Heating-free Interlayer Tunneling Spectroscopy in $Bi_2Sr_2CaCu_2O_{8+x}$ Intrinsic Junctions

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Abstract. The interlayer tunneling spectroscopy (ITS) in $Bi_2Sr_2CaCu_2O_{8+x}$ (Bi-2212) intrinsic junctions (IJs) reveals the quasiparticle excitation spectrum in the material. In this study, using a proportional-integral-derivative (PID) temperature control scheme incorporated with the *in-situ* temperature measurements of stacks of IJs under study, we eliminate the artifact in the ITS, which is often caused by the self-heating in the high-bias region. Thus-measured spectral weight distribution with the clear peak-dip-hump structure exhibits subtle differences from that obtained without the PID control, which may provide in the long run a crucial guidance to understanding the mechanism of high-T_c superconductivity.

Keywords: Interlayer tunneling spectroscopy, Pseudogap, Density of states, Self-heating effect, PID control scheme
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Since the discovery of the tunneling effect in intrinsic junctions (IJs) in a $Bi_2Sr_2CaCu_2O_{8+x}$ (Bi-2212) single crystal [1] the interlayer tunneling spectroscopy (ITS) using a mesa structure fabricated on the surface of a Bi-2212 single crystal [2] has provided a useful means to investigate the density of states (DOS) of quasiparticle excitation. Contrary to the photoemission and scanning tunneling spectroscopy [3] exercised on the surface of single crystals the ITS probes the bulk tunneling properties of IJs embedded inside single crystals, with any surface-sensitive artifact eliminated.

An interesting feature revealed in the DOS of high-T_c superconductors is the existence of the pseudogap (PG), represented by the depletion of the DOS near the Fermi energy, at temperatures even above the superconducting transition temperature, T_c. It has been believed that the PG may offer the key to an understanding of the mechanism of high-T_c superconductivity. To confirm the point the relation between the superconducting gap (SG) and the PG should be clarified. In measurements of the ITS, for instance, the SG and PG were observed simultaneously at a temperature near T_c [2], which led to the suspicion that two gaps may have different origins. The serious problem in the ITS, however, is the local heating in the high bias region [4]. Although the reduction of the junction area and the number of the junctions, and the pulsed-current biasing reduce the heating partially one cannot get rid of the heating problem entirely.

In this study we performed constant-temperature ITS using the combination of *in-situ* monitoring the temperature of IJs under study and employing the computerized proportional-integral-derivative (PID) temperature control [5]. Although the overall feature of the measurements turns out to be similar to the previous ITS results [2], our study reveals delicate differences in the temperature and magnetic-field dependencies of the peak-dip-hump spectral distribution. We believe our results without any artifact due to self-heating will provide a crucial guidance to clarifying the mechanism of high-T_c superconductivity.

Bi-2212 single crystals were grown by the solid-state-reaction method. One gets mostly a slightly overdoped single crystal phases using this method. But, sometimes, one also obtains the locally formed underdoped phases. In this study we used both overdoped and underdoped single crystals, among which we report only the results from an underdoped sample. Instead of a mesa structure, we fabricated a $3\times3\ \mu m^2$ stack sandwiched between two Au-film electrodes, where the double-side-cleaving of Bi-2212 crystals, micropatterning, and ion-beam etching were employed [6]. The temperature of the sample stack was monitored by placing another stack of IJs (the thermometer stack) in proximity to the sample stack, where the two stacks were in strong thermal coupling through the common bottom Au electrode. The inset of Fig. 1(a) shows the sample configuration; the left (right) part represents the sample (thermometer) stack.

The sample stack contained N=15 IJs, as determined by the number of quasiparticle branches at 4.2 K (not shown). The transition temperature T_c=75.2 K indicates that the sample was a well-underdoped one. The constant-temperature ITS was performed in the following way. We first set up the sample temperature at a certain value using the heater coil wound around the substrate holder, while keeping the bath temperature at 4.2 K. The heat generated by the bias current in the sample stack was directly transferred to the thermometer stack through the bottom Au electrode. The resulting temperature increase of the thermometer stack was monitored by comparing its resistance change in a low-enough bias

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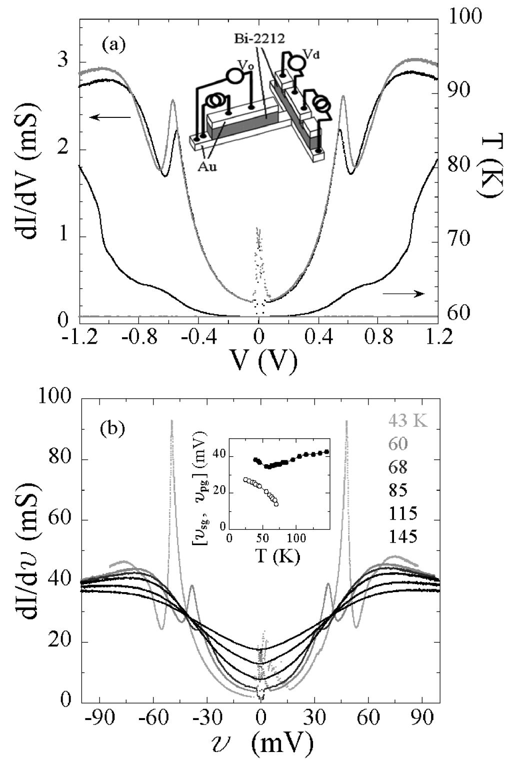

FIGURE 1. (a) dI/dV curves and the sample-stack temperature as a function of the bias voltage, for the setup temperature of 59.9 K, with (gray) and without (black) the PID temperature control. The inset of (a): the sample configuration. (b) The temperature dependence of dI/dv (v; bias across a single junction) curves for a single junction from 43 K to 145 K with the PID control. The inset of (b): the temperature dependence of the SG (open circles) and the PG (closed circles), obtained from one half of the maximum positions of the peak and the hump.

current with the pre-determined resistive transition data of the thermometer stack. The initial sample temperature was then recovered by reducing the heater current with the computerized PID control. Measurements were done along the highest-bias quasiparticle curve, *i.e.*, the last branch.

Fig. 1(a) illustrates the dI/dV and the temperature variation of the sample stack as a function of the bias voltage for a setup temperature of 59.9 K, with (grey curves) and without (black curves) the PID control. The bias current, 5 μA, for the thermometer stack was low enough that it did not cause any self-heating by itself. The distinct peak-dip-hump structure is visible in both cases. The positions of the peak and the hump correspond approximately to the edge of the SG and the PG, respectively. One notices that, without the PID control, the sample stack starts being heated from the bias slightly above 0.2 V, reaching 81 K for the bias of 1.2 V. It implies that the ITS without the PID control can be highly affected by the self-heating, as seen by the reduced spectral weight together with the reduced peak and hump positions in Fig. 1(a).

Fig. 1(b) displays the temperature dependence of dI/dv versus v curves (v=V/N; the bias voltage across a single junction), with the PID temperature control. At temperatures sufficiently below T_c one has a dominant superconducting peak and a clear dip. Closer to T_c, the superconducting peak reduces rapidly and disappears completely above T_c, but the hump retains even above 250 K. The size of the SG also shrinks rapidly as the temperature approaches T_c from below. By contrast, the size of the PG shows a very slow temperature dependence, *with its minimum around* T_c . We observe the coexistence of the SG and the PG near T_c [inset of Fig. 1(b)], which strongly suggests that the two gaps are of different origins. One also notices that the curves at temperatures above T_c converge to a single point inside the PG, the implication of which should be further traced.

The dependence of the spectral distribution on the perpendicular magnetic field up to 6 T was also measured in this study (data not shown). In previous measurements [2] magnetic fields tend to reduce the superconducting peak, with almost no changes in the dip and the hump. In our study, however, the reduced spectral weight in the superconducting peak is transferred to the dip and to the superconducting gap, which poses a major difference from the previous measurements. The spectral weight was found to be conserved in any magnetic fields.

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