Tunneling Characteristics for Bi2212 Intrinsic Josephson Junctions With Little Influence of Self-Heating Using Short Pulse Technique on 60 ns Time Scale

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Abstract—A small mesa structure (10 \( \mu \text{m} \times 10 \mu \text{m}, 15 \text{ nm} \) thick) of intrinsic Josephson junctions in \( \text{Bi}_2\text{Sr}_2\text{Ca}_n\text{Cu}_{2n+2}O_{8+\delta} \) is employed to observe the tunneling characteristics and the superconducting gap magnitude by short pulse technique (short pulse interlayer tunneling spectroscopy). In the measurement on 60 ns time scale, the effect of self-heating is almost negligible in the sample, whose resistivity is as small as 10 \( \Omega \cdot \text{cm} \). In slightly overdoped region, the maximum Josephson current density increases from 0.85 to 2.1 \( \text{kA/cm}^2 \) with increasing doping level. The superconducting gap magnitude \( 2\Delta \) decreases from 62 to 37 meV with increasing doping level. The value for \( 2\Delta /k_B T_c \) decreases from 8.3 to 5.2 with increasing doping level. These values in slightly overdoped region are smaller than those in optimum and underdoped region.

Index Terms—\( \text{Bi}_2\text{Sr}_2\text{Ca}_n\text{Cu}_{2n+2}O_{8+\delta} \), high-temperature superconductor, intrinsic Josephson junction, pseudogap, superconducting gap, tunneling spectroscopy.

I. INTRODUCTION

The Josephson tunneling junctions with superconductor/insulator/superconductor structure are the basic elements in the cryoelectronics based on superconductors [1]. When a high-\( T_c \) superconductor (HTSC) was found, as a matter of course, it was expected that the application of superconductivity would be expanded. However, at least as far as the Josephson devices are concerned, those with HTSC are not necessarily put to practical use so far. This is mainly because it is difficult to fabricate the Josephson tunneling junction with oxide HTSC whose performance is comparable to those with the conventional superconductor. On the other hand, it has been found that in strongly anisotropic HTSC such as \( \text{Bi}_2\text{Sr}_2\text{Ca}_n\text{Cu}_{2n+2}O_{8+\delta} \) (Bi2212), all \( \text{CuO}_2 \) planes are connected by the Josephson effect [2]. These built-in tunnel junctions in a layered crystal structure are called the intrinsic Josephson junctions (IJJ’s). Among the various Josephson junctions with HTSC, the IJJ is found to be an ideal tunneling junction with a flat interface between superconductor and insulator in atomic scale. A large study on IJJ is now under way to put them to practical use [3].

IJJ can also be used for tunneling spectroscopy, which is a technique that directly probes the electronic states of a metal or a superconductor [4]. This technique, which is called interlayer tunneling spectroscopy (ITS), [5], [6] is free from surface problems that obscure the original properties. Moreover, it is an advantage of this technique that the probed part can be characterized by transport measurements, providing a solid basis and reliability for the specimen that yielded the results. On the other hand, self-heating, which is a problem associated with ITS, occurs when a large current is injected. Short-pulse technique on a 600 ns time scale has ever been employed and demonstrated that it is effective to reduce self-heating [7]. Owing to these advantages, short-pulse ITS has revealed, for instance, the coexistence of the superconducting gap (SG) and the pseudogap (PG) in underdoped and optimally doped Bi2212 [8]. However, it was found in overdoped samples that self-heating shows up again even on a submicrosecond time scale since their resistivity is lower than that of optimum or underdoped samples. Studies on overdoped Bi2212 are still necessary because their maximum Josephson current density is larger and suitable for the application. Therefore, it is imperative for the short pulse ITS technique to operate on shorter time scale than previously to investigate overdoped samples.

This paper reports a short pulse ITS technique on a time scale as short as 60 ns using an impedance-matched measurement system. This technique enables us to observe the SG with little influence of self-heating even in overdoped sample, and we have found that the value for \( 2\Delta /k_B T_c \) decreases from 8.3 to 5.2 with increasing doping level. These values in slightly overdoped region are smaller than those in optimum and underdoped region [9].

II. EXPERIMENTAL

A. Characterization of Samples

The samples with the mesa structure were fabricated on a cleaved surface of Bi2212 single crystal. The mesa pattern area \( S \) is ranging from 24 to 94 \( \mu \text{m}^2 \) and its thickness is about 15 nm. This value corresponds to \( N = 10 \), where \( N \) is the number of IJJ’s in the mesa. The sample has a three-terminal configuration, as shown in Fig. 1(c). 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 described in detail elsewhere [10].

Fig. 1(a) shows the temperature dependences of the mesa resistance $\rho_c(T)$ of Samples A–C in the $c$-axis direction. $T_c$ for the sample is estimated from the resistive transition in Fig. 1(a). The values for $T_c$ of Samples A–D are listed in Table I. Samples A–C are found to be slightly overdoped from the decrease of $\rho_c(T)$ with temperature near 300 K in Fig. 1(a) [6], [11]. In Sample C, the value of $\rho_c$ is smaller than the half of that for Sample A and $\rho_c(T)$ shows rather metallic behavior than semiconductive behavior above $T_c$, as seen in the curve of Sample A. Thus, Sample C is a little more overdoped than the other samples. Such sample has a smaller normal tunneling resistance $R_N$ and can be overheated by the larger self-injection current.

Fig. 1(b) shows an oscilloscope image of the current ($I$)-voltage ($V$) characteristics for Sample C measured at 11 K. The number of junctions $N$ in this sample is 10, as seen in the number of resistive branches. The maximum Josephson current $I_c$ was estimated to be 0.9 mA from the resistive branch in Fig. 1(b).

In the measurement using the three-terminal sample, the contact resistance $R_{\text{cont}}$ in the upper electrode should be much smaller than the sample resistance. In Fig. 1(a), Sample B has rather large $R_{\text{cont}}$ than that of the other samples and its value was estimated to be 1.4 $\Omega$ from the residual resistance of the sample below $T_c$. This value is no greater than 6% of $R_c$(300 K). In addition, the voltage reduction in $R_{\text{cont}}$ is much smaller than that in normal resistance, because $R_{\text{cont}}$ usually has non-linearity. Therefore, $R_{\text{cont}}$ is neglected in the data analysis.

**B. Measurement System Setup**

We constructed an impedance-matched measurement system to reduce voltage ripples superposed on pulses, which prevent precise measurements on a shorter than sub-$\mu$s time scale. In the measurement system, the sample was connected to an arbitrary waveform generator with an output impedance of 50 $\Omega$ and to a four-channel digital oscilloscope with an input impedance of 50 $\Omega$ via 50 $\Omega$ cryogenic coaxial cables. We used the composite current pulses of 1.2 $\mu$s 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.

**III. RESULTS AND DISCUSSION**

**A. Influence of Self-Heating**

Fig. 2 shows the current and voltage pulse responses at 4 input levels from Sample A 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. 2(a) and (b) show $I(t)$ and $V(t)$ at a level of $V(60 \text{ ns}) = 0.50$ V, which is smaller than the SG voltage of $V_g = 0.65$ 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 $\mu$s 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 current density $J \sim 40$ kA/cm$^2$ and area-normalized power $Q \sim 44$ 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 $J \sim 55$ kA/cm$^2$ and $Q \sim 88$ 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.

Fig. 3 shows the $I$-$V$ curves measured in Sample A 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 is the shift in the I-V curve. This shift is caused by the self-heating since \( R_N \) increases with increasing \( T \) as shown in the inset to Fig. 3. This implies that the self-heating starts to be influential again even in the short pulse method on a 300 \( \mu s \) time scale.

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 \( dR_N/dT = dR_c/dT = 21 \text{ K}/\Omega \) in Sample C. At 120 K, \( R_N \) measured at \( t = 60 \text{ ns} \) increases by \( \Delta R_N \approx 1.1 \text{ } \Omega \) from \( V = 1 \text{ V} \) up to 1.3 V, and hence \( \Delta T < 25 \text{ K} \). In the case in which \( R_c = R_N \) is further assumed, \( \Delta R_N = R_N - R_c = 0.2 \text{ } \Omega \) at \( V = 1 \text{ V} \) in Sample C, as seen in Fig. 1(c), \( \Delta T \) could be estimated to be no higher than 5 K. However, the estimate for \( R_N \) in Sample C includes an uncertainty of 0.5 \( \Omega \), which implies a \( \Delta T \) uncertainty of 10 K. Consequently, in the sample with small value for \( \rho_c \), such as Sample C, the influence of self-heating is little significant in the tunneling characteristics measured at \( t = 60 \text{ ns} \).

Below \( T_c \), it is difficult to estimate \( \Delta T \) from \( \Delta R_N \) because of strong nonlinearity in I-V curves.

### B. Tunneling Characteristics

Fig. 4(a) shows the \( dI/dV - V \) characteristics measured at various \( t = 60 \text{ ns} \) at various temperatures for Sample B. In this figure, the abscissa indicates the voltage normalized by \( N \). The sharp conductance peak corresponds to the SG structure below \( T_c \). The depletion in low voltage characteristics corresponds to the pseudogap (PG) structure above \( T_c \). The flat characteristics at 140 K indicates that the PG structure disappears. This is consistent with the almost linear temperature dependence of \( \rho_c(T) \) in Sample B at 140 K [6].

The gap magnitude \( 2\Delta_{SG} \) and \( 2\Delta_{PG} \) for SG and PG, respectively, are defined from the half of the conductance peak separation. \( 2\Delta_{SG} \) for Sample B is estimated to be 50 meV at 10 K. \( 2\Delta_{PG} \) for Sample B is estimated to be 67 meV at 90 K. These values are consistent with the previous results in slightly overdoped region [8].

The temperature dependence of \( 2\Delta_{SG} \) and \( 2\Delta_{PG} \) for Sample B is exhibited in Fig. 4(b). \( 2\Delta_{SG}(T) \) decreases monotonically with the increase in temperature below 80 K in the measurement on 60 ns time scale with little influence of self-heating. This indicates that the SG closes at \( T_c \) in HTSC. \( 2\Delta_{PG}(T) \) increases with increasing temperature and remains almost unchanged above 100 K. The behavior of both \( 2\Delta_{SG}(T) \) and \( 2\Delta_{PG}(T) \) agrees with the previous results [6].

### C. Doping Dependence

Figs. 5(a)–(c) show the doping dependence of the maximum Josephson current density \( J_c \). \( T_c \), and \( 2\Delta_{SG}(10 \text{ K}) \), respectively. The value for the conductivity at 300 K of the samples, \( \sigma_c(300 \text{ K}) \) is the reference of the doping level in the samples. In Fig. 5(a), \( J_c \) increases from 0.85 to 2.1 kA/cm² with increasing doping level. This is consistent with the doping dependence of \( J_c \) in IJI’s of Bi2212 [12] and Bi₂Sr₂Ca₂Cu₃O_{10+δ} [13].
Figs. 5(b) and (c) show that both $T_c$ and $2\Delta_{SC}(10\ \text{K})$ have a tendency to decrease with increasing doping level in slightly overdoped region. $T_c$ decreases from 87.5 to 82 K and $2\Delta_{SC}(10\ \text{K})$ decreases from 62 to 37 meV. In Sample D, $T_c$ is smaller than that in Sample A by $\sim$6% and $2\Delta_{SC}(10\ \text{K})$ is smaller than that in Sample A by $\sim$34%. Thus, it is found that the value for $2\Delta_{SC}/k_B T_c$ decreases from 8.3 to 5.2 with increasing doping level in slightly overdoped region. These values are smaller than those in optimum and underdoped region [9].

REFERENCES