

Superconducting gap and pseudogap for overdoped $\text{Bi}_{2-x}\text{Pb}_x\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$ using 60 ns time-scale short-pulse interlayer tunneling spectroscopy

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We have measured the interlayer tunneling spectra for overdoped $\text{Bi}_{2-x}\text{Pb}_x\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$ single crystals with a doping level p ranging from 0.20 to 0.22 and a T_c from 80 to 67 K using a small mesa structure and a 60 ns time-scale short-pulse technique. It is found that, with increasing doping, the superconducting gap decreases from 46 to 18 meV, while the pseudogap decreases from 42 to 10 meV. The result indicates the existence of the pseudogap in the overdoped region even at a doping level p higher than 0.19, at which the pseudogap is expected to disappear in some generic phase diagram models. Furthermore, the values obtained for the superconducting gap, normal tunneling resistance, and the maximum Josephson current indicate the likeliness of the inhomogeneous superconducting state even in the overdoped region.

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I. INTRODUCTION

The issue concerning the quasiparticle energy spectrum related to the superconducting gap (SG) and the pseudogap (PG) in high- T_c superconductors (HTSC) still remains active.^{1,2} For the further understanding of these gap structures, it is important to reveal their doping dependence.² In the underdoped and optimally doped regions, the PG structure was observed clearly in various experiments.¹ In the overdoped region, on the other hand, the PG was not observed clearly, because the PG and the SG are in close proximity and the difference in their magnitudes is rather smaller than that in the case of underdoped and optimally doped samples. In some generic phase diagram models, the PG disappears at $p \geq 0.19$, where p is the carrier doping level defined by the empirical relationship $T_c/T_c^{\text{max}} = 1 - 82.6(p - 0.16)^2$ with a value of $T_c^{\text{max}} = 90$ K (Ref. 2). Or, it is expected that the whole energy gap structure itself, which remains finite even at a temperature T higher than T_c for underdoped samples, disappears at T_c in the case of overdoped samples.³ Therefore, it is imperative to know the energy gap spectrum and its T -dependence in the overdoped region. Thus the energy gap structure in the overdoped region has become an important key to the understanding of the occurrence of high- T_c superconductivity.

The density of states (DOS) and the energy gap structure can be known by tunneling spectroscopy.⁴ Generally, however, tunneling spectroscopy measurements in the overdoped region are accompanied by a number of technical problems which remain to be solved. They are partly associated with samples themselves and partly with techniques. Among several tunneling spectroscopy techniques for HTSC, the interlayer tunneling spectroscopy^{5,6} (ITS) is unique and effective since it probes into bulk properties with a high energy resolution by employing superconductor/insulator/superconductor (SIS) tunnel junctions, called intrinsic Josephson junctions⁷ (IJJs), which are made of a layered crystal structure itself in Bi-based systems. The ITS is free

from surface problems associated with complicated chemical imperfections or adsorption accompanying tunneling spectroscopy samples. Furthermore, it is an additional advantage of this technique that the doping level of a sample is determined from the T -dependence of sample resistance at the time of ITS measurements. Our experience shows that the doping level of the very surface of an overdoped sample changes quite easily so that surface-sensitive spectroscopic probes are often subject to ambiguity concerning the doping level. Therefore, the ITS is a most suitable technique to measure the doping dependence of the SG and PG structure, especially for overdoped samples. While possibility of serious self-heating, i.e., Joule heating due to self-injection of current, and its influence were pointed out,⁸ it was also reported that the effect of self-heating is largely suppressed by using a small mesa structure together with the short-pulse technique.^{5,9,10}

In this paper, we report the results of the ITS measurements on overdoped $\text{Bi}_{2-x}\text{Pb}_x\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$ single crystals using 60 ns time-scale short-pulse technique together with a small thin mesa structure. It is shown that the PG is observed even in the overdoped region with $p \sim 0.22$, and that the PG magnitude is reduced to approximately half the SG magnitude; it should be noted that the PG is nearly the same as or larger than the SG when the doping level is near optimal. Accompanied by these changes in the energy gap structure, it is also found that the maximum Josephson current of the IJJs increases with increasing p and reaches the plateau near $p \sim 0.21$. Even with this increase in the maximum Josephson current, its density is still far below the Ambegaokar-Baratoff¹¹ (AB) value and we argue that the inhomogeneous superconducting state still remains to a greater or less degree even in the overdoped region and that in this sense the PG structure and the inhomogeneous superconducting state are likely to be essential in HTSC.

II. EXPERIMENTS

For overdoped samples, we employed single crystals of $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$ (Bi2212) and $\text{Bi}_{2-x}\text{Pb}_x\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$

TABLE I. Various physical properties $\rho_c(300\text{ K})$, T_c , ΔT_c , p , $2\Delta_{\text{SG}}$, $2\Delta_{\text{PG}}$, R_N , J_c , sample dimensions S , d , and the numbers of IJJs in samples N for representative samples A – D .

Sample	A	B	C	D
x	0.4	0.4	0.2	0
$\rho_c(300\text{ K})$ ($\Omega\text{ cm}$)	4.15	6.08	9.73	12.3
T_c (K)	67	73	80	78
ΔT_c (K)	5.6	6.0	2.8	4.2
p	0.216	0.208	0.197	0.200
$2\Delta_{\text{SG}}$ (meV) (10 K)	18	33	40	46
$2\Delta_{\text{PG}}$ (meV) ($\sim 10\text{ K}+T_c$)	10^{+6}_{-3}	17 ± 4	$27^{+2.1}_{-2.6}$	37 ± 3
S (μm^2)	33.1	27.7	35.5	29.6
d (nm)	13.5	9	15	7.5
N	9	6	10	5
R_N (Ω)	0.75	1.21	2.15	2.42
J_c (kA/cm 2) (10 K)	16.9	23.4	6.2	8.1

(BiPb2212), i.e., Pb-substituted Bi2212 (Ref. 12), both annealed in oxygen. For BiPb2212 single crystals, T_c was found to become lower than that for Bi2212 single crystals even when they were oxygenated under an identical condition in oxygen atmosphere. Therefore, overdoped samples were mainly obtained from BiPb2212 crystals.

The BiPb2212 single crystals were grown by the self-flux method. Appropriate amount of Bi_2O_3 , PbO , SrCO_3 , CaCO_3 , and CuO powders were mixed at an atomic ratio of $\text{Bi}:\text{Pb}:\text{Sr}:\text{Ca}:\text{Cu}=2-x:x:2:1:2$ with $x=0.2$ and 0.4 . The mixed powders were calcined and ground several times and then placed in an Al_2O_3 crucible, and heated at $1100\text{ }^\circ\text{C}$ for 6 h in air. Then, they were cooled down to $1000\text{ }^\circ\text{C}$ at a rate of $4\text{ }^\circ\text{C/h}$ and to $800\text{ }^\circ\text{C}$ at a rate of $1\text{ }^\circ\text{C/h}$. Finally, they were cooled to room temperature at a rate of $100\text{ }^\circ\text{C}-200\text{ }^\circ\text{C/h}$. Part of the crystals used were annealed at $600\text{ }^\circ\text{C}$ for 48 h in flowing oxygen. The Bi2212 single crystals were grown by the traveling-solvent-floating-zone method.¹³ They were annealed at $600\text{ }^\circ\text{C}$ for 100 h in flowing oxygen.

Small thin mesa structures were fabricated on a cleaved surface of Bi2212 and BiPb2212 single crystals. The mesas are of square shape and the planar area S is typically $30\text{ }\mu\text{m}^2$, its thickness ranging from 7.5 to 15 nm. These thicknesses correspond to the number of IJJs in the mesa N from 5 to 10. During the process, the samples were annealed in flowing oxygen for 3–20 h at $360\text{ }^\circ\text{C}-400\text{ }^\circ\text{C}$. By this oxygenation, T_c was reduced to 67 K and the doping level p was increased to greater than 0.19 in the overdoped region. Values for T_c and p are listed in Table I for representative samples A – D . These samples have a three-terminal electrode configuration, as shown in the inset to Fig. 1. The top of the mesa is covered with a 425 nm thick Au upper electrode, which effectively functions to remove the heat generated in the mesa due to current injection. In this configuration, the sample resistance is the sum of the mesa resistance and the contact resistance. Because of the large anisotropy of the Bi2212 system, the current flows perpendicularly to the mesa plane so that the mesa resistance reflects the c -axis resistivity ρ_c . The other sample fabrication details were described elsewhere.^{5,14}

In the short-pulse tunneling measurements, an impedance-matched high-frequency measurement system was employed to reduce voltage ripples superposed on the pulse responses, which prevent precise measurements on a shorter than sub- μs time scale. Using this system, the 60 ns short-pulse tunneling spectroscopy⁹ was conducted on small mesas described above. Voltage values were acquired at 60 ns from the pulse rise and then smoothed to give numerical differential dI/dV - V curves.

III. RESULTS

Figure 1 shows the T -dependence of sample resistivity ρ_c for samples A – D with various Pb contents x ($0\leq x\leq 0.4$). These values for ρ_c at 300 K are much smaller than those for slightly overdoped mesa samples made of Bi2212 single crystals reported before,^{15,16} and its T -dependence is metallic almost down to T_c . Similar ρ_c - T curves were also observed for overdoped Bi2212 and BiPb2212 bulk single crystals.^{12,17} It is clearly seen that the semiconductive upturn, which is

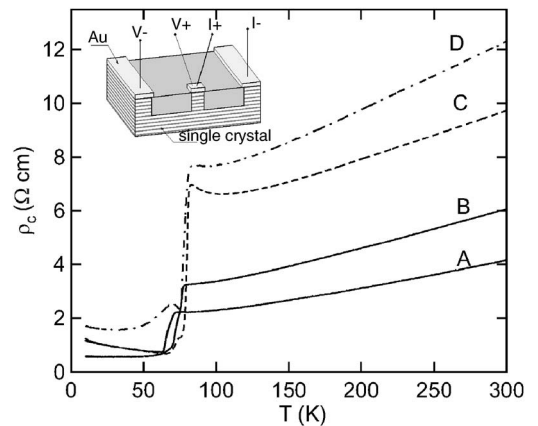


FIG. 1. Temperature dependence of ρ_c for samples A – D measured at a bias current of $5\text{ }\mu\text{A}$. Residual resistance seen below 60 K is the contact resistance. The inset shows a schematic of the electrode configuration for the samples.

conspicuous in the optimally doped and underdoped region, is scarce or almost missing. T_c for the present samples ranged from 67 K to 80 K, as determined from the midpoint of the resistive transition of the mesa resistance. The resistive transition width from 10% to 90% (ΔT_c) is typically 2–3 K and tends to increase to ~ 6 K as the doping level increases. For example, T_c for sample A with $x=0.4$ is determined to be 67 K with $\Delta T_c=5.6$ K. These values for samples A–D are listed in Table I together with the sample dimensions and other related characteristics. The doping level p for these samples ranges from $p=0.20$ in a slightly overdoped region to $p=0.22$ in the overdoped region, where the value for p is evaluated using the relationship¹⁸ $T_c/T_c^{\max}=1-82.6(p-0.16)^2$. For Pb-substituted Bi2212 crystals, T_c^{\max} is 89–90 K (Ref. 19), and for TSFZ Bi2212 crystals employed in the present experiments, [Bi]:[Sr]=2.1:1.9 and T_c^{\max} is 90 K (Ref. 20), so that we used the value of $T_c^{\max}=90$ K in the evaluation of p .

In the ρ_c - T curves in Fig. 1, a finite residual resistivity is seen below T_c . This is the contact resistance due to the three terminal configuration in these samples. The contact resistance for most of the samples ranged from 2 to 5 Ω ($0.5\text{--}2 \times 10^{-6} \Omega \text{ cm}^2$ in contact resistivity), which is approximately 10%–30% of the sample resistance at 300 K. For samples with a larger contact resistance, the I - V characteristics show nonlinearity in a small current range. For such samples, the voltage drop ascribed to the contact resistance does not increase proportionally to the current in a large current range due to its nonlinearity. Thus, the contact resistance at a large current bias decreases significantly. Therefore, the contact resistance is thought not to influence much on the tunneling characteristics in a large current range of $I > 10$ mA, in which the gap magnitude is probed. A typical contact resistance is $\sim 1/10$ of the total mesa resistance R_c . Then, the error due to the contact resistance in the magnitude of the gap values is always additive and estimated to be 10% or less.

Figure 2 shows an oscilloscope image of the I - V characteristics at 10 K for sample B. The number of junctions N for this sample is 6, as determined from the number of resistive branches seen in Fig. 2. The magnitude of the voltage per single junction is obtained by normalizing with N . The error due to this normalization is considered to be less than 10% (Ref. 21). In the lower voltage region of $V < 50$ mV in Fig. 2, there are several small voltage steps. This structure may be related to the coupling of Josephson current to optical phonons, as reported by Schlenga *et al.*²² For samples with $x=0$ and 0.2, this step structure was observed only occasionally.

The I - V characteristics in Fig. 2 indicate that one of the six junctions has a small maximum Josephson current I_c . This is thought to be partially due to the junction on the top of the mesa which might be damaged during the mesa fabrication. Therefore the value for I_c was determined from the other IJJs. In the case of sample B, I_c was determined to be 6.5 mA. I_c values for other samples were determined similarly and values for the maximum Josephson current density J_c at 10 K are listed in Table I.

Figure 3 shows a set of I - V characteristics for sample C measured by the 60 ns time-scale short-pulse technique at

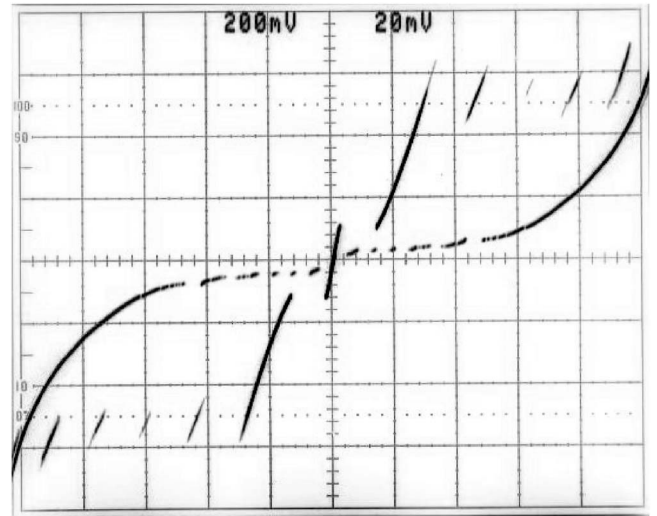


FIG. 2. A typical oscilloscope image of the I - V characteristics for sample B measured at 10 K. X axis, 20 mV/div and Y axis, 2 mA/div.

various temperatures from 10 to 140 K. In this figure, the abscissa scale indicates the single junction voltage obtained by dividing the observed voltage by N . The I - V curve at 85 K (the dashed line), which is slightly above T_c , shows nonlinearity near $V=0$, indicating the presence of the PG. Above T_c , I - V curves show little nonlinearity in a voltage range up to higher than 40 eV. Slight downward deviation of the I - V curve obtained at 140 K for $V > 40$ mV is probably due to the self-heating. As reflected by these I - V characteristics, the influence of the Joule heating is small in the present measurements above T_c , and the tunneling characteristics observed in the present measurement are thought to reflect the genuine PG structure in the overdoped range. The normal tunneling resistance R_N was determined by V/I for $V > 40$ mV, namely, just above the gap structure. Values for R_N thus obtained are listed in Table I.

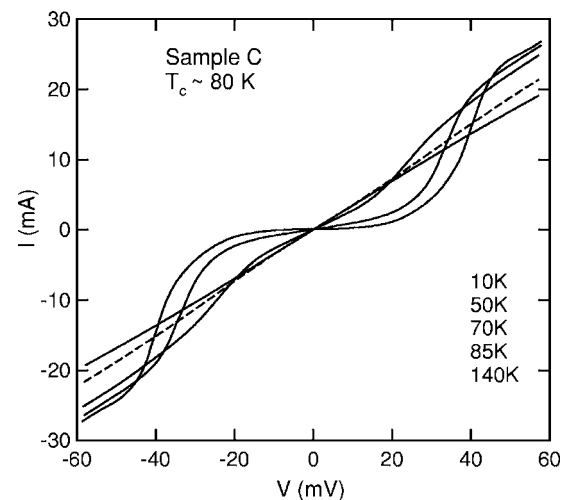


FIG. 3. Typical I - V characteristics for sample C at various temperatures measured by the 60 ns time-scale short-pulse method. V indicates the single junction voltage. The broken line denotes the characteristics at 85 K, which is slightly above T_c .

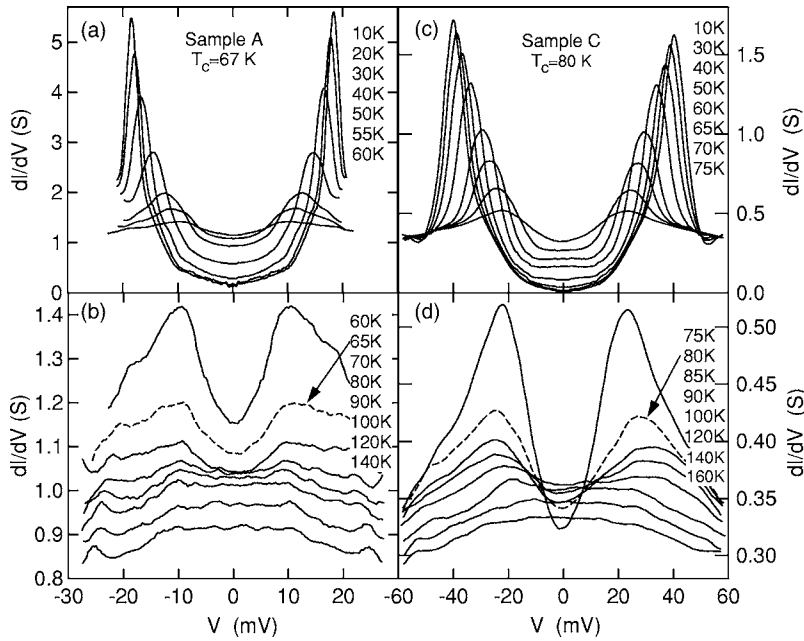


FIG. 4. dI/dV - V characteristics for sample A [(a) and (b)] and sample C [(c) and (d)] at various temperatures. V indicates the single junction voltage. The broken lines indicate the dI/dV - V characteristics near T_c .

Figures 4(a)–4(d) show the dI/dV - V characteristics at various temperatures for samples A and C. In these figures, the abscissa scale also indicates a single junction voltage. As shown in Figs. 4(a) and 4(c), a sharp conductance peak decreases in height and position with increasing T and disappears near T_c . Therefore, this conductance peak corresponds to the superconducting peak. We define the superconducting gap magnitude $2\Delta_{SG}$ as half the peak separation, so that $2\Delta_{SG}=18$ meV for the overdoped sample A ($p=0.216$). This value is approximately half the $2\Delta_{SG}$ values obtained by break junction tunneling spectroscopy²³ and scanning tunneling spectroscopy (STS)²⁴ for overdoped Bi2212 samples with a similar T_c . This small value for $2\Delta_{SG}$ in sample A is not ascribable to the Pb substitution since $2\Delta_{SG}$ turned out to be independent of the Pb content x .²⁵ The large difference between the present results and the previous ones may be partially due to the gap suppression caused by self-heating and partially due to the ambiguity concerning the doping level in the latter. However, when the I - V characteristics are recast in the close examination with respect to self-heating, it is unlikely that the gap magnitude is reduced to its half value, which we discuss later. Therefore, we believe that the present results reflect values close to the genuine $2\Delta_{SG}$ magnitude.

From the dI/dV - V curve at 10 K in Fig. 4(c), we find $2\Delta_{SG}=40$ meV at 10 K for slightly overdoped sample C. When the dI/dV - V curves are compared with those for sample A in Fig. 4(a), it is clearly seen that the superconducting peak becomes larger and sharper with increasing doping level. This behavior is thought to be closely related to the phase separation in the BSCCO system,²⁶ which we discuss later in more detail.

In the dI/dV - V curves for sample A in Fig. 4(b) for $T > T_c$, a broad peak is seen at approximately 10 mV. This structure demonstrates the existence of the PG in the low energy electronic states even in the overdoped Bi2212 at $p=0.216$ for sample A. Although the structure characteristic of the pseudogap is not significant in the dI/dV - V curves com-

pared with the case for underdoped samples, it is definitely seen to exist up to a temperature of 100 K. This temperature is much higher than the onset T_c of 70 K, so that the dip structure at $V=0$ is not due to a rather broad transition of sample A. Therefore, this structure is definitely due to the PG in sample A. When we define the pseudogap magnitude $2\Delta_{PG}$ as half the separation of the broad peaks, the dI/dV - V curves in Fig. 4(b) provide a value of $2\Delta_{PG}=10$ meV for sample A ($p=0.216$) and Fig. 4(d) provides a value of $2\Delta_{PG}=27$ meV for sample C ($p=0.197$). The ambiguity associated with the definition is approximately ± 4 meV just above T_c and tends to increase as T increases. The values for dI/dV for sample A at higher temperatures show a significant decrease at higher V , indicating a significant heating. This self-heating modifies the peak structure of the dI/dV - V curve, leading to the underestimation of $2\Delta_{PG}$ at higher V . For the same reason, the temperature T^* , at which the pseudogap disappears, is also underestimated to a small extent. The underestimation is considered to be less than 30 K, because the T^* value obtained from the ρ_c - T curve for sample A is 130 ± 5 K (Ref. 27), which is higher than the value obtained from the dI/dV - V curves by approximately 30 K. For sample C, the dI/dV - V curves show that the PG is filled when T comes close to 140 K. In this case, this temperature almost coincides with the value for T^* obtained from the ρ_c - T curve in Fig. 1, reinforcing that the influence of self-heating on the PG magnitude is small.

It was pointed out that ITS measurement can be seriously subjected to self-heating, i.e., Joule heating due to the injection of current.⁸ On the other hand, however, it was also demonstrated that nearly genuine tunneling characteristics with small influence from self-heating are obtainable using a 60 ns time-scale short-pulse measurement technique for a slightly overdoped small mesa sample with the three terminal configuration.⁹ In the present case, we estimate the influence of self-heating when the bias voltage is near the superconducting peak in the dI/dV - V characteristics at 10 K. The injected power in the case of samples A–D ranges from

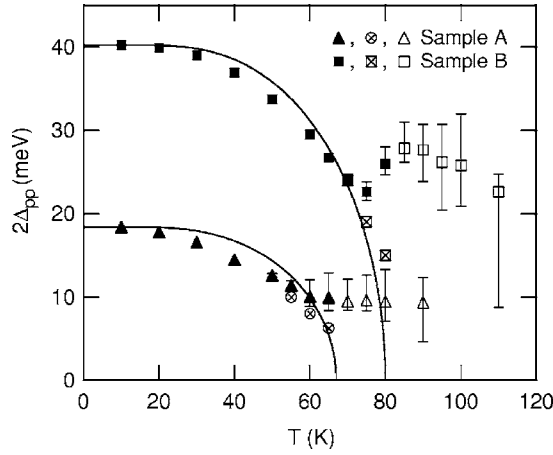


FIG. 5. T -dependence of $2\Delta_{pp}$, i.e., $2\Delta_{SG}$ for $T < T_c$ and $2\Delta_{PG}$ for $T > T_c$ for samples A and C. Solid symbols indicate the value for $T < T_c$ ($2\Delta_{SG}$) and open symbols indicate the value for $T > T_c$ ($2\Delta_{PG}$). The solid lines show the T -dependence of the superconducting gap magnitude in the BCS theory. Crossed squares and crossed circles indicate the gap magnitude obtained by fitting the d -wave SIS junction I - V characteristics with a finite quasiparticle lifetime.

2.9 to 5.2 mW. These values are smaller than the value of 8.4 mW in the previous measurement for a slightly overdoped sample.⁹ The difference comes from the fact that the present mesa size for samples A–D is by a factor of approximately 0.3 smaller than the previous one. The Joule heat thus generated in the mesa escapes immediately into the upper Au electrode due to a quite small aspect ratio of less than $\sim 0.3\%$ in the present three-terminal mesa configuration. Therefore, the temperature rise in the present samples mostly depends on the temperature rise in the upper Au electrode, and hence depends primarily on the injection power into the mesa structure, as confirmed by the finite-difference-time-domain numerical analysis.²⁸ Therefore, in the present measurements, the influence of the self-heating on the values for $2\Delta_{SG}$ is less than a few % or less, as revealed previously.⁹

Figure 5 shows the T -dependence of $2\Delta_{pp}$, i.e., half the peak separation in the dI/dV - V characteristics, representing $2\Delta_{SG}$ below T_c , and $2\Delta_{PG}$ above T_c . The error bars depicted on the plots for $2\Delta_{SG}$ and $2\Delta_{PG}$ indicate the ambiguity associated with the definition of Δ_{pp} . Since the PG structure gradually diminishes as T increases, the error increases as T increases. It is clearly seen in Fig. 5 that $2\Delta_{SG}$ decreases with increasing T , roughly tracing the T -dependence of the superconducting gap magnitude in the BCS theory. Near T_c , however, $2\Delta_{SG}$ starts to deviate from this T -dependence, remains at a finite value of approximately half the low temperature $2\Delta_{SG}$ value, and then apparently switches to the PG. It is known that the superconducting peak position in the dI/dV - V curve shifts toward higher V values as T approaches T_c , especially when the quasiparticle lifetime is finite and the order parameter symmetry is d -wave type. Therefore, we also plot in Fig. 5 the $2\Delta_{SG}$ values obtained by fitting the dI/dV - V curve numerically calculated for a d -wave superconductor junction with a finite quasiparticle lifetime for a number of temperatures near T_c (Ref. 29). The result shows a

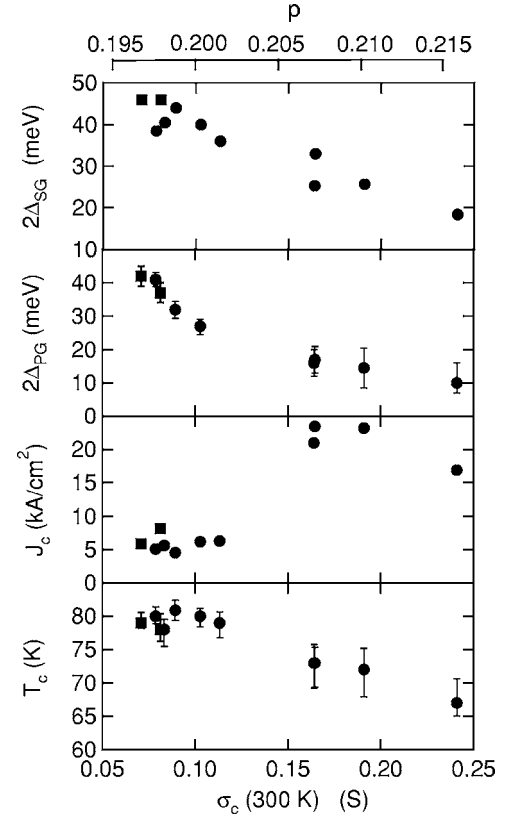


FIG. 6. Doping dependence of $2\Delta_{SG}$, $2\Delta_{PG}$, J_c , and T_c . The doping levels for samples are represented by the c -axis conductivity for samples at 300 K, $\sigma_c(300\text{ K})$. Filled squares indicate the data obtained from Bi2212 crystals. Error bars in the $2\Delta_{PG}$ plots indicate the ambiguity associated with the $2\Delta_{PG}$ definition. The error bars in T_c data indicate the transition width from 10% to 90%.

clear tendency for $2\Delta_{SG}$ to decrease as T approaches T_c , though it still shows a deviation from the BCS temperature dependence. In the proposition by Fine,³ the value for $2\Delta_{SG}$ for a sample with a ratio of $\Delta_{SG}(0)/T_c < 4$ becomes zero at T_c . In the present experiments, values for $2\Delta_{pp}$ hardly vanish at T_c for samples A and C, in which the values for $\Delta_{SG}(0)/T_c$ are 1.6 and 2.9, respectively. It also appears that the values for $2\Delta_{SG}$ obtained from the fitting remain finite even at T_c .

IV. DISCUSSION

Figures 6(a)–6(d) show the plots for $2\Delta_{SG}$, $2\Delta_{PG}$, J_c , and T_c for various samples as a function of the c -axis conductivity at 300 K, i.e., $\sigma_c(300\text{ K}) = \rho_c^{-1}(300\text{ K})$. These plots indicate the doping dependencies of these physical properties, since $\sigma_c(300\text{ K})$ is nearly proportional to the doping level.^{13,26} Then, the abscissa of Fig. 6 is approximately proportional to p in a limited range. This plot is found reasonable directly by observing that T_c decreases almost linearly with increasing $\sigma_c(300\text{ K})$ (Ref. 30). In Fig. 6, the scale on the top indicates an approximate p obtained from the relationship between p and T_c mentioned above.

As shown in Fig. 6(a), $2\Delta_{SG}$ decreases monotonically from 46 to 18 meV with increasing doping level. Similarly,

$2\Delta_{\text{PG}}$ also decreases from 42 to 10 meV. The present data for $2\Delta_{\text{SG}}$ and $2\Delta_{\text{PG}}$ is considered to cover a doping range from a slightly overdoped level of $p=0.197$ to an overdoped level of $p=0.216$. This range corresponds to an extension of the previously reported doping dependence.¹⁵ When the present and previous values for $2\Delta_{\text{SG}}$ from the short-pulse ITS are compared with those of Renner *et al.* for a similar p values, the previous values for $2\Delta_{\text{SG}}$ in the slightly underdoped and nearly optimally doped levels are smaller by 5% to 10% than those of Renner *et al.* For slightly overdoped samples, on the other hand, the present and previous values are smaller by 30%, and for overdoped samples, the present value is smaller by greater than 50% than the Renner *et al.* The difference may be ascribed either to the self-heating effect in the short-pulse ITS or to the ambiguity of the T_c value of the topmost layer in the STS, which might be different from the bulk T_c .³¹ However, as described above and in Ref. 9, the estimate of the temperature rise by the self-heating is no higher than 10 K, or the change of $2\Delta_{\text{SG}}$ due to the self-heating is no greater than a few %. Therefore, we believe that the values obtained in the present study reflect the genuine values for $2\Delta_{\text{SG}}$ in the slightly overdoped and overdoped samples within an error of approximately 10%.

In the recent STM/STS results,³² it was found that $2\Delta_{\text{SG}}$ is spatially modulated on a nm scale. If this is likewise in the bulk, then the ITS spectrum represents the sum of the whole distribution within the mesa area. In that case, the ITS peak represents the mode value and the peak width represents the broadness of the distribution. Actually, it is certainly true that the peak width increases with decreasing doping level, as shown in Fig. 4. The fact that the peak location shifts to higher energies with decreasing doping level implies that the value for $2\Delta_{\text{SG}}$ defined as the mode value certainly represents the doping dependence as a physical parameter describing the system. On the other hand, T_c depends sensitively on the compositions or chemical imperfections as well as on the doping level, so that the doping dependence of T_c is not always consistent in the presence of chemical disorder. If we think phenomenologically that T_c is primarily determined by the superconducting order parameter $2\Delta_{\text{SG}}$ and by the depairing effect of various kinds, and that $2\Delta_{\text{SG}}$ is doping dependent while the depairing effect depends on chemical imperfections or disorders among others, then it is reasonable to think that the SG exhibits an unambiguous and more straightforward doping dependence rather than T_c . The present result together with the previous one¹⁵ unambiguously demonstrates that both $2\Delta_{\text{SG}}$ and $2\Delta_{\text{PG}}$ decreases with increasing doping in a wide doping range from an underdoped level of $p=0.108$ to an overdoped level of $p=0.216$.

In Fig. 6(c), J_c at 10 K, which is proportional to $2\Delta_{\text{SG}}$ at low temperatures in the AB theory, saturates near $\sigma_c=0.17 \text{ S cm}^{-1}$ ($p\sim 0.208$) and then decreases for $\sigma_c(300 \text{ K}) > 0.19 \text{ S cm}^{-1}$ ($p\sim 0.210$) (Ref. 33). This behavior is in accord with the doping dependence of the superfluid density estimated by angle-resolved photoemission spectroscopy.³⁴ If we use the values for $2\Delta_{\text{SG}}$ and R_N in Table I, the value for the maximum Josephson current I_c for sample

A is calculated to be 19 mA from the low temperature formula $I_c=\pi\Delta_{\text{SG}}/2eR_N$ of the AB theory.³⁵ On the other hand, the observed value of $I_c=5.6 \text{ mA}$ is approximately one order of magnitude (or by a factor of 0.3) smaller than the AB theory. Although the ratio of this value to the AB theory is orders of magnitude larger than that for underdoped samples, the present result implies that J_c is still much smaller than the AB theory even for overdoped samples. This large difference is explained when we assume that the superconducting state is inhomogeneous.²⁶ Therefore, this may indicate the existence of phase separation or inhomogeneous superconducting state even in the overdoped region of the BSCCO system, as shown in the case of Bi2223 system.²⁶

Figures 6(b) and 6(d) show that $2\Delta_{\text{PG}}$ decreases from 42 to 10 meV, and T_c decreases linearly from 80 to 67 K, both with increasing doping. These changes correspond to the change in the doping level p from 0.197 to 0.216 (Ref. 36). Thus the experimental results clearly demonstrate that the PG still exists in the overdoped region even at a doping level p larger than the critical value of $p=0.19$, at which the PG structure disappears in some phase diagram models.² It appears that the PG decreases with increasing p and vanishes at much larger p , at which T_c may also vanish. If this is the case, this may imply that the inhomogeneous superconducting state and the PG structure are essential ingredients in high- T_c superconductivity.

V. CONCLUSIONS

We have measured the interlayer tunneling spectra for overdoped $\text{Bi}_{2-x}\text{Pb}_x\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$ single crystals using a small thin mesa structure and a 60 ns short-pulse technique. It is found that, when the doping level increases from $p=0.197$ to 0.216, $2\Delta_{\text{SG}}$ decreases from 46 to 18 meV and $2\Delta_{\text{PG}}$ decreases from 42 to 10 meV. This implies that the pseudogap exists in the overdoped region even at a doping level greater than a critical doping of $p=0.19$ in some phase diagram models. It is also found that J_c increases with increasing doping and reaches the maximum near $p=0.21$. Based on the values obtained for J_c , $2\Delta_{\text{SG}}$, and R_N , we argue that the superconducting state in the $\text{Bi}_{2-x}\text{Pb}_x\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$ system is inhomogeneous even in the overdoped region. These results may imply that the pseudogap and the inhomogeneous superconducting state are closely related and essential to high- T_c superconductivity.

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