Zero Bias Conductance Peak Enhancement in $Bi_2Sr_2CaCu_2O_8/Pb$ Tunneling Junctions

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We found strong zero bias conductance peak enhancement in $Bi_2Sr_2CaCu_2O_8$ by tunneling in the ab-plane direction. Our results are consistent with the recent studies on Andreev reflection between a d-wave superconductor and normal metal. We have also observed exotic behaviors of the conductance peak if the counter electrode is a conventional superconductor. If these characteristics are better understood, they can be very useful in studying the pairing properties in high T_c superconductors. [S0031-9007(98)05312-5]

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Recently, there is a tremendous amount of interest in the zero bias conductance peak (ZBCP) observed in tunneling spectra of high T_c superconductors because several theories have been proposed in extending the Blonder, Tinkham, and Klapwijk (BTK) theory [1] to d-wave superconductors [2–5]. According to the conventional BTK theory, low energy electrons ($E < \Delta$) can be Andreev reflected as holes at a normal metal-superconductor (N/S) interface. This produces the ZBCP because of the electron pairs formed at the superconducting side, and hence the peak height cannot exceed 2 times the normal conductance. In the extended theories for d-wave superconductors, the ZBCP will increase dramatically in small gap directions because of the interference between the electronlike and holelike tunneling quasiparticles. In this Letter, we are presenting experimental results that are consistent with these theories. We will also report findings that have not been addressed by previous theories, in the hope of further refining the model.

Samples of $Bi_2Sr_2CaCu_2O_8$ (BSCCO) single crystals were grown by the self-flux method, with T_c of about 85 K. Proper stoichiometry was ensured by microprobe analysis. For junctions of ab-plane tunneling, one BSCCO single crystal of approximate size 0.3 cm $\times$ 0.3 cm $\times$ 0.05 mm was molded into a block of epoxy. The block of epoxy was polished to expose the sample edge, and the final roughness of the surface was about 3000 Å. Though we can fit some of our data by assuming tunneling in a single direction, the tunneling direction is not controlled in the present stage of the experiment. The surface smoothness and cleanliness of some controlled samples were monitored with scanning electron microscope [Fig. 1(a)]. A strip of Pb (2 mm in width) was then evaporated across the edge of the BSCCO single crystal on the top surface. For tunneling along the c-axis direction, the BSCCO single crystal was glued flat on the top of a glass substrate. It was cleaved and then coated with collodion, with a strip opening of about 1 mm in width. Pb electrode was then evaporated to form the junction. As in many other tunneling experiments [6], the surface of the BSCCO forms a good natural barrier. Also Pb getting oxygen from BSCCO surface (which is later replenished by oxygen from bulk BSCCO) can make a good oxide barrier. However, our Ag/BSCCO junctions also show similar tunneling behavior, making the surface barrier idea more likely. The sample forms a natural barrier of the tunneling junction. It is in

(a)
(b)

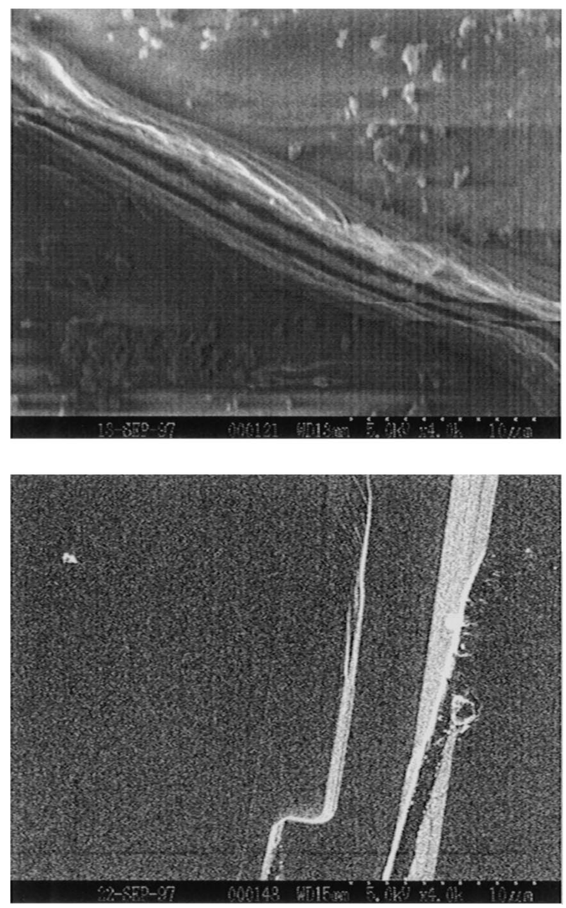

FIG. 1. (a) The diagonal strip in the scanning electron microscopy (SEM) picture is the ab-plane edge. The flakes shown on the side are the epoxy surface. (b) SEM picture of the c-axis surface. Surface steps are selected for better contrast of the smooth surface. Both pictures are at the 10 μm scale.

general difficult to characterize the surface conditions at the junction area. However, the internal consistency in all of the data we have accumulated, including the Ag/BSCCO junctions, clearly demonstrates the validity of the present experiment. Most of our junctions have resistance between 50 Ω to 500 kΩ. Though we have no precise control on junction resistance, the junction resistance is an effective parameter in categorizing the junction behavior [7]. The junctions were measured by four point measurement, with a constant current driving bias. Both I and V were measured and recorded, and the conductance dI/dV was calculated numerically.

As a control measurement for comparison purpose, we have measured junctions of similar structures between conventional superconductors (Pb) and normal metal (Al foils). All junctions exhibit conventional BTK behavior [8]. The Andreev reflection peak occurs at temperatures below the T_c of Pb, and the peak height increases with decreasing temperature. The normalized peak height h (peak height divided by the background conductance) is always significantly less than 2 at all temperatures down to 4.2 K [9]. The width of the peak is always slightly larger (because of thermal smearing), but of the same order of the energy gap of Pb. There are experimental concerns that the ZBCP can be due to local heating or current depairing effects. They are unlikely for the present experiment because of several reasons. First, local heating will cause hysteresis in the I-V curves between forward and reverse swings of bias voltage. We have measured all data in both forward and reverse swing directions. None of them show signs of this hysteresis effect. Second, if the ZBCP is due to local heating, there should be a correlation between the peak height and the junction resistance. In all the junctions with ZBCP enhancement that we have studied, we find that the peak height is quite independent of the junction resistance. Finally, if there is local heating effect, the I-V curve has to return to the normal curve (pass through the origin) at higher bias. This will actually produce a dip next to the zero bias peak, and this will not affect the results of this paper [10]. If the ZBCP is caused by any critical current effect, then there must be some superconducting linkage between the two sides of Pb/BSCCO junction after Pb becomes a superconductor. This will produce a sudden surge of supercurrent. Our observation below T_c of Pb ignores such a possibility.

Besides the edge junctions described above, we have also studied junctions in the c-axis direction. These junctions have smaller resistance because of the larger tunneling area. The conductance curves of all these junctions show linear rising background [11]. ZBCP is observed in some junctions, but none of them is very pronounced. In Fig. 2 we show a typical ZBCP in the c-axis direction, at 8 K. The ZBCP is small with $h = 1.14$ and can be easily accounted for by the conventional BTK theory. This is reasonable even from the viewpoint of d-wave superconductivity, since Andreev reflection in the c-axis direction always produces electronlike and holelike quasiparticles symmetrically in opposite directions with no sign difference in the order parameter. However, we should not ignore the possibility of surface defects (such as atomic steps) at the junction interface. The small peak can then be attributed as a result of ab-plane tunneling by the surface steps. Some of these steps can be seen in Fig. 1(b). This will be consistent with the observation by some authors that the ZBCP cannot be seen along the c axis [12].

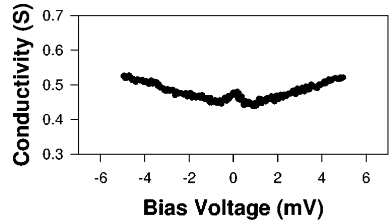

FIG. 2. Conductance curve for tunneling in c-axis direction. This is the curve with the most pronounced ZBCP from all of our c-axis tunneling data.

In this Letter, we want to focus our discussion on the behavior of the ZBCP when the tunneling is in the ab-plane direction, because it has many interesting features that cannot be explained by conventional approaches. For instance, most of the ZBCP in this direction are distinct and have a peak height several times larger than the background resistance. In Fig. 3(a) we show an I-V curve and the ZBCP in the conductance curve for a typical junction. The dramatic difference between these curves and those from the c-axis junctions leads us to conclude that the major component of the tunneling current is indeed in the ab-plane direction. Since the Pb counter electrode is normal at that temperature, and also the finite conductance near zero bias, we can rule out the possibility of Josephson tunneling in these junctions. The solid line in Fig. 3(b) is a theoretical curve [2] generated by assuming d-wave Andreev reflection with $\Delta = 13$ meV, barrier strength $Z = 2$ [a dimensionless quantity equals $H/\hbar v_F$, if the tunneling potential is defined as $H\delta(x)$], and the angle between tunneling direction and maximum gap direction $\alpha = 21$. It should be noted that α is just a fitting parameter, and it is not measured experimentally. The curve has been smeared with a Gaussian distribution function of half width equals $2\Gamma = 3.08$ meV to account for the limited lifetime of quasiparticles [13]. As a simple model Γ includes thermal smearing and all other depairing mechanisms. We should also note that kT is much smaller than 3.08 meV. Δ is smaller than the commonly quoted values because the model we used here allows electrons to tunnel in all directions with equal probability. Experimentally this is not the case since electrons are more likely to tunnel in the forward direction [14]. This results in a lesser gap as the ZBCP is more enhanced in the small gap direction.

We have also studied the behavior of ZBCP at temperatures below T_c of Pb. None of our junctions has small

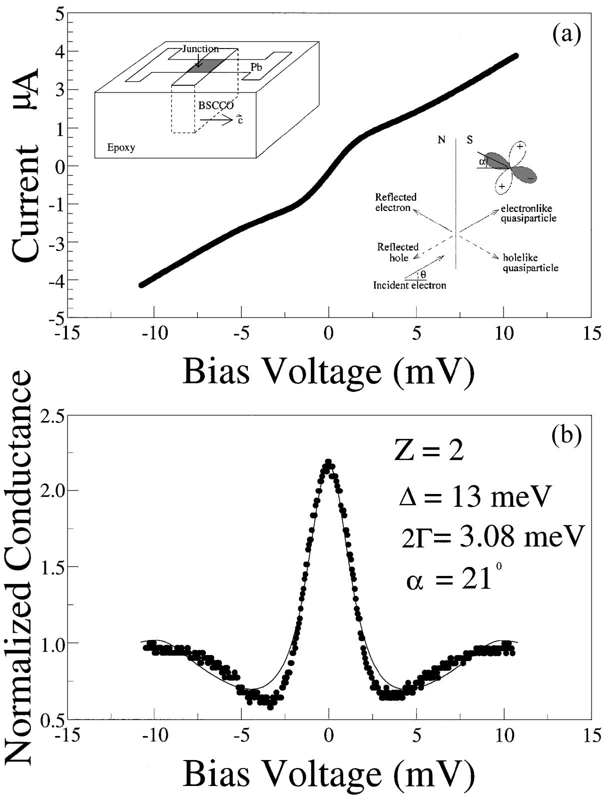

FIG. 3. (a) Typical *I-V* curve showing ZBCP enhancement for tunneling in the *ab*-plane direction. Upper inset: Schematic for our junction structure. Lower inset: Possible outcomes of a tunneling electron from normal metal to *d*-wave superconductor. (b) Derivative of the top curve. Solid line is a theoretical curve based on the extended BTK theory.

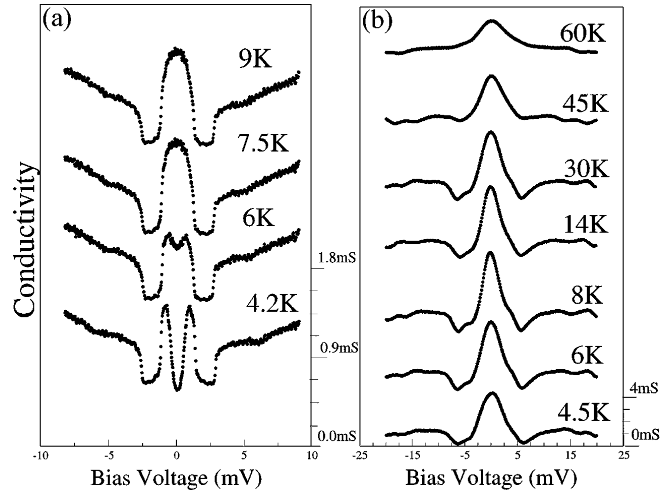

FIG. 4. (a) Temperature dependence of ZBCP as the Pb counterelectrode becomes superconducting. For the junction at 9 K, background resistance is 1.5 kΩ, *h* is 1.38, and the ratio *R* (see text) is 0.65 mV^{-1}. (b) The ZBCP decreases when the Pb counterelectrode becomes superconducting (below 7.2 K). For the junction at 8 K, background resistance and *h* are 0.8 kΩ and 4.3, respectively. The ratio *R* is 2.04 mV^{-1}. The vertical scales of (a) and (b) are for the lowest curve in each graph.

enough resistance for observable Josephson tunneling to occur. Some junctions showed periodic structures that resemble features from multiple Andreev reflection [15]. In this Letter, we want to focus on the response of the ZBCP to the superconductivity of Pb. All our junctions with ZBCP fall into one of these two categories, depending on the general appearance of the ZBCP. For broader ZBCPs, a gaplike feature will develop as Pb is becoming superconducting. As a result, it seems that the ZBCP is being split at temperatures below Pb T_c. It is possible that the portion of the high T_c surface at the junction area is actually normal, and there will be zero bias conductance depression for tunneling at this area as the Pb gap is opening up. However, this possibility is unlikely because the gaplike feature in some of these junctions is so distinct that the original ZBCP is completely depressed at 4.2 K [for example, see Fig. 4(a)]. There are other more plausible explanations to elucidate why splitting occurs. For instance, the splitting can be considered as a convolution between the ZBCP and the Pb quasiparticle density of states [16]. More interestingly, similar splitting is also observed by Covington *et al.* [17] for $YBa_2Cu_3O_{7-x}$ (YBCO)/Cu and YBCO/Pb junctions. Since they observe the splitting to occur even for a normal counter electrode (Cu), they attribute this effect to broken time reversal symmetry due to a subdominant *s*-wave surface at the top of the high T_c superconductor [18]. The T_c of the subdominant layer is actually quite close to the Pb T_c, making the model a possible candidate in explaining our results. However, we want to point out that we have also prepared BSCCO/Ag junctions in this course of study on ZBCP. So far we see no splitting in any ZBCP of these junctions at temperatures down to 4.2 K.

The other interesting behavior is that the ZBCP will become shorter as Pb becomes superconducting. In general, this feature occurs for the sharper ZBCPs. Experimentally, whether the ZBCP is sharp or broad can be clearly defined by calculating the ratio (R) of peak height to the full width at half maximum for the conductance curve at 8 K. All ZBCPs that split have R less than 0.8 mV^{-1}, while ZBCPs that decrease in height always have R larger than 1.1 mV^{-1} [19]. Typical data for the latter case is presented in Fig. 4(b). At around Pb T_c, the height of the ZBCP decreases as the temperature is lowered. This situation reflects the interaction between the superconductivity of BSCCO and Pb, due to the incompatibility of pairing symmetries. We believe that whether the ZBCP splits or decreases in height depends on the junction condition and barrier quality. If the barrier strength is weak, it is likely that the Pb will induce the *s*-wave component in the high T_c superconductor by proximity effect and will depress the peak height. Otherwise, the tunneling will be more quasiparticlelike and cause splitting of the ZBCP. Again, none of our BSCCO/Ag junctions demonstrates similar behavior, where the ZBCP increases as

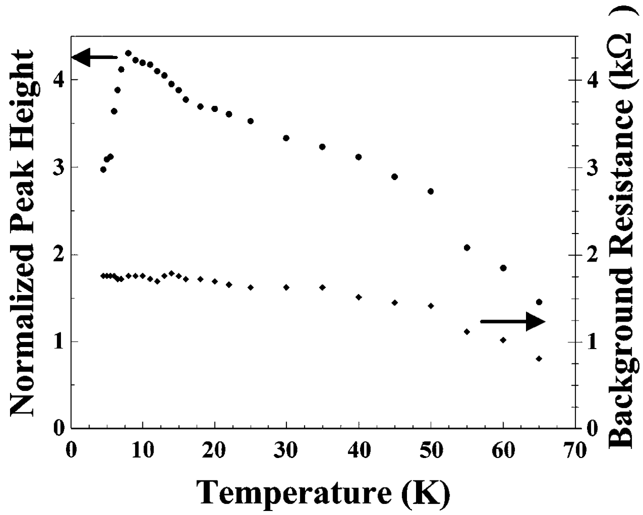

FIG. 5. Upper curve is the plot of h vs temperature for the junction shown in Fig. 4(b). The lower curve is the plot of background resistance vs temperature for the same junction with the axis on the right.

temperature is lowered, consistent with the fact that Ag is normal at all temperatures.

Normalized peak height (h) versus temperature curve for the junction shown in Fig. 4(b) is plotted in Fig. 5. Here [Fig. 4(b)] the peak is measured from the zero conductance, hence h has a value of 1 for $T > T_c$. For convenience, we use the conductance at -14.5 mV as the background conductance used to normalize the peak height. At temperatures below 50 K, h has already exceeded the BTK limit of 2. As Pb becomes superconducting for $T < 7.2$ K, h drops dramatically from its maximum value of 4.3 at $T = T_{c,\mathrm{Pb}}$ to less than 3 at $T = 4.2$ K. There are two interesting features at $T \sim 15$ K and at $T \sim 52$ K. First the lower temperature feature (at 15 K) appears in all Pb/BSCCO junctions, independent of the ratio R. To distinguish whether these features are intrinsic to superconductivity, or due to junction changes, we also plot the background resistance at -14.5 mV versus temperature at Fig. 5. The second feature at 52 K is due to the stuctural change of the junction as can be seen by comparing the two curves. Note that the junction conductance decreases with temperature, showing typical tunneling characteristics. Naturally, the h versus T curve in Fig. 5 demonstrates similar behavior. However, for temperatures below 15 K, the ZBCP behaves quite differently from the background resistance, showing the feature to be intrinsic to high T_c superconductivity. While the theories successfully predict the ZBCP enhancement, none of them foresees the exotic behaviors of the ZBCP we have observed (especially in the presence of a conventional superconductor). More careful study of these behaviors will certainly help in understanding the interaction between high T_c and other conventional superconductors, and to comprehend the pairing characteristics in high T_c superconductors.

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Note added.—We have studied magnetic field dependence (up to 5 T) of the Pb/BSCCO junctions and have observed the low temperature split of the ZBCP to disappear when the applied field is greater than the H_c of Pb. This will be published in a subsequent paper.

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[19] For all the junctions (more than 20) that show ZBCP, the peak either splits or decreases at temperatures below Pb T_c. For ZBCP that splits, R is between 0.2 to 0.8. For ZBCP that decreases in height, R is between 1.1 and 3.