Observation of quasiparticle Andreev bound states using $YBa_2Cu_3O_{7-y}$/Ag ramp-edge junctions with different interface geometries

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We present measurements on quasiparticle tunneling using $YBa_2Cu_3O_{7-y}$ (YBCO)/Ag ramp-edge junctions. The tunnel direction was toward the CuO_2 planes. Two junctions with different tilted angles between the *a* axis of YBCO and the junction boundary were fabricated on the same substrate simultaneously. For the junctions with the tilted angle of 45°, the zero-bias conductance peak (ZBCP) was observed. On the contrary, for those fabricated with the tilted angle of 0°, a dip structure around zero bias was mostly observed. The results are consistent with the recent studies on the Andreev reflection between a $d_{x^2-y^2}$-wave superconductor and a normal metal. The dependencies of ZBCP on temperature and magnetic field are also presented.
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It is generally accepted that the high-T_c superconductors might have the $d_{x^2-y^2}$-wave pairing symmetry. Such a pairing state gives rise to an anisotropic energy gap which is zero along the nodes of an essentially cylindrical Fermi surface. A sign change of the pair potential exists in orthogonal *k* directions, implying a π-phase shift of the wave function at the nodes of the pair potential in the (110) direction. The phase sensitive measurements using planar or corner formed Josephson junctions made between a high-T_c superconductor and a BCS low-T_c superconductor demonstrated that there existed such a phase difference and gave a strong evidence for a *d*-wave pairing.[1,2] So the behavior of the order parameter near the interface boundary has become considerable attention. Recent theoretical works show that the Andreev reflection at a normal-metal–superconductor (NS) interface can be also phase sensitive, and might give useful information to the symmetry of the order parameter.[3–7] In particular, the Andreev reflection[8] caused by the rotation of the internal state of an excitation from *particle-type to hole-type* (and vice versa) will lead to the Andreev bound states at zero energy on the Fermi surface. It was pointed out that the Andreev bound states formed at the interface are a robust feature of the spectrum depending only on the sign change of the order parameter.[4] It will not occur if the superconductor is *s*-wave, whether it is isotropic or anisotropic; hence, it may be taken as a clear evidence for the *d*-wave pairing symmetry.

The Andreev bound states have many observable consequences, one of them is that they can give rise to a zero bias conductance peak (ZBCP) when the tunnel boundary is formed at the (110) surface of a $d_{x^2-y^2}$-wave superconductor. In a series of works, Tanaka and co-workers showed that ZBCP was observable at any ideal surface when the *a* axis of the *d*-wave superconductors was deviated from the direction normal to the surface.[5,6] ZBCP takes its maximum value at the (110) surface, and changes from the maximum value to zero continuously according as a continuous change of the boundary surface from (110) to (100) or (010) for the $d_{x^2-y^2}$-pairing symmetry. In contrast, for the d_{xy} symmetry, the maximum ZBCP is observable for the (100) interface, and for the *s*-wave symmetry, such a ZBCP would not appear at any interface orientation. So the observation of the interface orientation dependence of ZBCP will give definite evidence for the order parameter changing sign on the Fermi surface.

ZBCP has been observed in many quasiparticle tunneling experiments performed using either planar $S/I/N$ junctions or scanning tunneling microscope (STM).[9–23] The planar junction fabricated by vacuum evaporation of a metal layer directly on the surface of high-temperature superconductor (HTSC) proved to be the simplest and most direct way to observe the tunneling spectra. When a single crystal was used, only the junctions made on the (001) surface were usually possible because of the fabrication difficulties. Some groups reported the observation of ZBCP on the (001) surface of YBCO and BSCCO,[9,10] but the other groups observed only a dip structure in the tunneling spectra in the similar case.[11,12] An improved technique for growing epitaxial HTSC thin films with different crystal orientation made it possible to fabricate the planar junction on the (001), (100), and (110) surfaces of YBCO. Many early experiments reported the observation of ZBCP on the (001) surface of YBCO thin film,[13–15] while only a few groups reported ZBCP on the (100) and (110) surfaces but not on the (001) surface.[16] Most of the early experiments explained that ZBCP was due to inelastic magnetic spin-flip scattering of electrons tunneling through the barrier using Anderson-Appelbaum model (AA model).[24] But it was pointed out later that the nonlinear dependence of ZBCP on magnetic field could not be explained using the AA model.[3]

When the theory of Andreev bound states for the *d*-wave superconductor at the interface boundary comes into attention, the tunneling experiments have been considered by a different insight again. Many measurements were performed and discussed in terms of the *d*-wave scenario. In the recent experiments,[17–22] the mutual agreement has been obtained for the fact that ZBCP was produced by tunneling into the *ab* plane.[23] It has been reported that, in the planar junction experiments[17,18] and STM experiments,[19,20] the (001)-

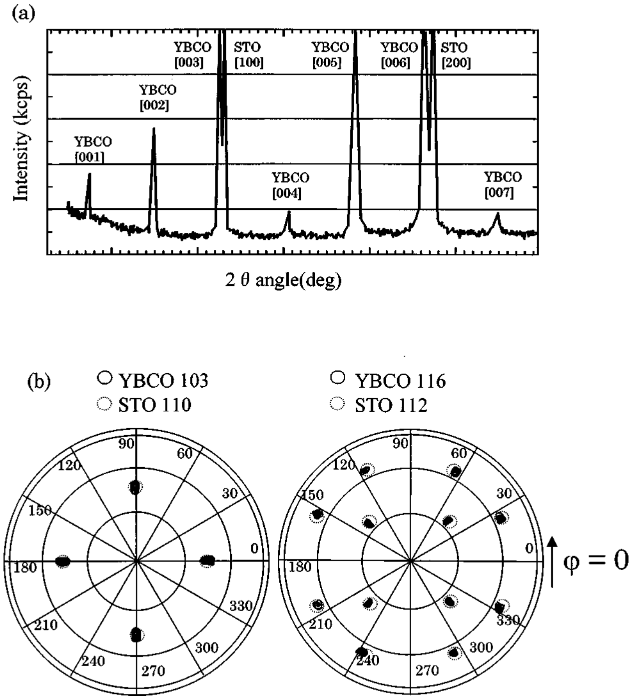

FIG. 1. (a) XRD pattern of the YBCO thin film grown on $SrTiO_3$ substrate. (b), (c): Pole figure of the YBCO thin film observed at the detection angles 2 θ of 32.84° and 58.20°, respectively.

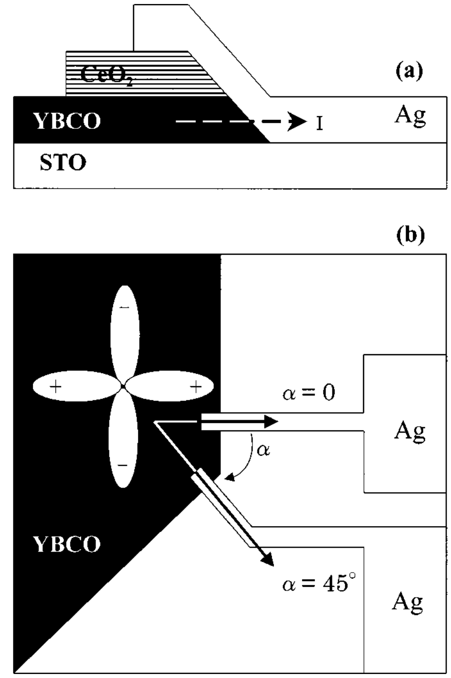

FIG. 2. (a) Schematic cross-sectional view of ramp-edge junction. (b) Two ramp-edge junctions fabricated on one STO substrate with tilted angles of 45° and 0° against the *a* axis of YBCO film.

oriented tunneling yielded a dip conductance around zero-bias voltage which was qualitatively different from the *ab*-plane tunneling. So it is instructive to see how the ZBCP will change when the crystal orientation angle in the *ab* plane is varied. Reference 17 reported that the tunneling conductance was the same for all non-*c*-axis planar tunnel junctions, while Refs. 19 and 20 tended to support that the maximum of ZBCP appeared for the tunneling through (110)-oriented surface of YBCO single crystal. Such controversial results might be caused by the roughness effects.[25–28] It is well known that the naturally grown surface of thin film must contain considerable amount of grains and the non-(001) surfaces of single crystal were always produced by the process of mechanical polishing, which makes it difficult to obtain a homogeneous surface necessary for these measurements. It is also emphasized here that the measurements until now were performed using individual samples with different crystal orientations. There is no report on the direct comparison of the tunnel conductance between the junctions fabricated under the same condition.

Here we report a quasiparticle tunneling experiment using ramp-edge S/N junctions. A ramp-edge junction[29–31] has very small junction area and an easily controllable junction structure. Using a ramp-edge junction, the tunnel direction in the *ab* plane can be easily controlled by changing the boundary angle relative to the sample crystal orientation (i.e., *a* axis), and it will provide an only possible method to change the tunnel direction in the *ab* plane continuously to demonstrate the predicted dependence of the Andreev bound-state spectral weight on the relative orientation of the boundary interface. Note that, using planar junctions or STM, it is impossible to observe the interface property with the intermediate tilted orientation angle from the *a* axis other than 0° or 45°. In this experiment, two ramp-edge S/N junctions with different tilted angles are fabricated on the same substrate simultaneously and compared.

High quality epitaxial films are necessary for fabricating the ramp-edge junctions used in our measurements. When a YBCO film is grown on a substrate with large crystal mismatch like MgO, or when the film is not completely epitaxially grown on the substrate, the grains with titled angles other than 90° may be usually observable. The existence of such grains will affect the tunneling result, hence should be avoided. We prepared high quality YBCO thin films on $SrTiO_3$ (STO) substrates by pulsed laser deposition. The films were grown at 750 °C at 0.2 Torr O_2 atmosphere with the laser beam power of 300 mJ and the deposition rate of 5 nm/s. The film thickness was 200 nm. T_c of the films was about 90 K with the transition width less than 3 K.

Figure 1 shows an x-ray-diffraction pattern (XRD) of the YBCO thin film, in which only (001)-orientation YBCO phase can be observable. The result shows that YBCO is epitaxially grown on a STO substrate. To investigate the in-plane orientation relationship between the *c*-axis thin film and the substrate, the x-ray pole figure measurement was used. Two pole figures were measured by fixing the detector at 2 θ position of 32.84° and 58.20°, respectively. The pole figures were obtained by scanning the tilted angle of beam/detector plane from 0°–90°, only the peaks corresponding to the reflection of (013) [which is (013), (103), (013), (103)] from the (001)-oriented YBCO was observed when the detection angle 2 θ was 32.84°. When 2 θ was fixed at 58.20°, 12 peaks corresponding to 12 equivalent reflection of (116) for (100)-oriented YBCO were observed. The two pole figures are exactly the same with the pole figures of the substrate measured at the reflection corresponding to (110) and (112) of (100)-oriented STO crystal, showing that YBCO has

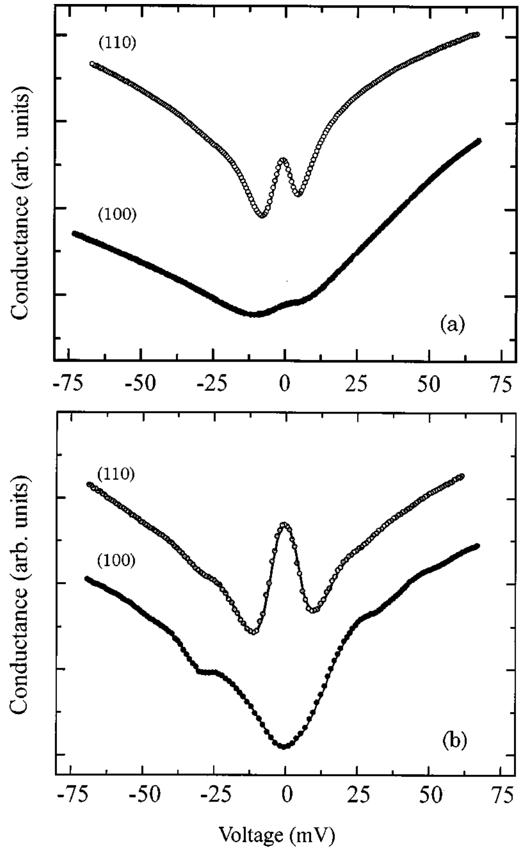

FIG. 3. Typical conductance vs voltage curve for the (110) and (100) junction fabricated on the same substrate.

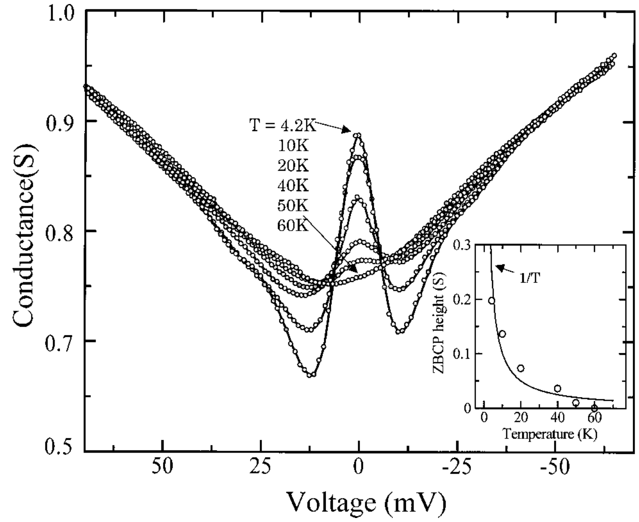

FIG. 4. Conductance vs voltage curves measured at different bath temperatures. The inset shows the temperature dependence of the zero-bias peak height for a (110) junction.

an almost perfect orientation relationship with the substrate, so no grains in the *ab* plane with possible titled angles other than 90° were present.

To fabricate the junction, a 150-nm CeO_2 was deposited on the YBCO film as an insulating layer and patterned by photolithography and ion-milling processes. The sample was set on a water-cooled rotatable holder and etched by ion milling. The sample rotation was done to make the interface boundary much more smoothing after etching. The accelerator voltage was 250 V, and the etching rate was 25 nm/min for YBCO and 10 nm/min for CeO_2. As observed by atomic force microscopy, a highly flat edge with an angle of about 30° was obtained. After etching, photoresist was removed by acetone, then etched by ion milling again at an accelerator voltage of 150 V to clean the edge surface. An evaporation source built in the same chamber with the ion gun made it possible to deposit a 200-nm-thick Ag layer *in situ* after cleaning and then the sample was patterned again by ion milling to form the junction geometry. Two junctions with the tilted angles of 45° and 0° against the *a* axis of YBCO film and the width of 20 μm were fabricated on the same substrate simultaneously as shown in Fig. 2, and they are mentioned as (110) and (100) junctions, respectively, in this article.

We have measured more than ten samples with each sample containing two junctions. The resistance of the junctions was around $1\times10^{-4}\,\Omega\,cm^2$; in most cases, the (100) junctions showed slightly larger resistance than the (110) junctions fabricated on the same substrate. The measurements on the conductance vs voltage curves were performed by a standard four-terminal method using a lock-in amplifier. Figure 3(a) shows typical conductance results for the samples measured. ZBCP was observed for all the (110) junctions, showing that the clean junction interface was obtained after the processes of ion milling and *in situ* evaporation of Ag electrodes. In some of the (100) junctions, very weak ZBCP as compared to the (110) junctions was visible, but striking V-type curve with clear gap structure around 25 mV was also often observable as shown in Fig. 3(b). It is clearly seen that the two junctions fabricated in the same substrate simultaneously gave qualitatively different results and large ZBCP was specially obtained for the junctions with the (110) interface.

The temperature dependence of ZBCP versus voltage for the (110) junction was shown in Fig. 4. ZBCP took a maximum value at 4.2 K and disappeared at about 60 K. The changes of zero conductance peak height as a function of temperature was shown in the inset of Fig. 4. It increased nonlinearly as bath temperature was reduced. Alff *et al.* reported a $1/T$ dependent of ZBCP using bicrystal junctions[32] and our results had a similar tendency against temperature. The tunneling spectra showed asymmetric background conductance against the junction voltage, which is usually expected for the tunneling junction fabricated with different electrode materials.

The effect of magnetic field on the tunneling conductance is shown in Fig. 5. The magnetic field (H) was applied parallel to the (110) junction boundary in the a-axis direction. As the magnetic field was increased from 0–5 T with 1 T steps, the conductance at zero bias decreased, while that at 3–10 mV voltage range increased. It is more easily seen when the $G(H,V)$-$G(0,V)$ vs voltage curve is plotted out, as shown in the inset of Fig. 5. The ZBCP was slightly broadened when H was increased.

We discuss our results in terms of the Andreev bound-states model based on the d-wave pairing symmetry. In this model, the Andreev reflection can sense the phase or the sign change of a superconducting order parameter, and the stable zero energy bound states will be formed at the surface or the interface of a high-T_c superconductor if the Andreev scatter-

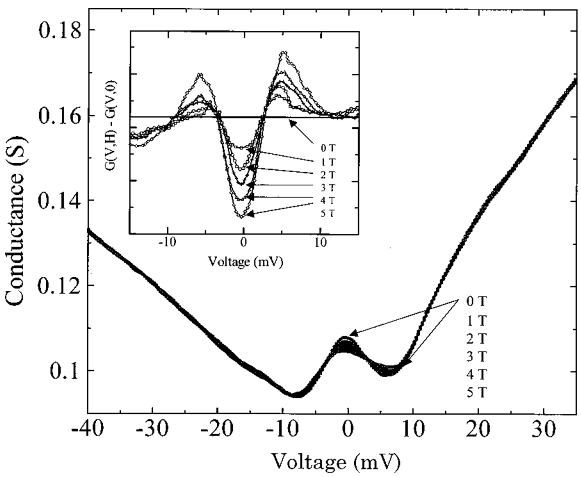

FIG. 5. Magnetic-field dependence of the conductance for a (110) junction at 4.2 K. The inset shows the relationship between $G(V,H)$-$G(V,0)$ and bias voltage V.

ing induces a sign change of the order parameter. For the d-wave symmetry, such a sign change is possible at the interface where the lobe directions are not perpendicular to the boundary. These Andreev bound states can give rise to an observable ZBCP in quasiparticle tunneling experiments. According to the theories, ZBCP depends on both temperature and magnetic field.[5,26,28] It will be reduced when bath temperature is increased, and it will be broadened and split when a magnetic field is applied. ZBCP will be also dependent on the interface orientation angle, and the maximum of ZBCP will be given at (110) or (100) interface for $d_{x^2-y^2}$ or d_{xy} pairing symmetry, respectively.[4] In our experiment, stable temperature dependent ZBCP was observed for the (110) junctions as predicted, but the (100) junctions showed slightly deviated behavior. For the latter, in some cases, a very weak ZBCP was observable, while in other cases, complete V-shape conductance with appreciable gap structure and no ZBCP was traced out. The appearance of very weak zero bias anomaly may be attributed to either the slight misalignment of the boundary angle against the crystal orientation of the YBCO film or the possible boundary roughness effect. For the misalignment problem, it is very likely since the zero bias anomaly reveals at any finite angle other than 0° or 90° according to Ref. 27. Considering the roughness of the boundary, if the interfaces are not perfectly flat, the contributions from different interface orientations should be taken into account. One may argue that how the c-axis tunneling affects the observed characteristics because the possible existence of microstructures in the ramp-edge junction will permit a c-axis tunneling component certainly. We consider that if the c-axis tunneling is assumed not to produce ZBCP (as reported in most of the experiments), it will surely not contribute to ZBCP appeared in the ramp-edge junction conductance because it is in a parallel path to the ab-plane tunneling. In our experiment, the junctions fabricated with (110) and (100) boundary gave clearly different behaviors enough to discriminate the two junction conditions. ZBCP observed at the (100) junctions were strongly reduced as compared to the (110) junction, so using the Andreev bound-state model, a $d_{x^2-y^2}$ pairing symmetry, not a d_{xy} pairing symmetry, is supported. The predicted splitting of the ZBCP in an applied magnetic field was not observed in our experiment. Hu discussed that a possible screening effect may prevent the applied magnetic field from reaching the grain boundary inside a superconductor, and made the magnetic field effect too weak to be observed,[3] while Alff *et al.* in a recent article argued that the faceting of the grain-boundary plane together with impurity scattering might be the reason for the suppression of field splitting of ZBCP.[32] Until now, the magnet field splitting effect has been reported only by a few groups.[16,18] To clarify this issue, further experimental and theoretical works are needed.

In conclusion, the quasiparticle tunneling experiment has been carried out using the ramp-edge junctions fabricated in different boundary interface geometries. Two tunnel junctions with different tilted orientation angles of 45° and 0° from the a axis of YBCO film were fabricated on the same substrate simultaneously by photolithography technique. A stable ZBCP with relatively large density was observed in the (110) junctions and very weak or no ZBCP was observed for the (100) junctions. The results give strong evidence for the $d_{x^2-y^2}$ pairing symmetry which leads to the formation of Andreev bound states and the observable maximum ZBCP at the (110)-oriented interface. Our experiments show that it is possible to study the tunneling spectrum at any crystal orientation angle in the CuO_2 plane in HTSC superconductors using ramp-edge tunnel junctions.

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