# 60 ns time scale short pulse interlayer tunneling spectroscopy for $Bi_2Sr_2CaCu_2O_{8+\delta}$

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We utilize the short pulse interlayer tunneling spectroscopy on a 60 ns time scale for the $Bi_2Sr_2CaCu_2O_{8+\delta}$ system. The results indicate that the influence of self-heating is negligible up to an injection current density of $\sim$60 kA/cm$^2$ and an injection power areal density of $\sim$90 kW/cm$^2$. By means of this technique, we are able to observe the superconducting gap, the pseudogap, and the dip-and-hump structure precisely with little influence from the self-heating. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1612891]

Tunneling spectroscopy is a technique that directly probes the electronic states of a metal or a superconductor.[1] Recently, this is expected to shed light on the nature of high-$T_c$ superconductors (HTSC). Among various tunneling spectroscopy techniques for HTSC, short pulse interlayer tunneling spectroscopy (ITS)[2,3] is unique in that it uses intrinsic Josephson junctions (IJJs) as a tunnel junction. Here, IJJs are built-in tunnel junctions in a layered crystal structure in some HTSC,[4] such as $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi2212). ITS is a spectroscopy technique based on superconductor/insulator/superconductor (SIS) tunneling and has two advantages: a high energy resolution owing to SIS tunneling and the absence of problems arising from surface chemical instability in samples. Owing to these advantages, ITS has revealed, for instance, the coexistence of the superconducting gap (SG) and the pseudogap (PG) in underdoped Bi2212.[5,6] This technique is expected to play an important role in elucidating further details of the HTSC energy gap structure.

A problem associated with ITS is the self-heating, which manifests itself in the $I-V$ curve as its deformation when a high current is injected. In order to suppress the self-heating, ITS employs samples with a small and, in particular, very thin mesa, containing approximately 10 IJJs or less. However, even the smallness of a mesa is not sufficient for the suppression of the self-heating when the current density $J$ and the area-normalized power $Q=JV$ exceed 5 kA/cm$^2$ and 2.5 kW/cm$^2$, respectively. In this situation, the short pulse method is useful for the further suppression of the self-heating. Using this method on a submicrosecond time scale, it was demonstrated that the influence of self-heating is almost negligible near and below the superconducting peak voltage in tunneling spectra.[7] However, at greater than 100 mV voltages per single junction and higher than $\sim$20 kA/cm$^2$ current densities, i.e., well above the SG voltage, the appreciable self-heating starts to show up again even on a submicrosecond time scale and affects the tunneling characteristics. In order to extend the ITS energy range and improve its accuracy by reducing the self-heating, it is imperative for the short pulse ITS technique to operate on one order of magnitude shorter time scale than previously.

In this letter, we report a short pulse ITS technique on a time scale as short as 60 ns using an impedance-matched measurement system. By this technique, it is found that the self-heating becomes much less significant than previously. This provides a sufficient accuracy for the observation of the energy gap structure in the Bi2212 system.

A sample we used is a mesa on a Bi2212 single crystal having a lateral size of $10\times10\ \mu$m$^2$ and a thickness of 15 nm, which corresponds to $N=10$, where $N$ is the number of IJJs in the mesa. The sample has a three-terminal 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 is effective to remove the heat generated in the mesa by current injection. The sample fabrication was detailed elsewhere.[8] From the temperature ($T$) dependence of the mesa resistance $R_c$ in the $c$-axis direction, we found that $T_c=87$ K and that the sample is slightly overdoped ($\delta=0.27$),[3,9] having a smaller normal tunneling resistance $R_N$ and a tendency to be overheated by self-injection.

In the three-terminal ITS, the contact resistance $R_{cont}$ in the upper electrode should be much smaller than $R_c$. In the present case, $R_{cont}$ was estimated to be 1 Ω from the residual resistance of the mesa below $T_c$. This value is no greater than 2% of $R_c$(300 K) so that $R_{cont}$ is neglected in the data

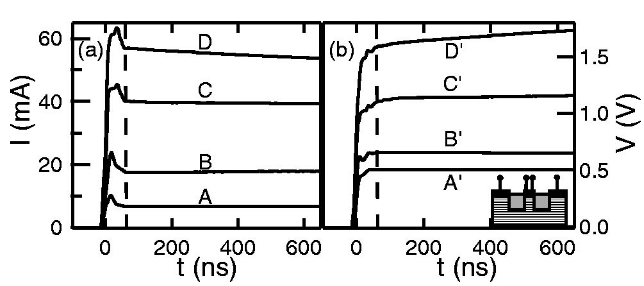


FIG. 1. (a) Current and (b) voltage pulse responses measured at 10 K for a mesa of $10\times10\ \mu$m$^2$ and $N=10$. The broken line indicates the data acquirement time of 60 ns. The inset shows a schematic of the sample.

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analysis. In the case of four-terminal configuration for ITS as in Ref. 10, the magnitude of $R_{cont}$ does not directly affect the tunneling characteristics. In that case, however, the current-terminal contact on top of the mesa becomes another source of heating, disabling the heat flow channel to the upper electrode, and finally leads to a significant self-heating. Therefore, we employed the three-terminal ITS at the expense of the contact resistance.

We constructed an impedance-matched measurement system to reduce voltage ripples superposed on pulses, which prevent precise measurements on a shorter than submicrosecond time scale. In the measurement system, the sample was connected to an arbitrary wave form generator with an output impedance of 50 Ω and to a four-channel digital oscilloscope with an input impedance of 50 Ω via 50 Ω cryogenic coaxial cables. We used the composite current pulses of 1.2 μs width, which consist of three parts: a sharp rise part of 30 ns width, a flat part of 700 ns width, and a smooth fall part of 500 ns width like a quarter-period sinusoidal curve.

Figure 1 shows the current and voltage pulse responses at four input levels from the sample at 10 K. In the responses, no significant ripple is seen after 60 ns from the rise of a pulse, enabling the short pulse ITS on the 60 ns time scale. We define, respectively, $I(t)$ and $V(t)$ for a pulse as the magnitude of the current and voltage as a function of time $t$ after the rise of a pulse. The curves A and A′ in Figs. 1(a) and 1(b) show $I(t)$ and $V(t)$ at a level of $V(60\,\text{ns}) = 0.50\,\text{V}$, which is smaller than the SG voltage of $V_g = 0.65\,\text{V}$. Both responses show a flat $t$ dependence, indicating clearly the absence of the self-heating. At this current level, $I-V$ curves scarcely suffer from the influence of self-heating even on a 0.6 μs time scale. The curves B and B′ show the pulse responses near $V_g$. The $t$ dependence is still flat and there is little difference between $V(60\,\text{ns})$ and $V(600\,\text{ns})$, showing again little influence from the self-heating at this current level.

At larger voltages, however, $I(t)$ and $V(t)$ start to show an appreciable $t$ dependence. For curve C for $J \sim 40\,\text{kA/cm}^2$ and $Q \sim 44\,\text{kW/cm}^2$, $I(600\,\text{ns})$ is smaller than $I(60\,\text{ns})$ by 2%. For curve C′, $V(600\,\text{ns})$ is larger than $V(60\,\text{ns})$ by 5%. The conductance, $\sigma(600\,\text{ns}) = I(600\,\text{ns})/V(600\,\text{ns})$, is smaller than $\sigma(60\ \text{ns})$ by 7%. Similarly the curves D and D′ at a level of $J \sim 55\,\text{kA/cm}^2$ and $Q \sim 88\,\text{kW/cm}^2$ show that $\sigma(600\ \text{ns})$ is smaller than $\sigma(60\ \text{ns})$ by 13%. The variation in $\sigma(600\ \text{ns})$ from $\sigma(60\ \text{ns})$ reflects the influence of self-heating. Thus, it is seen that the self-heating becomes significant as $V$ increases, that is, as the current injection increases at $t = 600$ ns.

Figure 2 shows the $I-V$ curves measured at various $t$ from 60 to 600 ns. Josephson current in the low voltage region was suppressed by the magnetic fields (0.5 T) in the $c$-axis direction. Below $V_g$, all the $I-V$ curves fall onto a single curve. This means that the self-heating exerts almost no influence on the $I-V$ curves below $V_g$ on these time scales. For $V > V_g$, on the other hand, the $I-V$ curve systematically deviates toward the positive $V$ direction. Clearly, the larger the value for $t$, the greater the shift in the $I-V$ curve. This shift is caused by the self-heating since $R_N$ increases with increasing $T$ (Ref. 3), as shown in the inset to Fig. 2. This implies that the self-heating starts to be influential again even in the short pulse method on a 300 μs time scale.[11]

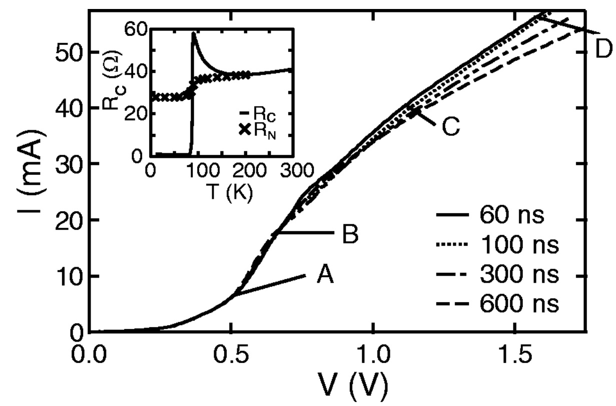


FIG. 2. $I-V$ curves at 10 K measured at various $t$ from 60 to 600 ns. The points indicated by A–D correspond to the current levels in Fig. 1. The inset shows the $T$ dependence of $R_c$ and $R_N(T=60\,\text{ns}, V=1.4\,\text{V})$.

Above $T_c$, the temperature rise $\Delta T$ due to self-heating can be roughly estimated from $\Delta R_N$, an increase in $R_N$ when $V$ is increased, by assuming that $dR_N/dT = dR_c/dT = 32.5\,\Omega/\text{K}$. At 200 K, $R_N$ remains almost unchanged from $V = 1.2$ up to 1.7 V, indicating that $\Delta R_N < 0.1\,\Omega$ and, hence, $\Delta T < 3.3$ K. In the case in which $R_c = R_N$ is further assumed, $\Delta R_N = R_N - R_c = 0.3\,\Omega(\text{at } V = 1.4\,\text{V})$, $\Delta T$ could be estimated to be no higher than 10 K. However, the estimate for $R_N$ includes an uncertainty of 0.4 Ω, which implies a $\Delta T$ uncertainty of 13 K. Below $T_c$, it is difficult to estimate $\Delta T$ from $\Delta R_N$ because of strong nonlinearity in $I-V$ curves. The finite-difference-time-domain numerical analysis[12] results in $\Delta T \lesssim 3$ K at 10 K and $Q = 88\,\text{kW/cm}^2$.

The present result is at variance with a previous report by Fenton *et al.*,[10] who employed the four-terminal ITS and observed the severe self-heating on a nanosecond time scale. We presume that their significant self-heating is closely related to their four-terminal configuration, as mentioned before. This is confirmed by the numerical analyses,[12,13] which show that more than half of the heat generated in the mesa flows out via the upper electrode channel in the present three-terminal configuration.

Figures 3(a) and 3(b) show the $dI/dV-V$ characteristics measured at various $t$ from 60 to 600 ns below and above $T_c$, respectively. In these figures, the abscissa indicates the voltage normalized by $N$. From the aforementioned time-resolved analysis, the $dI/dV-V$ curve measured at $t = 60$ ns most likely represents the genuine quasiparticle tunneling characteristics for a single IJJ. The sharp peak at $V = 60$ mV in Fig. 3(a) corresponds to the superconducting conductance peak. When we define the SG magnitude $2\Delta_{SG}$ as half the peak separation, $2\Delta_{SG} = 62$ meV at $t = 60$ ns, while $2\Delta_{SG} = 60$ meV at $t = 300$ ns. The difference is approximately 3% and nearly negligible.

In a greater than 120 mV normalized voltage range, the value for $dI/dV$ at a longer than 60 ns $t$ decreases monotonically as $V$ increases due to the influence of self-heating. On the other hand, the value for $dI/dV$ at $t = 60$ ns is constant up to 150 mV. This indicates that the short pulse ITS measurements on the 60 ns time scale provide $dI/dV-V$ curves

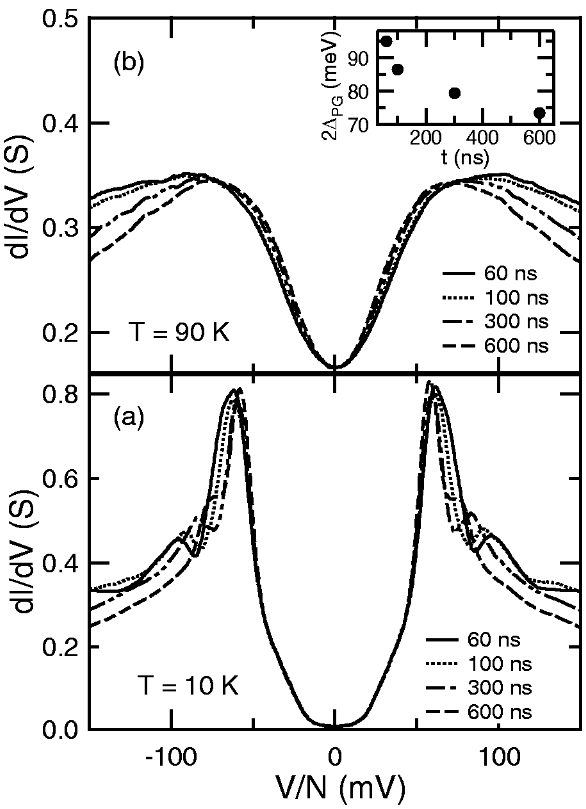


FIG. 3. $dI/dV-V$ curves measured at various $t$ from 60 to 600 ns. The voltage is normalized by $N$. (a) $T=10$ K. (b) $T=90$ K. The inset plots the variation of $2\Delta_{PG}$ at various $t$ from 60 to 600 ns.

which scarcely suffer from the influence of self-heating at least in this voltage range.

In Fig. 3(a), a dip-and-hump structure is clearly observed in a greater than $2\Delta_{SG}/e$ voltage range. This structure was observed by various spectroscopy methods,[14–16] and is believed to provide a key to the mechanism of HTSC. It is seen that the dip-and-hump structure is clearer and located at a higher energy position in the 60 ns curve than others. The clear and precise observation of the dip-and-hump structure as above may contribute to its basic understanding.

Figure 3(b) shows the $dI/dV-V$ curves at 90 K. The broad peak near 90 mV corresponds to the PG structure. As shown in the inset to Fig. 3(b), the PG magnitude $2\Delta_{PG}$, defined as half the peak separation at 90 K, decreases in inverse proportion to $t$. For instance, the observed value for $2\Delta_{PG}$ decreases from 95 meV at $t=60$ ns to 80 meV at $t=300$ ns. The systematic decrease in the observed value for $2\Delta_{PG}$ is caused by a decrease in $dI/dV$ brought about by the self-heating via an increase in $R_N$. Therefore, it turns out that the previous short pulse ITS result,[17] which roughly corresponds to the present result at $t=300$ ns, underestimated $\Delta_{PG}$ by approximately 16%.

In conclusion, we have developed the short pulse ITS on the 60 ns time scale with an impedance-matched measurement system. The results show that the self-heating due to current injection is negligible even in a higher than $\sim 20$ kA/cm$^2$ current densities and $Q\sim 20$ kW/cm$^2$. This enables us to observe the genuine energy gap structure for the Bi2212 system including the pseudogap and the dip-and-hump structure with little influence from the self-heating.

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