Intrinsic tunneling study of underdoped $Bi_2Sr_{2-x}La_xCuO_{6+\delta}$ superconductors*

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We report on a tunneling study of underdoped submicron $Bi_2Sr_{2-x}La_xCuO_{6+\delta}$ (La-Bi2201) intrinsic Josephson junctions (IJJs), whose self-heating is sufficiently suppressed. The tunneling spectra are measured from 4.2 K up to the pseudogap opening temperature of $T^\star = 260$ K. The gap value found from the spectral peak position is about 35 meV and has a weak temperature dependence both below and above the superconducting transition temperature of $T_c = 29$ K. Since the superconducting gap should have a value of 10–15 meV, our results indicate that the pseudogap (∼35 meV) plays an important role in the underdoped La-Bi2201 intrinsic tunneling spectroscopy down to the lowest temperature of 4.2 K. However, the contribution of the superconducting gap can be separated by normalizing the spectra to the one near and above T_c, which shows that the IJJs can be a useful tool for the study of the electronic properties of the La-Bi2201 cuprate superconductors.

Keywords: $Bi_2Sr_{2-x}La_xCuO_{6+\delta}$ intrinsic Josephson junctions, tunneling spectra, superconducting gap, pseudogap

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1. Introduction

Pseudogap is one of the most fascinating phenomena of high-T_c cuprate superconductors.[1] Since the pseudogap is regarded as a key ingredient in understanding the mechanism of cuprate supercnductivity, it is crucial to know its property and its relation to the superconduting gap.[2]

Presently, there are two scenarios about the origin of the pseudogap: One is the precursor pairing above the superconducting transition temperature T_c, as suggested from the angle-resolved photoemission spectroscopy (ARPES) experiments[3,4] on mostly studied materials of $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi2212) which demonstrate that the property and symmetry of the pseudogap above T_c are similar to those of the superconducting gap below T_c. Scanning tunnelling microscope (STM) experiments[5] also provide an important piece of evidence that the superconducting gap smoothly evolves to the pseudogap as the temperature increases across T_c. Another view of the pseudogap is that it originates from a different source unrelated to, and probably competing with, superconductivity. This is supported by other STM[6,7] and ARPES experiments in which particle–hole symmetry breaking is observed[8] and the measured gap has a strong deviation from the standard d-wave form.[9,10] These results have been interpreted as two coexisting gaps: A d-wave superconducting gap below T_c and a pseudogap whose magnitude is temperature-independent.

Previous experiments indicate that the two-gap behaviour appears more prominent in single-layered Bi-based cuprates $Bi_2Sr_2CuO_{6+\delta}$ (Bi2201). Compared with Bi2212, single-layered Bi2201 is not complicated by the bilayer band splitting problem and for near optimally doped samples, it has a superconducting gap of about 10–15 meV which is much smaller than the pseudogap of about 35–40 meV. Recently, STM experiments on Bi2201[6] show that a previously unidentified narrow and homogeneous superconducting gap superimposed on the frequently observed broad and inhomogeneous pseudogap can be seen by normalizing the tunneling spectra to those at appropriate temperatures near and above T_c.

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Along with the tunneling techniques such as STM and break junctions, intrinsic tunneling spectroscopy utilizing intrinsic Josephson junctions (IJJs)[11] is a distinct and effective method in probing the material's electronic properties. In this work, we successfully fabricated submicron IJJs on an underdoped $Bi_2Sr_{2-x}La_xCuO_{6+\delta}$ (La-Bi2201) crystal and measured the intrinsic tunneling spectra in a wide temperature range from 4.2 K up to the pseudogap opening temperature of $T^\star = 260$ K. We find a broad pseudogap structure at all temperatures that smoothly evolves across T_c. When the spectra below T_c are normalized to that near and above T_c, the superconducting gap of about 11 meV can be clearly seen. These results indicate that the pseudogap plays an important role both above and below T_c in the tunneling experiment and its contribution can be separated from that of the superconducting gap.

2. Experiment

Bi-based IJJs have the crystal's single or double CuO_2 layers as the superconducting electrodes to form superconductor–insulator–superconductor tunnel junctions. They directly reveal the inner property of the materials and therefore have the advantage of avoiding the surface deterioration and uncertainties which may appear in STM and ARPES experiments. However, intrinsic tunneling studies using IJJs have been severely hampered by the self-heating effect due to the materials' poor thermal conductivity and relatively large current density needed to reach the gap voltage, which is evidenced in both Bi2212[12−19] and Bi2201[20−22] IJJs experiments. To solve the problem, many efforts including using intercalated crystals,[12,19] short-pulse measurements,[13,14] and reducing the IJJs sizes[15,17,18] have been made.

In this experiment, we adopted the latter approach and used the same fabrication procedure, which proved successful for Bi2212 IJJs,[17,18] for the intrinsic tunneling study of underdoped La-Bi2201 superconductors. Mesa-structured IJJs down to submicron sizes on an underdoped La-Bi2201 crystal were fabricated. Crystal cleavage and Au-film counter-electrode evaporation were done in vacuum to ensure low contact resistance.[16] The single crystal which had T_c equal to 29 K and transition width lower than 2 K, was grown by the traveling solvent floating-zone method.

Mesas of different sizes from 4 μm to 0.3 μm were fabricated on the same single crystal and their properties, such as the temperature dependence of the resistance R–T across the mesa and the tunneling I–V characteristics (or tunneling conductance or tunneling spectra), all changed systematically as the size decreased. When the size was decreased below 1 μm, the self-heating effect was found to be suppressed significantly, as in the case for the Bi2212 IJJs described in Refs. [17] and [18]. These results allow to measure the tunneling spectra from the submicron mesas with negligible heating while determine the superconducting transitions from larger micron-sized mesas located tens of microns away on the same crystal. This avoids the difficulty caused by the fact that for submicron mesas the Josephson critical currents are too small to display superconducting transitions in the R–T curves.[17,18]

The temperature dependence of the resistance across a 2-μm mesa, which is close to the submicron mesa discussed below, is shown in Fig. 1. A sharp superconducting transition at $T_c = 29$ K can be seen. The oscilloscope trace of the I–V curve, in low bias region of this mesa is shown in the inset. It can be seen that the number of branches are nine, which should equal the number of IJJs in the mesa.

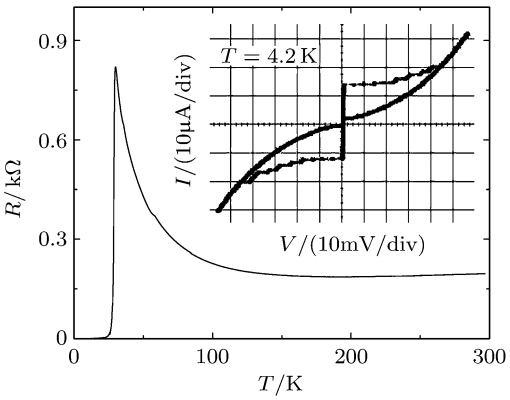


Fig. 1. Resistance versus temperature across a 2-μm mesa fabricated on an underdoped La-Bi2201 crystal showing a T_c of 29 K. Inset displays the oscilloscope image of its I–V curve at 4.2 K, indicating 9 branches and correspondingly 9 IJJs in the mesa.

3. Results and discussion

In Fig. 2, we show the temperature dependence of the tunneling conductance ($\sigma = \mathrm{d}I/\mathrm{d}V$) measured on a mesa with area of 0.3 μm × 0.3 μm. The spectra are normalized to that at $T^\star = 260$ K, above which

the curves become gapless. Compared with the previous work of Yurgens *et al.*,[20] the present results have broader and less sharp spectral peaks after the self-heating is sufficiently suppressed by reducing the mesa size below 1 μm.[17,18] The spectral shapes look similar to those observed in STM[5] and ARPES[4,7,9,10,23] experiments. On the other hand, the present pseudogap opening temperature $T^\star = 260$ K appears comparable to those observed in nuclear magnetic resonance (NMR)[24] and transport[25] experiments. Taking our $T_c = 29$ K and $T_{c,max} = 34$ K,[26,27] we estimate the hole concentration p to be slightly below 0.12 from the general relation $T_c/T_{c,max} = 1 - 82.6(p - 0.16)^2$ (This should be true for the La-Bi2201 material if disorder does not play an important role). At this hole concentration, the NMR and transport measurements give a $T^\star$ of about 250 K.[24,25]

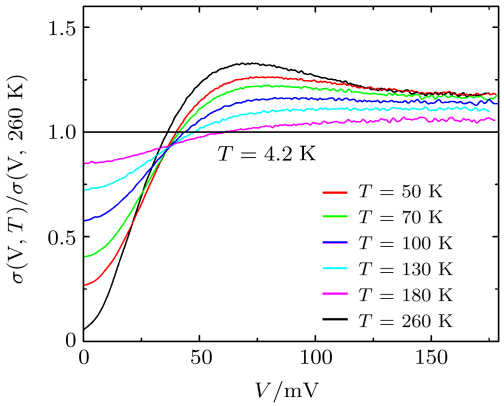


Fig. 2. (colour online) Intrinsic tunneling spectra at several temperatures for a mesa having area of 0.3 μm × 0.3 μm. V corresponding to the voltage per IJJ. The spectra are normalized to the one at the pseudogap opening temperature of $T^\star = 260$ K.

The tunneling spectra in Fig. 2 show a smooth and continuous evolution in the entire temperature range of the experiment, as usually seen in the STM[5] and ARPES[4,7,9,10,23] experiments. The pseudogap above T_c obtained directly from half the conductance peak position is about 35 meV, which is consistent with the magnitude of pseudogap determined from the antinodal spectra of ARPES results.[9] Detailed values versus temperature are shown in Fig. 3, in which we see the gap value does not change much. Since the superconducting gap for the sample is expected to be about 10–15 meV,[3,4,7,9] these data suggest that the pseudogap exists and plays a dominant role in intrinsic tunneling spectra from $T^\star = 260$ K down to the lowest temperature of 4.2 K, which is reported previously in NMR,[24] STM,[6] time-resolved optical spectroscopy[28] experiments.

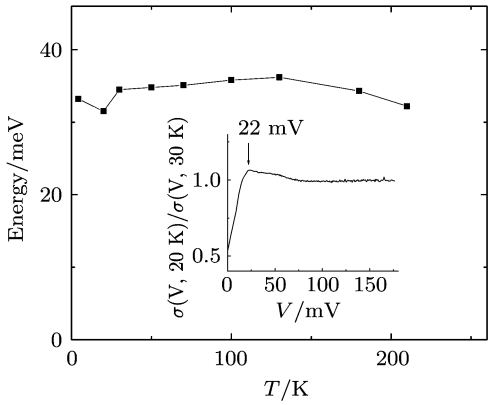


Fig. 3. Half the conductance peak position in meV versus temperature obtained directly from unnormalized raw spectra $\sigma(V, T)$. Inset shows the spectrum at 20 K normalized to that near and above T_c in which the peak position clearly indicates a superconducting gap of $22/2 = 11$ meV.

In order to obtain the information of the superconducting gap embedded in the overall measured tunneling spectra, we note that for the classical Bardeen–Cooper–Schrieffer (BCS) superconductors, McMillan and Rowell have successfully removed the effect from the source other than superconductivity in the tunneling spectra by normalizing them to the one above T_c.[29] Such a normalization technique is also applied recently to the tunneling measurements of cuprate superconductors.[6,30] In the inset of Fig. 3, we show an example of the normalized spectrum $\sigma(V, 20\ \mathrm{K})/\sigma(V, 30\ \mathrm{K})$. The normalized spectrum, in which the pseudogap contribution is removed, demonstrates a clear superconducting gap structure with the gap value of $22/2 = 11$ meV. This result therefore indicates that the contributions from the superconducting gap and pseudogap can be separated in the intrinsic tunneling spectroscopy, which can thus be an effective technique for the studies of the electronic properties of Bi2201 cuprate superconductors in which the pseudogap effect is still influential in the temperature range below T_c.

4. Conclusion

Mesa-structured submicron intrinsic Josephson junctions of underdoped La-Bi2201 with T_c of 29 K, whose self-heating was effectively reduced, were successfully fabricated for the first time and used to study the material's electronic properties. Tunneling spectra from the pseudogap opening temperature $T^\star$ of 260 K down to 4.2 K were measured. Our results showed that the spectral features are pseudogap dominant, with a gap value of around 35 meV determined from the spectral peak position nearly unchanged in

the whole temperature range of the experiment. An important result was that when the tunneling spectra below T_c were normalized to that near and above T_c, they exhibited clear features of the superconducting gap with a size of 11 meV. These data are in good agreements with previous observations, which demonstrate that intrinsic tunneling spectroscopy is a useful technique for the studies of Bi2201 cuprate superconductors whose pseudogap behaviour remains prominent at temperatures below the superconducting transition temperature T_c.

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