

Heating-compensated constant-temperature tunneling measurements on stacks of $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+x}$ intrinsic junctions

Myung-Ho Bae, Jae-Hyun Choi, and Hu-Jong Lee^{a)}

Department of Physics, Pohang University of Science and Technology, Pohang 790-784, Republic of Korea

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In highly anisotropic layered cuprates such as $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+x}$ tunneling measurements on a stack of intrinsic junctions (IJs) in a high-bias range are often susceptible to self-heating. In this study we monitored the temperature variation of a stack (“sample stack”) of IJs by measuring the resistance change of a nearby stack of IJs, which was strongly thermal coupled to the sample stack. We then adopted a proportional-integral-derivative scheme incorporated with a substrate-holder heater to compensate the temperature variation. This *in situ* temperature monitoring and controlling technique allows one to get rid of spurious tunneling effects arising from the self-heating. © 2005 American Institute of Physics. [DOI: 10.1063/1.1940731]

Since the discovery of the intrinsic Josephson effect in highly anisotropic layered $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+x}$ (Bi-2212) high- T_c single crystals,¹ tunneling characteristics along the c axis have been extensively investigated using the mesa structure prepared on the crystal surface to probe the interlayer coupling characteristics as well as the superconducting properties of the Cu-O layers themselves.² Superconducting properties of Bi-2212 crystals have also been examined using tunneling in artificial surface junctions or the scanning tunneling spectroscopy.³ In this case, however, tunneling properties are susceptible to any surface degradation. The advantage of tunneling measurements using intrinsic junctions (IJs), in comparison, is that one can eliminate the surface-dependent effect.

The poor thermal conductivity of the Bi-2212 IJs, however, is known to cause serious local self-heating in tunneling measurements, when a high-density bias current is used.^{4,5} The resulting temperature variation often causes a serious spurious effect in the tunneling signal. Much effort has been made to avoid self-heating by reducing the lateral size and the thickness of the mesa, the contact resistance, and by employing the pulsed bias method.^{2,6} *In situ* temperature measurements even with the above precautions, however, show that the self-heating still persists and can significantly distort tunneling measurements.^{7,8}

In this letter we present a scheme of making tunneling measurements in a stack of IJs at a constant temperature in any finite bias currents. Our samples consisted of two separate stacks of IJs which were closely coupled laterally by a common Au electrode [inset of Fig. 1(b)]. We monitored the temperature of the stack of interest [“sample stack” (SmS)] including self-heating, which was then compensated using the proportional-integral-derivative (PID) temperature control method with another stack of IJs [“thermometer stack” (ThS)] as a thermometer and using a substrate-holder heater.

Bi-2212 single crystals were grown by the solid-state-reaction method.⁹ In this study, two samples (SH1 and SH2) were fabricated, where the double-side cleaving of Bi-2212 crystals, micropatterning, and ion-beam etching were employed.¹⁰ Resistive transition of the two samples exhibited

that SH1 was slightly underdoped ($T_c=85.8$ K, $x=0.21$) and SH2 was almost optimally doped ($T_c=90.3$ K, $x=0.23$) (Ref. 11). The inset of Fig. 1(b) shows the sample geometry and the measurement configuration. The left and right stacks are the SmS and the ThS, respectively. The lateral dimensions of the SmS in SH1 and SH2 were 15.3×1.6 and $16.2 \times 1.6 \mu\text{m}^2$, respectively. The ThS was placed laterally 1.4 and $1.6 \mu\text{m}$ apart from the SmS for SH1 and SH2, respectively, and was thermally coupled by a 100-nm-thick common Au electrode [inset of Fig. 1(b)]. Contrary to a mesa structure, without the poorly thermal-conductive Bi-2212 basal part in this geometry, the heat generated in the SmS diffuses effectively through the highly thermal-conductive

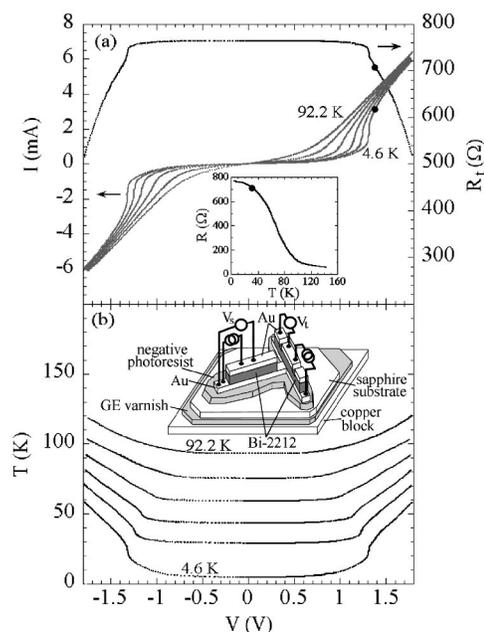


FIG. 1. (a) I - V characteristics of the sample stack (SmS) in SH1 for the substrate-holder temperature at 92.2, 75.1, 58.9, 43.5, 29.2, and 4.6 K, sequentially. The upper set of data is the resistance of the thermometer stack (ThS) at the substrate-holder temperature of 4.6 K in the bias of 0.1 mA, while the bias current of the SmS is swept. Inset: The R vs T curve of the ThS in the bias of 0.1 mA. (b) The temperature of the SmS corresponding to the I - V curves in (a) as a function of bias voltage. Inset: the sample geometry and the measurement configuration.

^{a)}Electronic mail: hjlee@postech.ac.kr

($\kappa = 100$ W/m K) bottom Au electrode, thus putting both the SmS and ThS in the thermal equilibrium at an equal temperature. The tunneling characteristics of the SmS and the ThS were measured in two- and three-terminal configurations, respectively, with the Au common ground electrode.

In our SmS, without the basal part, the temperature is almost uniformly distributed along the c axis. For instance, the SmS of SH1 (containing $N=25$ IJs) was 37.5-nm thick. According to the thermal-conduction relation, $\Delta T = j_c V t / \kappa_c$, with the top junction in the normal state in a high bias current density $j > j_c$, the temperature difference between the top and bottom of the stack is predicted to be only ~ 0.8 K. In this estimate, the c -axis critical current density of $j_c = 0.6$ kA cm $^{-2}$, the voltage per junction of $V = 30$ mV, and the c -axis thermal conductivity of $\kappa_c = 0.009$ W/m K at $T = 4.2$ K, were used.⁴ If all the junctions in the SmS are driven to the normal state the whole SmS acts as a heating element and the temperature may become more uniform.

The temperature increase in the ThS due to self-heating of the SmS reduces the quasiparticle tunneling resistance of the ThS. The inset of Fig. 1(a) shows the tunneling R versus T curve of the ThS of SH1 in the bias current of 0.1 mA, which is slightly above its tunneling critical current at 4.6 K. This R versus T curve was used to monitor the ThS temperature, while the bias current of the SmS was swept continuously. To illustrate the temperature monitoring scheme, one first notices in Fig. 1(a) that the bias current of 2.8 mA, for instance, corresponds to the voltage value of 1.3 V in the SmS as denoted by a dot on the I - V curve at 4.6 K. As illustrated with the right vertical scale, under these circumstances, the quasiparticle resistance of the ThS was reduced from 760 Ω , corresponding to $T = 4.6$ K, to 720 Ω because of the heat flow from the SmS. According to the inset of Fig. 1(a), the reduced resistance indicates that, due to self-heating, the temperature of both stacks increased from 4.6 to 30 K.

Figure 1(b) displays the variation of the actual temperature of the SmS, determined in the way described above along with the I - V curves shown in Fig. 1(a), for different biases and the substrate-holder temperatures. In principle, the bias current of 0.1 mA in the ThS may also generate self-heating. The I - V characteristics of the SmS with and without a bias current in the ThS, however, showed no noticeable difference between the two cases (data not shown). In our samples the averaged heating ratio (i.e., the temperature increase per dissipated power) was ~ 5 K/mW at 4.2 K, which was at least an order lower than the previously reported value of ~ 50 K/mW in the mesa structure.^{7,8}

Although the elimination of the basal Bi-2212 part and the strong thermal coupling through the Au ground electrode reduced the heating ratio, the self-heating was not completely eliminated. The main cause of the self-heating was the poor thermal conductivity of the gluing materials used. Negative photoresist was used to fix the Au-sandwiched Bi-2212 stack to the sapphire substrate, which in turn was attached to the copper substrate holder by GE varnish. The thermal conductivity of GE varnish, 0.08 W/m K (at $T = 10$ K), is much smaller than that of sapphire of 20 W/m K. The photoresist is expected to have even poorer thermal conductivity than GE varnish.

The PID system consisted of a manganin heater coiled around the substrate holder, where the feedback current was determined by the relation¹²

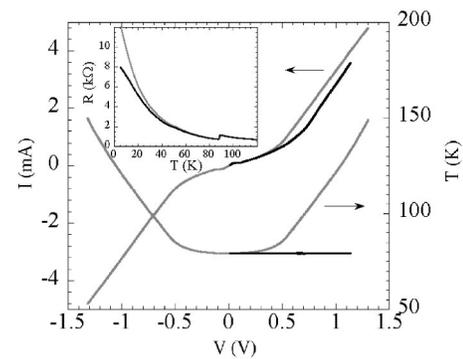


FIG. 2. (a) I - V characteristics and temperatures of the sample stack as a function of the bias voltage without (gray curves) and with (black curves; only the positive-bias data were taken) the PID temperature control scheme. Inset: The R vs T curves of the sample stack near zero bias without (gray curve) and with (black curve) the bias current of 0.28 mA in the thermometer stack.

$$I(t) = P\Delta T(t) + \frac{P}{\tau} \int_{-\infty}^t \Delta T(t') dt' + D \frac{d\Delta T(t)}{dt}. \quad (1)$$

Here, $\Delta T(t)$ is the difference between the set temperature and the actual temperature of the stacks; P is the proportional gain, τ the integration time constant, and D the time rate constant. To monitor the temperature of the SmS of SH2, using the R versus T curves of the ThS, the ThS was biased by 0.28 mA, which was slightly above the tunneling critical current of SH2. As illustrated in the inset of Fig. 2, the higher bias current in SH2 than in SH1 caused serious self-heating. The gray and black solid lines in the inset are the R versus T curves of the SmS ($I_{sample} = 0.5$ μ A) in zero current and 0.28 mA in the ThS, respectively. Using these two R versus T curves we eliminated any additional error in reading temperatures due to the bias current of 0.28 mA in SH2.

Figure 2 shows the I - V curves of SH2 without (the upper gray curve) and with (the upper black curve) adopting the PID scheme. The sweep speed of the bias in the SmS with the PID scheme was ~ 50 μ Hz, much slower than 1 MHz without the PID scheme. The lower gray and black curves in Fig. 2 illustrate the temperature variation of the SmS as a function of the voltage in the cases without and with the PID scheme, respectively. Without the PID scheme, for the substrate-holder and bath temperatures at 79 and 4.2 K, respectively, the temperature corresponding to the bias voltage of 1 V was ~ 120 K. Using the PID scheme with the parameters $P = 20$ mA/K, $\tau = 10$ s, and $D = 1.2$ s, however, the temperature of the SmS was kept fixed at 79 ± 0.4 K for all the biases used. For higher biases further decrease of the substrate-holder temperature is required to keep the SmS temperature constant, which limits the varying ranges of the bias and the substrate-holder temperature. The window of the varying ranges of the two parameters shrink for lower set temperatures of the SmS.

The lower and upper sets of data in Fig. 3 are I - V curves of the SmS and the corresponding temperatures monitored using the ThS, respectively. The 84-K curve was taken with the PID control as illustrated by the bias-independent temperature. Other curves at zero-bias temperatures below 84 K were taken without the PID scheme, for which the temperatures of the ThS increased with increasing the bias of the SmS. For any zero-bias temperatures below 84 K, when the temperature without the PID control in a finite bias reaches

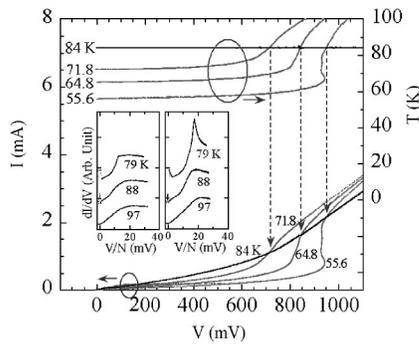


FIG. 3. The lower data set: I - V curves at 84 K with the PID temperature control and at 55.6, 64.8, and 71.8 K without the PID control. The upper data set: measured temperatures using the thermometer stack for varying bias. Inset: the dynamic tunneling conductance obtained by the lock-in technique without (left) and with (right) the PID scheme at 79, 88, and 97 K.

84 K, the corresponding I - V curve also crosses the PID-controlled 84-K I - V curve. This one-to-one correspondence between the crossing bias and the crossing thermometer temperature for different-temperature data sets indicates that the temperatures of the SmS and the ThS were identical.

The left (right) inset of Fig. 3 shows the dynamic tunneling conductance obtained by the lock-in technique without (with) the PID scheme at 79, 88, and 97 K. Here, the bias voltage values were normalized by the number of IJs, $N = 44$. Without the PID control the feature of the differential tunneling conductance is significantly smeared with reduced positions of the maximum conductance, which apparently illustrates the spurious local heating effect.

In conclusion, we devised a PID scheme to keep the temperature of stacks of IJs constant in a bias current by compensating the temperature increase of the stacks due to self-heating by lowering the substrate-holder temperature.

We demonstrated, with an example of tunneling-spectroscopic measurements, that eliminating the self-heating is essential in obtaining intrinsic tunneling properties for any finite biases in highly anisotropic layered cuprates such as Bi-2212.

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