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Pseudogap behavior in interlayer tunneling spectroscopy in $Bi_2Sr_2CaCu_2O_{8+x}$

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Abstract

A pseudogap in the normal-state quasiparticle density of states of high-T_c superconductors has been revealed in many different kinds of experiments. The existence of the pseudogap and the superconducting gap, and the correlation between them has attracted considerable attention because they are believed to be a key to understanding the mechanism of the high-T_c superconductivity. The interlayer tunneling spectroscopy, excluding the surface-dependent effect, is one of the most accurate means to examine the electron spectral characteristics both in the superconducting and the normal states. In this study, a new constant-temperature intrinsic tunneling spectroscopic technique, excluding the overheating effect using the in-situ temperature monitoring combined with the digital proportional-integral-derivative control, is introduced. The implication on the high-T_c superconductivity of the detailed temperature dependencies of the observed spectral weight in $Bi_2Sr_2CaCu_2O_{8+x}$ high-T_c material for overdoped and underdoped levels is discussed.

Keywords : Self-heating effect, Interlayer tunneling spectroscopy, Pseudogap, Antiferromagnetic correlation.

I. Introduction

The cuprate high-T_c superconductors show the pseudogap (PG) behavior, which is represented as the depletion of the quasiparticle density of states (DOS) below a certain onset temperature T^* in the normal state. One of the central issues of the recent research on the high-T_c superconductivity is to find whether the PG state is the precursor of the superconducting state or the antiferromagnetic insulating state [1]. The angle-resolved photoemission spectroscopy (ARPES) and the scanning tunneling spectroscopy (STS), both being the surface probes, provide the quasiparticle DOS as a function of the energy with momentum and spatial resolutions, respectively. Thus, the combination of ARPES and the STS gives detailed information on the momentum and spatial dependencies of the size of the PG as well as its onset temperature T^* [2].

On the other hand, the interlayer tunneling spectroscopy (ITS) using intrinsic Josephson junctions formed in highly anisotropic high-T_c superconductors such as $Bi_2Sr_2CaCu_2O_{8+x}$ (Bi-2212) single crystals shows the bulk information of the quasiparticle DOS. By contrast, usual tunneling measurements using break junctions [3] employs the planar tunneling. One should note that the c-axis electronic tunneling dynamics including the ITS in layered high-T_c superconductors is dominated by the quasiparticle excitation around the (π, 0) or the M point in the first Brillouin zone [4]. Thus, the ITS may show the response that is more sensitive to opening of the PG, because the PG is supposed to open up starting at the M point [1].

The crucial problem in ITS, however, is the local heating in a large current bias. Although reducing the

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junction size and the number of the junctions, or using pulsed bias current injection have been adopted to reduce the local heating, one cannot totally avoid the self-heating problem [5].

In this paper, we report the PG behavior in the normal and superconducting states and the interplay between the superconducting gap (SG) and the PG. To this purpose, we used heating-free ITS on a stack of overdoped and underdoped Bi-2212 IJJs, for varying temperatures. The spectral weight in the ITS can be easily affected by the self-heating arising from the bias current. Thus, the heating-free ITS as used in this study reveals the genuine electronic spectral distribution. In order to eliminate of the self-heating effect we adopted the in-situ temperature monitoring using another stack of IJJs combined with the proportional-integral-derivative (PID) temperature control. The PG observed in the normal state above the superconducting transition temperature T_c persists even in the superconducting state in the form of the peak-dip-hump (PDH) structure until the SG becomes comparable to the PG. This implies that the SG and PG are of different origins. The observed PG in the ITS will be considered as the antiferromagnetic correlation corresponding to the high-energy PG observed in the photoemission spectroscopy [6].

II. Experiments

As-grown slightly overdoped and underdoped Bi-2212 single crystals were prepared by the conventional solid-state-reaction method. Instead of a usual mesa structure, we fabricated a 3×3 μm^2 stacks sandwiched between two Au-film electrodes, where the double-side-cleaving of Bi-2212 crystals, micropatterning, and ion-beam etching were employed. Details of the sample fabrication are described elsewhere [7].

The temperature of the sample stack [refer to the inset of Fig. 1(b)] was monitored in-situ by placing another stack of IJJs (the thermometer stack) in proximity to the sample stack, where the two stacks were in strong thermal coupling through the common bottom Au electrode [8]. The inset of Fig. 1(b) shows the sample configuration; the left (right) part represents the sample (thermometer) stack. 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 then 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 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 in the current-voltage (*I-V*) characteristics. The *dI/dV* curves were obtained using a lock-in amplifier operating at frequency of 33.3 Hz.

III. Results and Discussion

The superconducting transition temperatures, T_c=75.2K and 88.2 K, obtained by the *c*-axis tunneling measurements indicate that the samples were underdoped and overdoped with the doping level of p=0.11 and 0.19, respectively, where we used the empirical relation [9], $T_c=95[1-82.6\,(p-0.16)^2]$ to determine p. The underdoped and overdoped sample stacks contained N=15 and 19 intrinsic Josephson junctions, respectively, as determined by the number of quasiparticle branches in the zero-field *I-V* curves at 4.2 K (not shown). The interlayer tunneling spectra, *dI/dv*, as a function of the bias voltage and the temperature of overdoped sample are displayed in Fig. 1(a), where the voltage is normalized by the number of the junctions as $v=V/N$. These spectra carry the information of the DOS of the excited quasiparticle states. The zero-bias conductance is most sensitive to opening of the gap in the spectra at the Fermi energy. Thus, the minimum of the zero-bias R vs T curve in the normal state has been used to obtain the PG onset temperature T^* [10]. As to be seen below, however, this scheme turns out not to be the correct method to obtain T^*.

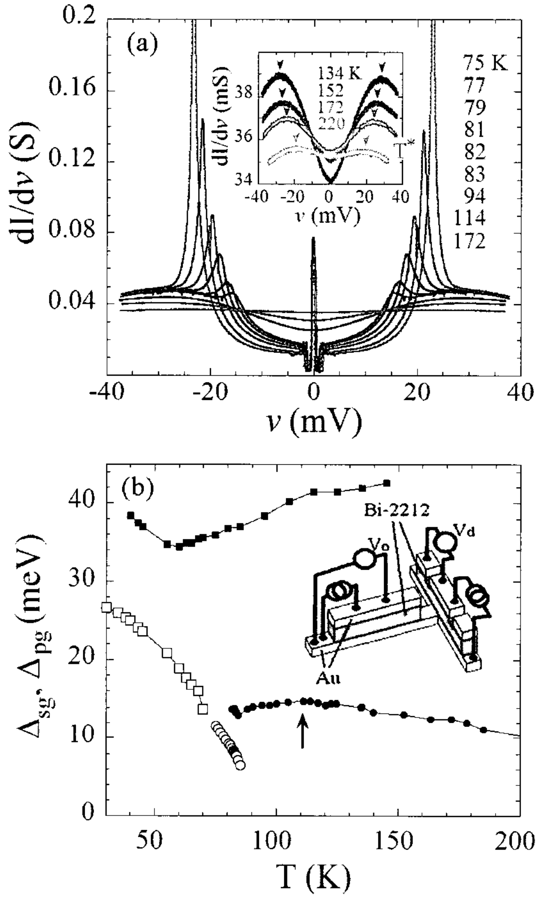

Fig. 1. (a) The interlayer tunneling spectra for the overdoped sample, *dI/dv*, as a function of bias voltage at various temperatures. The voltage axis was normalized by the number of junction, N=19. The inset of (a) shows the hump structure in the normal state. (b) The temperature dependence of the SG (open squares and circles) and the PG (filled squares and circles), which were obtained from one quarter of the voltage values between the peaks and between the humps, respectively, of the underdoped and the overdoped samples. The square and circular symbols represent the underdoped and overdoped cases, respectively. The inset of (b): the measurement configuration.

The minimum-resistance temperature of the overdoped sample, determined using the R *vs* T curve in the zero-bias limit (not shown), turned out to be T_{min}~175 K. With increasing temperature the zero-bias conductance in the spectra has a maximum near 170 K as shown in the inset of Fig. 1(a), which coincides with the temperature of the minimum tunneling resistance. The hump structure represents the PG state in the usual ITS below T^* [8]. Contraty to the usual heating-affected ITS, however, the heating-free ITS of the inset of Fig. 1(a) shows that the hump structure persists even above T_{min}, where the PG energies corresponding to the maximum *dI/dv* values in the hump structure are denoted by the arrows. The hump structure disappears at temperatures only around T^*~260 K (not shown).

ARPES, which measures the electronic structure at a particular k point in the first Brillouin zone, has shown that the destruction of the Fermi surface due to opening of the low-energy PG, with decreasing temperatures, starts from the M point in the normal state. It also reveals that the low-energy PG with the *d*-wave symmetry, as represented by the shifted middle point in the leading edge in the spectral distribution, is related with the SG with the *d*-wave symmetry [11]. This low-energy PG in the ARPES may correspond to the depletion of the DOS at the Fermi energy in the ITS, where T^*_{ARPES}~110 K at the Fermi surface closest to the M point in optimally doped Bi-2212.

On the other hand, the angle-integrated photoemission spectroscopy (AIPES), which shows the total DOS with integrated momentum dependence, has shown that the depletion of the DOS near the Fermi energy can also originate from the antiferromagnetic correlations (high-energy PG), where the depletion behavior persists up to T^*_{AIPES}~300 K in optimally doped Bi-2212, which is similar to T^* observed in our ITS [12].

In the main panel of Fig. 1(a) the spectral weight of the superconducting coherence peak reduces with increasing temperatures and disappears above T_c. The hump structure in the normal state evolves into the PDH structure with the coherence peak in the superconducting state around 80 K. The coexistence of the SG and the PG in the small temperature range with the PDH structure has been regarded as an evidence for the difference in the origins of two gaps in the ITS [13]. From T=79 K, the sharp coherence peak and the remnant of hump without the dip appear. In the underdoped sample the clear PDH structure was still observed at a temperature as low as 25 K because SG energy is sufficiently smaller than PG energy at the temperature (not shown). The conductance peaks near the zero bias in the superconducting state in the figure are caused by the Josephson coupling.

In the case of STS, which reveals the local DOS as a function of the spatial location and energy, the superconducting peak smoothly connects to the hump at T_c, indicating that the PG in STS may be the precursor of opening of the SG [14]. In addition, in contrast to the ITS, the dip structure in the STS were observed at all temperatures in the superconducting state. This difference in the PG spectra between the ITS and STS may originate from the difference in tunneling direction of electrons for the two cases. For the ITS the tunneling is through total CuO_2 layers along the c axis, while in STS the tunneling direction of electrons from a normal-metal tip forms a cone shape around the c-axis direction.

Fig. 1(b) shows the temperature dependence of the SG energy (Δ_{sg}, open squares and open circles) and PG energy (Δ_{pg}, filled squares and filled circles), where squares and circles in the figure represent the underdoped and overdoped case, respectively. In both cases, the SG energy reduces with increasing temperatures and disappears above T_c as Fig. 1(a). In the overdoped case, the PG energy developed from ~ 260 K reaches a maximum value of 15 meV at ~110 K [denoted by arrow in Fig. 1(b)]. The magnitude of the PG keeps decreasing while crossing T_c. Decreasing the temperature even further, the PG energy rises again with the PDH structure. Finally it is dominated by the developing SG spectrum as in Fig. 1(a).

In the underdoped sample, the similar behavior was observed except for the energy scale. This implies that in the underdoped regime also the PG is not related with the SG. Below T=40 K, we were not able to trace the PG of underdoped sample because the heating-free PID control was not available as the heater current was reduced completely to balance the self-heating due to the bias current. The SG as well as PG energy in underdoped case is larger than those of overdoped case, but T_c shows opposite behavior. Although it is beyond the scope of this paper the overall temperature dependence of the pseudogap can be qualitatively explained by taking the quasiparticle lifetime broadening effect into account.

IV. Conclusion

Contrary to the dome-shaped T_c, the SG and the PG in the ITS increase with decreasing hole doping [9]. This behavior has also been observed in ARPES and scanning tunneling spectroscopy [11]. The PG in the ITS, however, seems to be different from the low-energy PG that is known as the precursor of the SG in ARPES and STS. High-energy PG related with antiferromagnetic correlation has been observed in the AIPES, nuclear-magnetic resonance and heat-capacity measurement, etc. [15]. ARPES revealed flat band structure at the vicinity of the M point. The flat band provides large DOS, N (E_F), related to the van Hove singularity. Furthermore, the Fermi nesting structure combined with the flat band near the M point can generate a short-range antiferromagnetic spin correlation, which can be the origin of the high-energy PG observed in our genuine ITS without heating effect as well as other experiments [16].

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