

Zero bias conductance peak (ZBCP) is known to occur in junctions between normal metal and conventional superconductor. This phenomenon is conventionally explained by Andreev reflection of the tunneling electrons at the interface and the ZBCP height is limited to less than double of the normal conductance at higher bias. However, BSCCO is different from other conventional superconductors because of the d-wave characteristics of the order parameter. There are several theories describing the effect of Andreev reflection at the surface of a d-wave superconductor.¹⁻⁴ One common feature of these theories is that the ZBCP can be enhanced dramatically (theoretically a singularity) because of the interference effect between order parameters of opposite signs in a d-wave superconductor. We have prepared BSCCO/Pb planar junctions and performed careful measurements on many of these junctions to demonstrate that the ZBCP in some of these junctions can indeed be as high as predicted by the theories. Planar junction instead of scanning tunneling microscope (STM) is used in this experiment because we want to study the temperature and magnetic field dependence of the ZBCP from the same junction. STM is in general unstable against changes in temperature and external field. It is necessary to withdraw and re-approach for another junction as temperature or field is changed.

For the interaction between Pb and BSCCO, we discovered that the ZBCP could either be depressed in height or be split when the Pb counter electrode became superconducting. Analysis on data of more than 75 junctions allowed us to define a sharpness quantity (R) as the ratio of normalized peak height to the full width at half maximum. According to our data, R has no correlation with the junction resistance. We find that the splitting occurs only in ZBCP with $R < 0.8 \text{ mV}^{-1}$ (figure 1(a)). This splitting

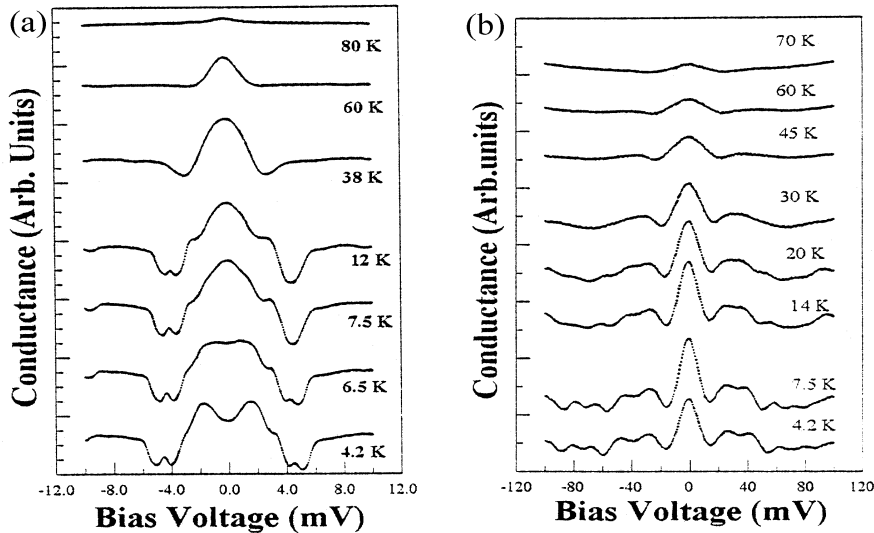


Figure 1. (a) Broader ZBCP will split as Pb becomes superconducting at 7.2K. For this particular junction, junction resistance is 50Ω at 85K and $R=0.4 \text{ mV}^{-1}$. (b) An example of sharper peak with $R=1.9 \text{ mV}^{-1}$. Junction resistance is $6\text{k}\Omega$ at 85K. The peak height is depressed by Pb superconductivity at 7.2K. There is no correlation between junction resistance and height sharpness R .

can be a signature of the opening gap of Pb. We have attempted to fit the data by convoluting the ZBCP above Pb T_c and the BCS density of states (dos) of Pb. The Pb gap needed to fit the data is often significantly larger than the real gap value at that temperature.

Another possible explanation is the induction of an s-wave superconducting layer

on the surface of BSCCO by proximity effect. It is in general believed that the s-wave

surface layer can split the Andreev bound states that appear as the ZBCP in tunneling measurement.⁴

We have also discovered that the ZBCP will be depressed in height instead of splitting if it is sharp with $R > 1.1 \text{ mV}^{-1}$ (figure 1(b)). We do not have junction falling in the range $0.8 \text{ mV}^{-1} < R < 1.1 \text{ mV}^{-1}$. This height depression phenomenon is even more puzzling. As the Pb gap develops, its convolution with the ZBCP will only split the peak but under no circumstance will it depress the peak height. This effect clearly demonstrates the interaction between s-wave (Pb) and d-wave (BSCCO) superconductivity.

We have also studied the magnetic field dependence of the ZBCP. We found that the depression in height (figure 2(a)) or the splitting (figure 2(b)) can be recovered when the applied field equals to the critical field of Pb. This confirms the phenomenon we have described above is indeed a result in the presence of Pb. More intriguingly, the ZBCP does not split as we increase the field up to 5T. In all cases, the ZBCP only decreases in height with increasing field. The variation of the ZBCP height with the external field depends on the same sharpness quantity R as defined before. For those sharp peaks with $R > 1.1 \text{ mV}^{-1}$, the peak height drops fast at small external fields and causes a concave curve in the peak height vs. field plot (figure 2(a)). Many of these junctions exhibit a tendency to a saturated minimum peak height at high fields. Broader peaks with $R < 0.8 \text{ mV}^{-1}$ show quite different behavior. The curve appears to be convex as the one shown in figure 2(b) and 2(c).

Another important experiment we have performed in the last few months is to study how different dopants affect the gap anisotropy in high T_c superconductors. This is considered as an effort of “proximity junction and impurities in high T_c superconductors” in the original proposal. We have successfully doped $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$ single crystal with Pb, Zn, and Ni and prepared a series of samples for our tunneling experiments. All these samples have been characterized with T_c measurement, electron microprobe, and X-ray diffraction. We use an STM to assemble mechanical junctions in this study. We have completed a very careful study and found that the doping of Pb has no effect on the in-plane gap anisotropy despite the decrease of T_c to 65K. Pb is chosen because it is different from the others in that it is substituting the interlayer Bi atoms rather than the in-plane Cu atoms. This result leads to an increasing value of $2\Delta/kT_c$ as the doping level of Pb is increased. There are other experimental results (Hall coefficient), confirming the fact that Pb doping has minimal effect on the carrier density in the ab-planes. Our results probe the role of

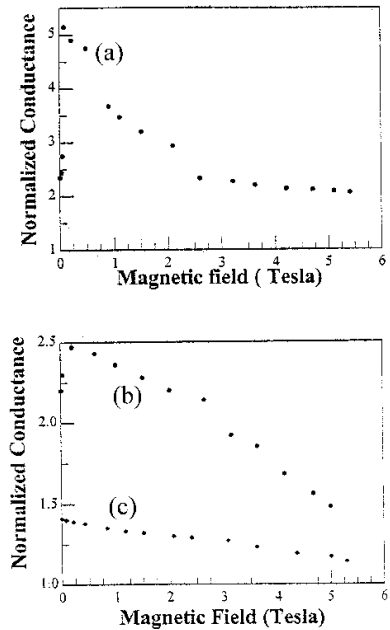


Figure 2. Magnetic field dependence of sharp (top) and broad (bottom) ZBCP. (a) and (b) are BSCCO/Pb junctions, note the change at Pb H_c at 0.08T. (c) is a BSCCO/Ag junction.

interlayer coupling in the determination of T_c . We believe, as indicated by other experiments, the coupling between the CuO_2 planes is essentially of Josephson type. As Bi atoms are begin replaced by that of Pb, the BiO layer will become more metallic like. This will in turn lower the T_c of the CuO_2 planes by proximity effect.

A natural extension of this experiment is to study how the value of $2\Delta/kT_c$ will be affected by the carrier density in the CuO_2 planes, which can be adjusted by the doping level of oxygen. This leads us to begin measurement on underdoped BSCCO, and eventually the pseudogap above T_c . The experiment is possible only after we have upgraded our cryogenics and achieved a thermal stability of 10 mK. The crystal orientation is determined by X-ray diffraction. Tunneling is in the maximum gap direction within the ab-plane. As a control experiment, we have also studied the energy gap of slightly overdoped BSCCO (very close to optimally doped) with a T_c of 85K. We have performed temperature dependence measurements, from 4.2K to 100K.

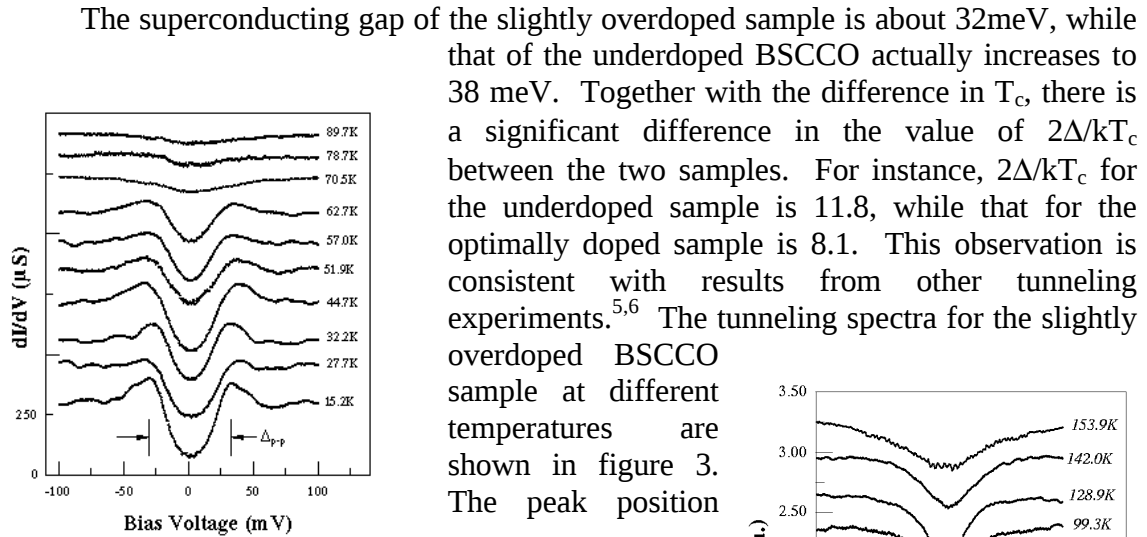


Figure 3. Tunneling spectra for the slightly over doped samples at different temperatures. Note the disappearance of energy at $T > T_c$. The vertical scale is for the lowest curve only.

temperature range is less the $k_B T \sim 5$ meV. No gap like features (i.e. pseudogap) can be seen at $T > T_c$ for slightly overdoped BSCCO. Tunneling spectra for underdoped BSCCO at different temperatures are shown in figure 4. The temperature dependence of the superconducting gap is similar to that of slightly overdoped BSCCO. However, the gap structure persists at temperatures higher than 65K, even when the temperature is significantly higher than T_c .

The superconducting gap of the slightly overdoped sample is about 32meV, while that of the underdoped BSCCO actually increases to 38 meV. Together with the difference in T_c , there is a significant difference in the value of $2\Delta/kT_c$ between the two samples. For instance, $2\Delta/kT_c$ for the underdoped sample is 11.8, while that for the optimally doped sample is 8.1. This observation is consistent with results from other tunneling experiments.^{5,6} The tunneling spectra for the slightly

overdoped BSCCO sample at different temperatures are shown in figure 3. The peak position remains essentially the same at all temperatures, up to 62.7K. This implies the decrease in gap value over this

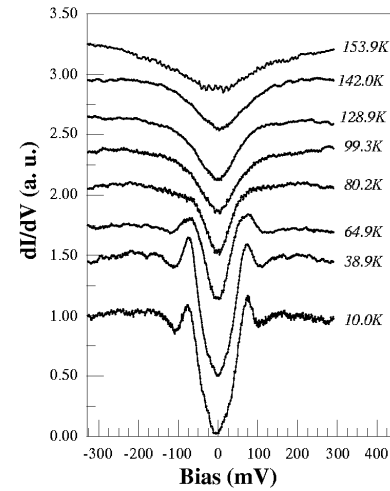


Figure 4. Tunneling spectra of the underdoped samples at different temperatures. Note the gap features at 142.0 K.

The nature of the pseudogap, according to our preliminary observation, is quite different from the superconducting gap. It is clear that the superconducting gap evolves continuously into the pseudogap as the temperature is raised, but the gap behavior changes quite dramatically at $T = T_c$. The peak to peak separation remains constant for the superconducting gap at $T < T_c$, but it increases relatively fast when $T > T_c$. This does not necessary mean the increment in gap value, but some broadening and smearing effects can also cause the separation of peaks to increase. The origin of these smearing effects will be interesting because thermal smearing is too small to account for the results. This theory is further strengthened by the observation that as the temperature is raised above T_c , the depth of the gap actually remains the same despite the further separation of the peaks. We would also like to point

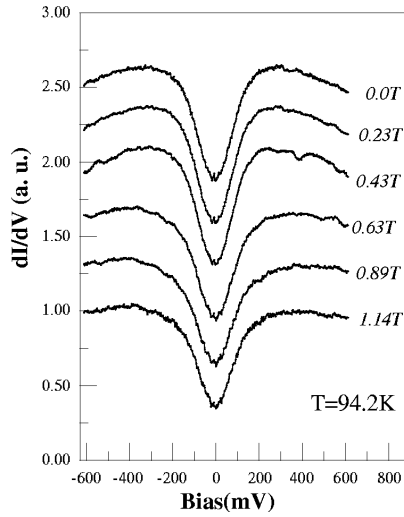


Figure 5. Pseudogap feature at different external fields.

out that while most tunneling curves appear symmetrical, there are often some curves showing the pseudogap peak at the positive bias side being rounded off. An example of this type of curve can be seen in figure 4 (the curve at $T = 83.4$ K). This feature has also appeared in tunneling data from other groups.⁶

One interesting question to ask is how will the magnetic field affect the pseudogap. We have observed the field dependency of an SIS junction kept at 94.2K ($T_c=65$ K) up to a field of 1.14T. We cannot go to a higher field because the deformation in the body of the STM will eventually lead to the destruction of the junction (this leads to our recent effort in the development of better low temperature STMs with higher resolution and stability). The result is shown in figure 5. It can be clearly seen that the gap is becoming shallower as the field is increased. Interestingly, despite changes in the general appearance of the spectra, we believe the pseudogap magnitude is not affected by the field. To demonstrate this point, we have displayed the derivative of the tunneling spectra in figure 6. In this figure, it is clear that the point of inflection in the density of states remains at the same position, independent of the field. From this viewpoint, the energy scale of the process behind the pseudogap phenomenon is significantly larger than the Zeeman splitting energy of 1.14T.

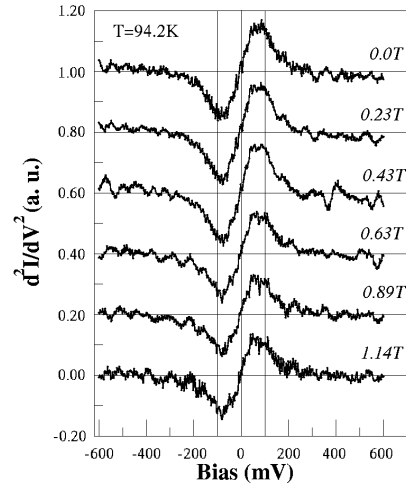


Figure 6. Derivative of the conductance curves in figure 5. This shows there is nearly no change in the peak position as the field is varied.

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