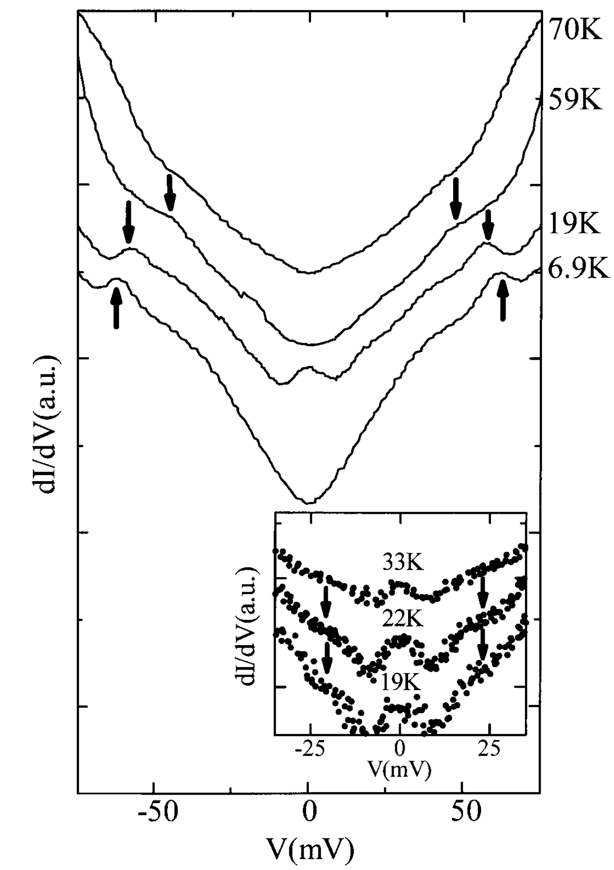

FIG. 2. Tunnel conductance characteristics for the Bi2212/YBCO junction, shown in Fig. 1(B-a) at different temperatures. The inset shows the detailed behavior of the zero-bias conductance peak and the derivative of the cusplike structures, as indicated by arrows.

behavior is seen in superconducting junctions with the same electrode materials. The decrease of R_J below 25 K in (b) may be attributed to the existence of a degraded region which has local T_c's appreciably smaller than bulk T_c. In contrast, curve (a) exhibited an upward increasing behavior of the junction resistance with reducing the temperature below about 20 K. We believe that this behavior may be attributed to either the localized states in PBCO or the effect of a possible additional barrier layer formed by the reaction of PBCO and Bi2212 at a high deposition temperature.

Figure 2 shows the tunnel conductance curve at different temperatures corresponding to Fig. 1(B-a). The resistance vs temperature curve of the Bi2212 film showed a single broad transition. The conductance peak around 60 mV at low temperatures is evident (indicated by arrows), and it decreased toward lower voltage as the temperature increased. Below 60 mV, some structures, possibly related to the derivative of a smeared cusplike structure, are also observable, as seen in the inset of Fig. 2 (also indicated by arrows). Hence, we may associate these structures with the sum and difference between the Bi2212 and YBCO gaps, i.e., Δ_B and Δ_Y, respectively. We then estimated $\Delta_B = 40$ meV and $\Delta_Y = 20$ meV, which yielded $\Delta_B/k_BT_c = 6.8$ and $\Delta_Y/k_BT_c = 2.6$, respectively. The gap values of this amount have been observed in several other reports.

The zero-bias conductance peak around zero voltage (ZBCP) was observable in the intermediate temperature range, as shown in the inset of Fig. 2. It appeared above 12 K and decreased at a higher temperature again. A puzzling aspect is that no ZBCP was present at low temperatures. The ZBCP is typical of the d-wave superconductor of fourfold order-parameter symmetry [19–21]. It appears as the formation of Andreev-bound states at the interface of the junction when the lobes of the pairing wave function are not parallel or perpendicular to the junction interface. In this respect, ZBCP should not be expected for our geometry if the junction interface boundary is perfectly sharp. However, by considering the possibility of a slightly inaccurate morphology of the real junction surface, small

ZBCP is expected to appear even in our geometry [10,11]. ZBCP is related to the sign change of the order parameter at the boundary; hence, it appears as long as the d-wave symmetry is maintained in close vicinity to the barrier interface. The disappearance of ZBCP at low temperatures might be closely related to the peculiar increase in junction resistance that occur when the temperature drops below 20 K [see Fig. 1(B-a)]. The formation of some localized states enables the opening of an additional channel that may inhibit the formation of Andreev-bound states at the interface or destroy the d-wave pairing symmetry.

To compare the observed experimental data with a theoretical model, we have calculated the tunnel conductance between two superconductors with different gaps based on the anisotropic d-wave model. The general expression was obtained using the extended Blonder-Tinkham-Klapwijk theory previously [22]. Since the junction in Fig. 1(B-a) had large tunnel resistance, we assume a high barrier approximation. Then, the electronic density of states is given by

$$N_k(E,\theta) = \frac{|\Delta(\theta)\Delta(-\theta)|^2 - |(E-\Omega_-)(E-\Omega_+)|^2}{||\Delta(\theta)\Delta(-\theta)| - (E-\Omega_-)(E-\Omega_+)e^{i(\phi_- - \phi_+)}|^2}, \tag{1}$$

where $\Delta(\theta)$ is an anisotropic order parameter, $\Omega_+ = \sqrt{E^2 - \Delta(\theta)^2}$, $\Omega_- = \sqrt{E^2 - \Delta(-\theta)^2}$, $e^{i\phi_+} = \Delta(\theta)/|\Delta(\theta)|$, and $e^{i\phi_-} = \Delta(-\theta)/|\Delta(-\theta)|$. The expression for tunnel current becomes proportional to

$$\begin{aligned} I(V) \propto \int_{-\pi/2}^{\pi/2} d\theta \int_{-\infty}^{\infty} & N_k^L(E - i\Gamma^L, \theta) \\ & \times N_k^R(E - eV - i\Gamma^R, \theta) \\ & \times [f(E-eV) - f(E)]\, dE, \end{aligned} \tag{2}$$

where Γ^L and Γ^R are the lifetime broadening factors of two superconductors. Because of the fabricated junction geometry (zero angle configuration), we assume that $\Delta_{L(R)}(\theta) = \Delta_{L(R)}(-\theta)$. Then the calculated conductance for the $d_{x2\text{-}y2}$ symmetry in the case of $\Delta_R/\Delta_L = 1/2$ corresponding to the observed gap ratio and $\Gamma^{L(R)} = 0.05\Delta_{L(R)}$ is depicted for different parameter values of $\beta = \Delta/k_BT$ in Fig. 3(a), where $\Delta = \Delta_L$ is the larger gap parameter between Δ_R and Δ_L. It is understood that gap structures corresponding to the sum and difference of two gaps in terms of derivative characteristics are recognizable, but they are considerably smeared. In the real junctions, the quasiparticle transport is more complicated due to the contributions from the resonant tunneling via localized states as reported by many authors [23]. By assuming the resonant tunneling via one and two localized states [$(a + bV^{4/3})$ contribution to the conductance], the calculated result showed a reasonable fit to the experimental data of $T = 19$ K as shown in Fig. 3(b).

Figure 1(B-b) corresponds to a case in which the junction resistance was appreciably low (~30 Ω), but no Josephson coupling had yet been attained. In this case, the observed current-voltage (I-V) characteristics exhibited a premature Josephson-like behavior. When the junction normal resistance grew even smaller (~0.1–1 Ω) [Fig. 1(B-c)], the supercurrent was observable in the current-voltage characteristics of the junction. After microwave irradiation of various frequencies (4, 7, and 10 GHz), the Shapiro steps were induced. Figure 4 shows the response of the YBCO/Bi2212 junction under microwave irradiation of 7 GHz in terms of the differential resistance. The dips correspond to the Shapiro steps. They appeared pronouncedly at the integer multiples of voltage $V_0 = hf/2e$, where f is the microwave frequency, h is the Planck constant, and e is the electronic charge. The Shapiro steps are also recognizable at the half-integer multiples of V_0, although their amplitudes were much smaller (indicated by arrows). According to

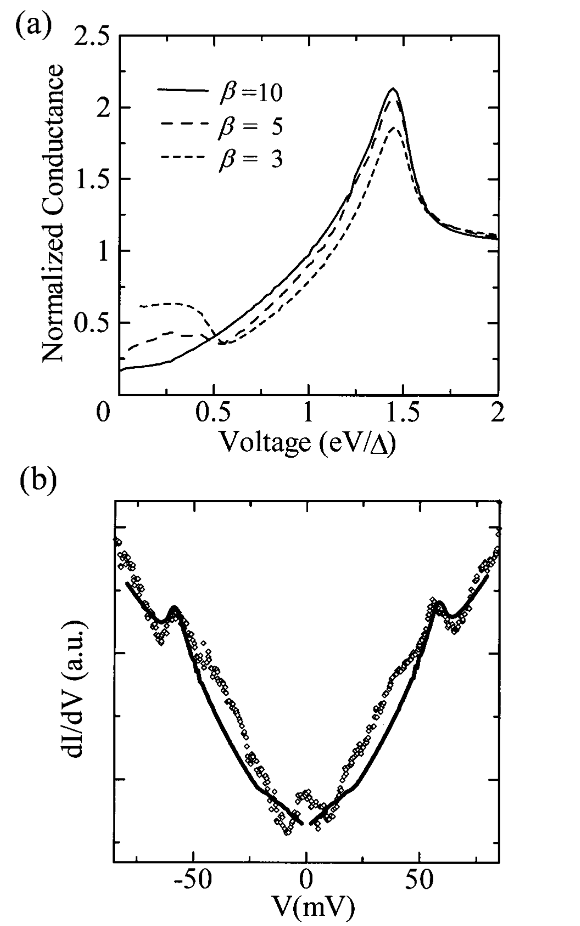

FIG. 3. (a) Calculated tunnel conductance for the junction with different gaps ($\Delta_R/\Delta_L = 1/2$) for various values of $\beta = \Delta/k_BT$, where $\Delta = \Delta_L$. (b) Tunnel conductance at 19 K (open dots) together with the calculated curve with taking the resonant tunneling via one and two localized states into account (solid line).

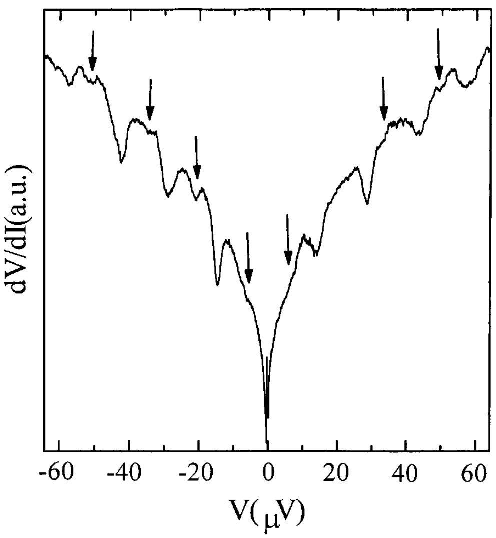

FIG. 4. Differential tunnel resistance dV/dI as a function of the junction voltage V for the Bi2212/YBCO junction, shown in Fig. 1(c) under microwave irradiation of 7 GHz. The Shapiro steps appeared pronouncedly at the integer multiples of V_0 and were also observable at the half-integer multiples of V_0, as indicated by arrows.

the d-wave calculation [20], the Josephson current in our geometry contains the sinφ term dominantly, where φ is the phase difference across the junction, consistently with the experimental observation. This result demonstrates the flow of Josephson current between dissimilar YBCO and Bi2212 oxide superconductors.

We have demonstrated for the first time the fabrication and measurements of high-T_c heterojunctions consisting of two different d-wave superconductors, YBCO and Bi2212. Clear tunneling characteristics were observed, including the sum and difference of two different gaps of YBCO and BSCCO, which was in reasonable agreement with the calculated result based on the d-wave tunneling. This indicates that the conventional tunneling scheme is also applicable to high-T_c heterojunctions with d-wave smeared gap structures. Some peculiar behavior in the junction resistance vs temperature curves typical to YBCO/BSCCO junctions was observed, which affected the conductance characteristics. The phenomenon is considered to be typical of high-T_c materials.

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