Pseudogap Behavior Revealed in Interlayer Tunneling in Overdoped Bi$_2$Sr$_2$CaCu$_2$O$_{8+x}$

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We report heating-compensated interlayer tunneling spectroscopy (ITS) performed on stacks of overdoped Bi$_2$Sr$_2$CaCu$_2$O$_{8+x}$ intrinsic junctions, where most of bias-induced heating in the ITS was eliminated. The onset temperature of the pseudogap (PG), revealed in the hump structure of the electronic excitation spectra, reached nearly room temperature for our overdoped intrinsic junctions, which represented the genuine PG onset. At a temperature below but close to $T_c$, both the superconducting coherence peak and the pseudogap hump coexisted, implying that the two gaps are of separate origins. The hump voltage increased below $T_c$, following the superconducting gap voltage, which led to a conclusion that the hump structure below $T_c$ in our ITS arose from the combined contribution of the quasiparticle spectral weights of two different characters; one of the superconducting state and another of the PG state near the antinodal region.

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I. INTRODUCTION

Conventional superconductors in their superconducting state are characterized by opening of the superconducting gap (SG) in the electronic density of states (DOS). Superconductivity appears when electrons bind into Cooper pairs and condense with long-range order below the superconducting transition temperature $T_c$. Cuprate superconductors, however, as one of the most intriguing characteristics in their normal state, show the unusual emergence of the pseudogap (PG) in the electronic excitation spectrum even above $T_c$, which persists up to a temperature $T^*$, the PG onset temperature. It has been widely accepted that understanding the PG origin and the relation between the PG and the SG may lead to a key to finding the basic mechanism of high-temperature superconductivity, which is not fully resolved up to the present.

There are two schools of thought as to understanding the PG in the cuprate physics: one-gap and two-gap ones. One-gap school regards the PG as the precursor of the SG, where thermal fluctuations destroy long-range order while maintaining gap-like features in the excitation spectra in a certain high-temperature range ($T \geq T_c$) of the normal state. Thus, the PG in question is believed to bring about the partial depletion of the DOS at the normal-state Fermi surface, resulting in the Fermi arcs. The other school interprets the PG, especially in the underdoped regime, in terms of two gaps: a small SG revealed in the nodal regions and a large gap of different origin in the antinodal regions. In the two-gap model, the Fermi arcs are believed to emerge due to long-range order that, however, is not associated with the superconducting order. Above $T_c$, the SG may vanish, leaving the other long-range order connected to the Fermi arcs, Fermi surface nestings or Fermi surface pockets. Recent Raman and angle-resolved-photoemission-spectroscopy (ARPES) measurements show the consequences of opening of two gaps in underdoped single-layer HgBa$_2$CuO$_{4+δ}$ superconductors and bilayer Bi$_2$Sr$_2$CaCu$_2$O$_{8+δ}$ superconductors, respectively.

The surface tunneling studies on the PG behavior suggest that the PG can evolve into the SG in the norm of one gap. In interlayer tunneling measurements on densely stacked intrinsic Josephson junctions (IJJs) formed in the layered cuprates, however, it has been proposed that the SG vanishes at $T_c$ and the PG may exist both below and above $T_c$. This experimental observation from IJJs is claimed to provide the norm of two gaps, where the SG and the PG are considered to be of different origins.

The interlayer tunneling reveals the intrinsic bulk tunneling properties between CuO$_2$ superconducting layers, which can be an advantage of this scheme compared to other surface-sensitive spectroscopic methods. Recently, however, it has been suggested that the experimental observations of the IJJs could be affected by the self-heating generated in a high-bias region, which was caused by the poor thermal conductivity of Bi$_2$Sr$_2$CaCu$_2$O$_8$ (Bi-2212) and other materials involved in the tunneling measurements.

The zero-bias tunneling process in the $c$ axis is very sensitive to the electronic DOS at the normal-state Fermi surface. In particular, the zero-bias tunneling resistance $R_c$ in the Bi-2212 is weighted by the tunneling of quasi-particles in the antinodal region of the Fermi surface. Thus, $R_c$ is expected to increase rapidly as the PG opens and the corresponding DOS is partially depleted at the Fermi surface. In this point of view, the onset temperature of the PG opening can be defined as the characteristic temperature $T^*_G$, at which $R_c$ deviates from the $T$-linear temperature dependence in $R_c$ vs $T$ curves.

Recently, Kawakami et al. based on the temperature dependence of $R_c$, have shown that both the
electron- and the hole-doped cuprates have common spin-singlet correlations in forming the PG, both of which thus close in high magnetic fields. The closing fields of the PG and the SG, however, show much different temperature dependencies from each other, which indicates that the two gaps are of separate origins. Difference in origins of the two gaps is in line with the coexistence of the superconducting state and the PG state observed by the interlayer tunneling spectroscopy (ITS) in hole-doped Bi-2212 IJJs, which is represented by the sharp peak and the broad hump structure below $T_c$. Relating the hump structure in the high-energy windows of the ITS to the formation of the PG was controversial up to the present, however, again because of possible self-heating in a high-bias region, although there have been many efforts to reduce the self-heating effect in the ITS, by adopting schemes such as reducing the junction area, reducing the number of stacked junctions, and adopting pulsed biasing.

In this study, for an overdoped Bi-2212 sample fabricated on an as-grown single crystal, we discriminate the PG onset temperature, defined by the appearance of the hump structure ($T_{hump}^*$) in the ITS while lowering temperature, from that obtained by the $R_c$ vs $T$ behavior ($T_{dev}^*$). To obtain the interlayer tunneling characteristics that are essentially free from self-heating artifact, we adopted the recently developed technique of heating-compensated ITS, where a large portion of the bias-induced self-heating was removed. In contrast to $T_{dev}^*$ ~ 190 K, the hump structure persisted up to temperatures much higher than commonly perceived. We then numerically illustrate that, with significant self-heating, $T_{hump}^*$ would reduce down to $T_{dev}^*$, which confirms the previous reports by others in the heating-dominated case. We thus suggest that the $T_{hump}^*$ represents the genuine onset of the PG. As in earlier works, with decreasing temperature below $T_c$, the hump voltages in our heating-free ITS increases, along with the increase of the superconducting gap size. It turns out that this unusual temperature variation of the hump voltage below $T_c$ results from the combined tunneling contribution of the quasiparticles associated with both the SG and the PG in the electronic state. Since the antinodal tunneling is weighted, the behavior of this PG obtained in the ITS of our overdoped Bi-2212 should be related to the electronic structure of the antinodal region in the first brillouin zone of the CuO$_2$ layers.

II. EXPERIMENT

Fig. 1(a) illustrates the schematic configuration of the sample. We fabricated an overdoped sample stack of Bi-2212 IJJs with the lateral size of 3×3 µm$^2$, sandwiched between two thin-film (top; 400 nm thick, bottom; 100 nm thick) Au electrodes. This structure, where the pedestal stack (large stack of IJJs outside of but coupled to the stack of IJJs of interest) in the usual mesa structure was eliminated, gave more uniform tunneling current distribution. The number of junctions contained in the stack, $N$, was 19. The hole concentration, $p=0.19$, was determined using the $c$-axis superconducting transition temperature $T_c=88.3$ K by the empirical relation of $T_c=95[1-82.6(p-0.16)^2]$ and the resistance ratio of $R_c$ between $T_c$ and $T=300$ K. A thermometer stack of IJJs, with the lateral dimension of 3×2 µm$^2$, was arranged less than 1 µm from the sample stack through a 100-nm-thick bottom Au electrode.

For the ITS the whole probe with a sample inside the vacuum can was cooled down to the liquid-helium bath temperature. Prior to the ITS measurements in a finite bias the sample was set at a higher working temperature by using a resistive heater coil wound on the substrate-holding copper block. The temperature variation of the sample stack during ITS measurements was
monitored in-situ by the change in the tunneling resistance of the thermometer stack taken in a constant bias current of $I_{th} = 120$ $\mu$A. To maintain the thermometer stack at a given set temperature during ITS measurements we compensated the bias-induced heating by lowering the current level to the heater coil wound on the copper substrate holder block. We repeated this heating-compensation scheme by using a computer-aided proportional-integral-derivative control of the thermometer stack incorporated with adjusting the heating-current level. By adopting this technique we were able to maintain the temperature of the thermometer stack within about 0.2 K in the whole bias range of the ITS. However, there could still be a temperature difference, $\Delta T$, between the sample stack and the thermometer stack due to the finite thermal conductance of the bottom Au electrode, through which the heat generated in the sample stack flowed to the thermometer stack, and due to the thermal leakage of heating to the surroundings.

We numerically estimated the temperature difference $\Delta T$ between the sample stack and the thermometer stack during ITS measurements. The COMSOL Multiphysics Program was used to calculate the temperature profile in the sample. In the estimation, we referred to the geometry and arrangement of the sample used in the measurement [Fig. 1(a)]. Namely, the common bottom Au electrode was attached to the sapphire substrate (0.4 mm thick and 5x5 mm$^2$ in the lateral size) using negative photoresist, which in turn was fixed on the heater-coil-wound copper block using GE varnish (assumed to be about 1 $\mu$m thick). The top Au electrodes in the sample and thermometer stacks were extended by up to 200 $\mu$m by two (300-nm-thick and 3-$\mu$m-wide) Au stripes (per each stack) deposited on the substrate that was precoated with an about 1-$\mu$m-thick negative photoresist layer. The end of each Au extension was then connected to a gauge-$\times$40 copper wire that was thermally anchored at the base copper-block temperature. The bottom common electrodes were also extended in the same manner by three Au stripes; two in the sample-stack side and one in the thermometer-stack side.

The inset of Fig. 1(b) shows the temperature dependence of the thermal conductivities of Au and Bi-2212 along the $c$ axis, which played a crucial role in the heat flow through the sample. The in-plane thermal conductivity of Bi-2212 was assumed to be ten times higher than the $c$-axis thermal conductivity. The thermal conductivities for sapphire, negative photoresist, and GE varnish were assumed to be insensitive to the temperature variation and set to be 40, 0.2, and 0.2 W/m-K, respectively. The heat generated at the sample stack was dissipated through both the top and bottom thermal channels, while the temperature of the thermometer stack was maintained at a fixed temperature during the heating-compensated ITS. Fig. 1(b) shows the discrepancy of temperature between the the sample stack and the thermometer stack as a function of the copper-block base temperature, corresponding to the heating power at the sample stack of 0.27, 0.70, and 1.35 mW. One notices that $\Delta T$ is governed by the temperature dependence of the thermal conductivity of the bottom Au electrode: $\Delta T$ increases in the temperature range of 20-80 K because of reduction of the Au thermal conductivity until it saturates at temperatures above 100 K. The heating power of 0.70 mW corresponds to the bias voltage that is high enough to observe the hump structure in the differential conductance in the inset of Fig. 2 ($V=525$ mV) and in Figs. 4 and 5(a) ($v=V/19=27.6$ mV). Then the estimation indicates that the heating-compensated thermometry adopted in this study allowed accuracy of the thermometry within 3.5 K for the heating power of 0.70 mW at any base temperatures. This is in remarkable contrast to the discrepancy of several tens of degrees, usually encountered without the heating compensation incorporated with the in-situ thermometry. Thus, the hump structure obtained from this heating-compensated ITS can be regarded to be almost heating-free.

III. RESULTS AND DISCUSSION

Fig. 2 shows the $R_c$ vs $T$ curve in the normal state of the sample, which was obtained by the inverse of zero-bias tunneling conductance $dI/dV|_{V=0}$ of the electronic excitation spectra in the inset of Fig. 2. This curve suggests the PG onset temperature to be $T_{dev} \sim 190$ K. The normal state of our overdoped sample in the inset of Fig. 2 shows a distinct zero-bias depletion of electronic excitation spectra with the PG size for each $T$
denoted by a pair of vertical segments. The onset temperature of the PG opening can also be determined by the appearance of the hump structure \((T^*_{\text{hump}})\) in the tunneling \(dI/dV\) spectra, which can be obtained either by the scanning tunneling spectroscopy \(\text{STS}\) or by the ITS. In contrast to a naive expectation and the existing observations,\(\text{[12, 15]}\) however, the depletion of the DOS near zero bias is evident even far above \(T^*_{\text{dev}}\) in \(R_c\) vs \(T\) curves. The spectral depletion around zero bias persists up to the maximum temperature examined, i.e., \(241\) K. We observed similar behavior in another overdoped sample. But, the deviation from the \(T\)-linear behavior in \(R_c\) vs \(T\) is supposed to become evident only when the DOS is sufficiently depleted at the characteristic temperature \(T^*_{\text{dev}}\) further below the onset temperature of the hump structure opening. This indicates that \(T^*_{\text{hump}}\) better represents the onset of PG opening than \(T^*_{\text{dev}}\). On the other hand, outside the gapped region (i.e., \(|V|>450\) mV) in the inset of Fig. 2, \(R_c\) monotonically increases with increasing temperature over the whole temperature range examined, which represents a metallic behavior. This PG onset temperature defined by \(T^*_{\text{hump}}\) at least in the overdoped regime is in clear contrast to that determined by the angle-resolved photoemission spectroscopy (ARPES) and by the STS,\(\text{[12]}\) where \(T^*\), representing the PG in the one-gap picture, disappears or merges into the bell-shaped \(T_c\) curve near the optimal doping point in the temperature-vs-doping-level phase diagram.

On the other hand, \(T^*_{\text{hump}}\) becomes comparable to \(T^*_{\text{dev}}\) in the presence of significant self-heating. Based on the heating-compensated \(dI/dV\) curves in the normal state of the inset of Fig. 2, we simulated the \(dI/dV\) curves of a stack under the influence of the serious self-heating. Fig. 3(a) displays \(R_c\)-vs-\(T\) curves obtained from the \(dI/dV(V)\) spectra given in the inset of Fig. 2 for varying biases from 0 to 360 mV (or from 0 to 18.9 mV per junction). With increasing the bias voltage, the up-turn deviation from the \(T\)-linear \(R_c\)-vs-\(T\) behavior gradually disappears. The sample temperature increases by a bias power defined at a fixed voltage with a given heating ratio \([\text{K/mW}]\). The heating ratio in a stack of IJJs is determined by the junction area and the number of junctions. The new value of \(dI/dV\) at an increased temperature due to self-heating for a finite bias voltage was traced through the \(R_c\)-vs-\(T\) curves of the corresponding voltage in Fig. 3(a). Since current-voltage \((I-V)\) characteristics had almost the same curvatures in the temperature range under investigation we assumed that the power at a fixed voltage remained almost the same in the temperature range.

Figs. 3(b) and 3(c) show the calculated \(dI/dV\) curves, which would be affected by self-heating with the heating ratio of 60 K/mW and 150 K/mW, respectively. Figures also show the effective temperature of the sample as a function of the bias voltage for two base temperatures, \(T_b=140\) K and 225 K. Since the hump structures in these figures are weakened by the self-heating the voltage positions and the heights of the humps get smaller than the ones shown in the inset of Fig. 2. In Fig. 3(c), a higher heating ratio than that in Fig. 3(b) makes the hump structure disappear at a lower temperature around \(T=210\) K, which is close to \(T^*_{\text{dev}}\). This calculation clearly shows that the disappearance of the hump structure near \(T^*_{\text{dev}}\) is indeed due to self-heating.\(\text{[12]}\) Our nonlinear \(dI/dV\) curves in the normal state are in contrast to the flat \(dI/dV\) behavior modeled for the normal state in Ref. 24. The hump structures for temperatures above \(\sim170\) K as in the inset of Fig. 2, which lead to the local minimum of \(R_c\) in the main panel, cannot be explained, either, in terms of the self-heating model with a flat \(dI/dV\) behavior. Therefore, the hump structure previously reported in the ITS\(\text{[13, 20]}\) should not have been solely from the self-heating effect but from the intrinsic depletion of the zero-bias electronic spectral weight, presumably affected by the self-heating. This PG behavior with high onset temperature, \(T^*\), in the overdoped regime, revealed by our heating-compensated ITS, has characteristics similar to that observed in the angle-integrated photoemission spectroscopy and in the
FIG. 4: (color online) The heat-compensated interlayer tunneling spectra $dI/dv$ for our overdoped sample as a function of bias voltage per junction ($v$) at various $T$. Inset: $L$-$v$ and $dI/dv(v)$ curves calculated using Eq. (1) for $T_0=1$ (dotted curves) and $T_0=t_{\perp}\cos^22\phi$ (solid curves) at $T=4.2$ K.

electronic magnetic susceptibility $\chi(T)$. This peculiar PG behavior displays a clear peak-dip-hump structure below but near $T_c$, where the peak pertains to the superconducting coherence.

A series of the overall feature of heating-compensated interlayer tunneling spectra $dI/dv(v)$ of our overdoped sample, for varying $T$, is displayed in Fig. 4, where the voltage is normalized by the number of junctions as $v=V/N$. In the normal state above $T_c$ the low-bias DOS is smoothly depleted, revealing the PG. At a $T$ below $T_c$ a sharper peak (the coherence peak) develops inside the PG, constituting the peak-dip-hump structure. Further lowering $T$, the fast sharpening coherence peak with the growing SG size overwhelms the spectrum, leaving only the coherence peak apparent. The PG with the hump becomes more conspicuous in underdoped samples (not shown). Below $T_c$, the tunneling spectra show the more U-shaped DOS in the subgap region than the one observed previously. The fluctuating conductance at zero bias sufficiently below $T_c$ in Fig. 4 was caused by the Josephson pair tunneling.

In the following we discuss features of the superconducting gaps and pseudogaps and the interrelation between them one can observe in or deduce from the heating-free ITS results. Fig. 5(a) shows $dI/dv(v)$ curves at $T=80$ K and 82.6 K below $T_c$ of our overdoped sample. The electronic spectra near and below $T_c$ show a peak-dip-hump structure. As the coherence peak in the ITS starts to develop below $T_c$ the height and voltage position of the peak increases with decreasing temperature as illustrated in Figs. 4 and 5(a). This represents the SG edge. The hump structure in the normal state in the inset of Fig. 2 is connected to that below $T_c$, which thus represents the PG state. This observation is consistent with the recently reported Raman response functions, which reveal a change of spectral weight from lower energies to higher ones when making a transition from the normal state into the superconducting state at the optimal doping and slightly overdoped levels. In particular, the changes of the Raman responses are more enhanced in the antinodal regime than in the nodal regime. The coexistence of the superconducting and PG states below $T_c$ reflects that the two gaps are of different origins. This is in contradiction to the characteristics of the one-gap concept observed in ARPES and STS, where the PG is smoothly connected to the SG near $T_c$ in the varied doping ranges.

The hump structure in the peak-dip-hump excitation spectral distribution provides valuable information on the interrelation between the PG and superconducting states. The inset of Fig. 5(a) shows the temperature dependence of the superconducting coherence peak volt-

FIG. 5: (color online) (a) $dI/dv$ curves for $T=80$ and 82.6 K in our overdoped sample. (b) the shape of imagined electron density of states of two identical superconducting electrodes of a junction, which contain both the superconducting coherence peak and the PG hump, with assumed gap sizes of $\Delta_{SG}=20$ meV and $\Delta_{PG}=80$ meV. One electrode is assumed to be biased with $V=100$ mV. Inset of (a): temperature dependence of voltage positions of the superconducting coherence peak ($V_{peak}$) and the PG hump ($V_{hump}$), along with the corresponding SG energy ($\Delta_{SG}$) and PG energy ($\Delta_{PG}$).
age ($V_{peak}$) and the PG hump voltage ($V_{hump}$) near $T_c$. Since the tunneling occurs between two neighboring superconducting layers, the SG energy $\Delta_{SG}$ should be one half of $eV_{peak}$. In fact, the value of $V_{peak}$ is seen to reduce rapidly along with the SG as the temperature approaches to $T_c$ (=88 K) from below. However, it turns out that the PG energy $\Delta_{PG}$ determined in relation with $eV_{hump}$, for the superconductor-insulator-superconductor (SIS) tunneling near $T_c$, [31] should be defined in a somewhat different way. For temperatures in the range of $T > T_c$, where $\Delta_{SG}$ vanishes completely, $\Delta_{PG}$ is supposed to be simply $eV_{hump}/2$. But for $T < T_c$ the value of $V_{hump}$ is affected by opening of the SG as well as the PG. The differential conductance as a function of the voltage bias in the SIS tunneling junction is given by [31]

$$\frac{dI}{dV} \propto \frac{d}{dV} \int_0^{2\pi} d\phi |T_\phi|^2 \int N_1(E, \phi)N_2(E + eV, \phi) \times [f(E, T) - f(E + eV, T)]dE,$$

where $N_1$ and $N_2$ are the electron DOS of two identical superconducting layers with the $d_{x^2-y^2}$ symmetry, $T_\phi$ is the tunneling matrix and $\phi = [\tan^{-1}(k_y/k_x)]$ is the azimuthal tunneling angle. The angle-integrated electronic DOS, $N_1(E) = \int_0^{2\pi} d\phi N_1(E, \phi)$ for an assumed $N_1(E, \phi)$ in the presence of both the superconducting and the PG states, is illustrated in Fig. 5(b). Here, two different kinds of quasiparticles dressed by the superconducting state and the PG state are assumed to be accumulated near $\Delta_{SG} = 20$ meV and $\Delta_{PG} = 80$ meV, respectively. Quasiparticles fill all states below zero bias. If the voltage bias, $V$, is applied to the counter-electrode superconductor $N_2$ is shifted by $eV$ along the energy axis. In this process, quasiparticles with an energy $E$ in the occupied region of $N_1$ tunnel to the unoccupied states of $N_2$ at the same energy. This tunneling weight determines the conductance at a given voltage bias in the measurement. Especially, superconducting coherence peak at $E = \Delta_{SG}$ of $N_1$ dominantly determines the conductance shape as a function of voltage if the peak is sufficiently higher than the hump in the electronic DOS.

The angle-integrated DOS of the counterelectrode, $N_2(E)$, shown in Fig. 5(b) is the case where the bias voltage $V = 100$ mV corresponds to $(\Delta_{SG} + \Delta_{PG})/e$. Here, the superconducting coherence peak and the PG hump filled with the quasiparticles of $N_1$ are respectively overlapped with the vacant PG hump and the superconducting coherence peak of $N_2$. In this condition, the conductance is enhanced at the voltage bias corresponding to the hump voltage in the $dI/dV(V)$ curves. Thus below $T_c$, $eV_{hump} = \Delta_{SG} + \Delta_{PG}$ rather than simply $2\Delta_{PG}$. This inclusion of the influence of opening of the SG, $\Delta_{SG}$, in $V_{hump}$ explains the reason why $V_{hump}$ increases along with $V_{peak}$ below $T_c$ as seen in the inset of Fig. 5(a). Thus, care should be taken in extracting gap values from $dI/dV(V)$ curves of an SIS junction. If the height of superconducting coherence peak is not much higher than that of the PG in the tunneling DOS close to $T_c$, the $eV_{hump}$ turns out to be positioned between $\Delta_{SG} + \Delta_{PG}$ and $2\Delta_{PG}$. Thus, the PG hump can be smoothly connected near $T_c$ as in the inset of Fig. 5(a) and also as reported previously [12, 20]. If $\Delta_{SG}$ gets close in its value to $\Delta_{PG}$ at sufficiently low temperatures, one cannot easily distinguish the hump position from the coherence peak position because $\Delta_{SG} + \Delta_{PG} \sim 2\Delta_{SG}$. This is the reason why no hump structure is visible below $\sim 80$ K in the inset of Fig. 5(a).

The inset of Fig. 5(a) also displays the temperature dependence of the two characteristic gaps extracted using the above analysis. With decreasing temperature near and below $T_c$, the PG increases abruptly. This unusual behavior arises because the apparent hump structure in the tunneling spectra of a junction largely depends on which spectral weight, the SG or the PG, of an electrode is coupled to the PG spectral weight of the counterelectrode; (i) for $T > T_c$, the PG DOS in one electrode is detected by the broad pseudogap DOS in the counterelectrode, which makes $\Delta_{PG}$ lower than the expected position because of the broadness and (ii) $T < T_c$, PG DOS in one electrode is detected by the sharp superconducting peak in the opposite electrode, giving the value of $\Delta_{PG}$ close to the expectation.

This DOS analysis indicates that the hump structure at temperature below $T_c$ is due to tunneling of quasiparticles associated with the SG (PG) in one electrode of a junction to a vacant quasiparticle state associated with the PG (SG) in the counter electrode. In this tunneling process of the quasiparticles, the key observation is that the quasiparticle tunneling constituting the hump structure is possible only if the SG and the PG arise from the combined electronic state of quasiparticles of two different characters in the same momentum space, i.e., the antinodal region. This picture implies that quasiparticles in a single state distribute either in the SG spectra or in the PG spectra, depending on external physical parameters such as temperature, magnetic field, doping, etc. This inference is consistent with our earlier observation that, in a several-tesla $c$-axis magnetic field, the tunneling spectral weight in stacks of Bi-2212 IJJ (for both overdoped and underdoped ones) redistributes from the superconducting coherence peak to the PG hump [32]. But, the fact that the superconducting and the PG states are based on the single electronic structure composed of quasiparticles of two different characters is in contradiction to the earlier tunneling measurements with claiming that the peak-dip-hump features arise from a simple overlap of spectral functions of antibonding and bonding states, associated with the bilayer splitting [33].

The anisotropic tunneling matrix element [14] in the interlayer tunneling in the Bi-2212 filters out the tunneling in the nodal region and weights the tunneling near the antinodal points on the momentum space in the Brillouin zone. The pronounced U-shape in the measured tunneling $dI/dV$ curves of Figs. 4 and 5(a), which is in contrast to the V-shape ones usually observed in the STS [10, 33] is caused by this filtering. The dotted curves
In the inset of Fig. 4, the numerically obtained $I$-$v$ ($v$ is the bias voltage per junction) and the differential conductance curves using Eq. (1) for a $k$-independent tunneling matrix element $T_\phi=1$, $\Delta_{SG}=20$ meV and the quasiparticle scattering rate $\Gamma=0.05$ meV for an assumed DOS, $N(E,\phi) = \text{Re} \{ (E-i\Gamma)/[(E-i\Gamma)^2-\Delta_{SG}^2\cos^22\phi]^{1/2} \}$ at $T=4.2$ K. The solid curves in the inset of Fig. 4 correspond to the anisotropic tunneling matrix element $T_\phi = t_\perp \cos^22\phi$, which is theoretically predicted for a crystal with the tetragonal symmetry. Indeed, it has been reported that the PG onset temperature will decrease with increasing doping if the PG energy scale and the PG onset temperature of the antinodal region the formation of the pseudogap is closely related to the electronic state in this region. It has been widely accepted that the antinodal regions in cuprates are related to the formation of an antiferromagnetic order or orders like the spin-density wave and the charge-density wave. This anisotropic $T_\phi$ reduces the low-energy quasiparticle tunneling near the nodal points and leads to the U-shaped tunneling conductance, while sharpening the coherence peak. Thus, the ITS in our heating-compensation scheme mainly shows the electronic state in the vicinity of the antinodal region and the PG formation is more closely related to the electronic state in this region.

It is widely accepted that a Fermi-surface nesting exists with a van Hove singularity (high DOS with a flat band) near the antinodal region, which is related to the formation of an antiferromagnetic order or orders like the spin-density wave and the charge-density wave. This Fermi surface nesting may be related to the formation of an antiferromagnetic order or orders like the spin-density wave and the charge-density wave. It thus strongly indicates that the electronic excitations spectrum of highly anisotropic materials containing naturally grown tunneling junctions is closely related to the electronic state in this region.

IV. CONCLUSION

In order to understand the nature of the PG, the interlayer tunneling spectroscopic characteristics of high-$T_c$ superconductors were investigated, while the self-heating was largely excluded using the heating-compensation technique incorporated with the in-situ thermometry. Since the ITS is sensitive to the bias-induced self-heating an extreme care should be taken, as in this study, to keep the sample temperature constant within a tolerance limit over the whole bias sweeping range. But, as demonstrated by Krasnov et al. most of the essential observations on the PG feature remain valid even in the earlier ITS results. Thus, ITS, with a precautious measure taken to eliminate the self-heating, should provide a very useful experimental tools to investigate the electronic excitation spectrum of highly anisotropic materials containing naturally grown tunneling junctions.

In this study, it is found that the genuine PG behavior in the overdoped cuprates reveals the following characteristics. Defined by the appearance of the hump at $T_{hump}$ in the differential tunneling conductance, the PG onset temperature $T^*$ reaches up to nearly room temperature, much higher than the estimation based on the tunneling resistive transition, $T_{dev}$. With significant self-heating, however, numerical simulation shows that $T_{hump}$ returns to $T_{dev}$. This observation indicates that the hump structure in the tunneling differential conductance provides far more accurate determination of the PG onset temperature than the tunneling resistive transition. The hump voltage revealed in the ITS below $T_c$ is shown to follow the SG value, which is, in fact, additional confirmation that the hump structure in the ITS represents a genuine electronic PG state. The hump structure in the ITS below $T_c$ is also affected by the relative height and the voltage of the superconducting coherence peak, which originates from the fact that tunneling quasiparticles in an IJJ are dressed by the presence of both the SG and the PG. Since the interlayer tunneling is sensitive to the electronic state in antinodal region existing in a flat band, the PG behavior in ITS, coexisting with the SG, should be related to the Fermi surface nesting induced by the van Hove singularity.

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