In situ Measurement of Self-Heating in Intrinsic Tunneling Spectroscopy

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Using advanced sample engineering we performed simultaneous measurements of interlayer tunneling characteristics and *in situ* monitoring of temperature in $Bi_2Sr_2CaCu_2O_{\{8+\delta\}}$ (Bi-2212) mesas. Together with a systematic study of size dependence of interlayer tunneling, this allowed unambiguous discrimination between artifacts of self-heating and gaps in the electronic spectra of Bi-2212. Such a confident spectroscopic information, which is not affected by self-heating or surface deterioration, was obtained for the first time for a high-T_c superconductor. We also derived general expressions and formulated main principles of self-heating valid for a large variety of materials.

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Surface spectroscopy of high temperature superconductors (HTSC) experiences considerable difficulties caused by rapid chemical deterioration of the surface and a very short coherence length, due to which surface and bulk properties can differ at a scale of ~1 atomic layer. Those problems are avoided in intrinsic tunneling spectroscopy (ITS), which utilizes intrinsic Josephson junctions (IJJ's) naturally formed in highly anisotropic HTSC [1]. ITS has a superior resolution due to the superconductor-insulator-superconductor structure of IJJ's and provides a unique opportunity to probe bulk electronic properties, indispensable for understanding HTSC [2–5]. Unfortunately, ITS is liable to self-heating caused by poor thermal conductivity of HTSC [6–9]. So far reports on self-heating in ITS differ by orders of magnitude even in similar short-pulse measurements [7,9]. In view of the unique abilities of ITS, lack of consensus between different spectroscopic studies of HTSC, and recent controversy about the role of self-heating in ITS [10,11], it is important to understand to what extent ITS is affected by self-heating.

Self-heating in superconductors is practically unstudied, even though it is clear that it can be substantial due to inherently poor thermal conductivity at low T. For example, it was suspected for a long time that hysteresis in current-voltage (I-V) characteristics of overdamped Josephson junctions may indicate a substantial self-heating. However, it is still unknown to what extent self-heating affects spectroscopy of superconductors even in more conventional cases of STM, photoemission, or I-V characteristics of low-T_c junctions. Self-heating is also a growing problem for semiconducting devices often having a mesa geometry [12].

Here we present a comprehensive study of self-heating in $Bi_2Sr_2CaCu_2O_{\{8+\delta\}}$ (Bi-2212) mesa structures. Advanced sample engineering allowed simultaneous measurement of I-V characteristics and T using a small portion of the mesa, nanopatterned by focused ion beam (FIB), as an *in situ* thermometer. Together with a systematic study of size dependence of ITS, this allowed unambiguous discrimination of self-heating artifacts from gaps in the electronic spectra of Bi-2212. Such confident spectroscopic information, not affected by self-heating or surface deterioration, was obtained for the first time for a HTSC. We also formulated main principles and derived general expressions for self-heating in diffusive and ballistic cases. Both the developed experimental technique and analytic results can be used for studying self-heating in a large variety of materials.

To distinguish artifacts of self-heating we first analyze the shape of I-V characteristics, assuming that electronic density of states (DOS) is featureless, but the resistance exhibit strong dependence $R(T)$ [10]:

$$V = IR(T_0 + \Delta T). \tag{1}$$

Here $T = T_0 + \Delta T$ is the mesa temperature, which is higher than the base temperature T_0 due to self-heating. We consider a small circular mesa of radius a, containing N IJJ's, on top of a crystal of thickness t with thermal conductivities $\kappa_{ab,c}$ in the ab plane and the c axis, respectively. Heat flow has phononic and electronic channels. The latter is likely to be diffusive and allows the exact solution [6], which for $a \ll 2t\sqrt{\kappa_{ab}/\kappa_c}$ is

$$\Delta T_{\mathrm{diff}} = \frac{\pi}{4}\frac{qa}{\sqrt{\kappa_{ab}\kappa_c}}, \tag{2}$$

where q is a power density. However, phononic transport is ballistic in the c-axis direction since the phononic mean free path $l_{\mathrm{ph}} \sim 1\ \mu$m [13] is much larger than the height of the mesa, containing few atomic layers. We estimate the ballistic contribution assuming that phonons first shoot to the depth $\sim l_{\mathrm{ph}}$ below the mesa and then spread via diffusion. In this case ΔT can be estimated from Eq. 3 of Ref. [6] with $r = 0$ and $z = l_{\mathrm{ph}}$, multiplied by the fraction of heat, f, carried by phonons. The total self-heating is the sum of phononic and electronic contributions:

$$\Delta T \simeq \frac{qa}{2\sqrt{\kappa_{ab}\kappa_c}}\left(f \arctan\left[\frac{a\sqrt{\kappa_c}}{l_{\mathrm{ph}}\sqrt{\kappa_{ab}}}\right] + (1-f)\frac{\pi}{2}\right) \tag{3}$$

As expected, it coincides with Eq. (2) for $l_{\mathrm{ph}} \to 0$. A large difference in anisotropies of electric $\rho_c/\rho_{ab} \sim 10^5$ [3,14] and thermal $\kappa_{ab}/\kappa_c \sim 8$ [13] conductivities implies that c-axis heat transport in Bi-2212 is predominantly phononic, $f \simeq 1$. Then we can write a simple estimation,

$$\Delta T_{\mathrm{ball}} \simeq \frac{qa^2}{4\kappa_{ab} l_{\mathrm{ph}}}, \tag{4}$$

valid for $a < l_{\mathrm{ph}}\sqrt{\kappa_{ab}/\kappa_c}$. Here we added a factor 1/2 since only ~1/2 of the heat is going back to the mesa.

To calculate the *I-V* characteristics we solved Eqs. (1) and (2), with $\kappa = \kappa(T_0 + \Delta T)$, using typical $R(T)$ and $\kappa_{ab}(T)$ dependencies [13], shown in the inset of Fig. 1, and $\kappa_{ab}/\kappa_c = 10$. Figure 1 shows simulated $dI/dV(V)$ and $T(V)$ curves for mesas with different geometry. Humps in $dI/dV(V)$ appear for the three largest mesas. The origin of humps is easy to understand. At low T_0 heating leads to a decrease of R. The ratio V/I reaches a minimum at the crossover temperature T^*; see inset in Fig. 1. At higher bias, *I-V* characteristics start to bend backwards because $R(T)$ increases at $T > T^*$.

Even though the shape of self-heating *I-V* characteristics depends on details of $R(T)$ and $\kappa(T)$, sample geometry, and heat transport mechanisms, artifacts of self-heating in all cases can be understood from the following three principles: (1) $T - q$ curves are single valued. At a given q, mesas will be heated to higher T if started from higher T_0. (2) For mesas with the same $R(T)$, $\kappa(T)$ and T_0 self-heating features in *I-V* characteristics occur at the same T irrespective of mesa geometry. This is clearly seen in Fig. 1(b). (3) Self-heating depends on the mesa size and the number of junctions. From the second principle and Eqs. (2) and (4), hump voltages in diffusive and ballistic cases are

$$v_{\mathrm{diff}} = V/N = K_1/\sqrt{aN} \propto N^{-1/2}A^{-1/4}, \tag{5}$$

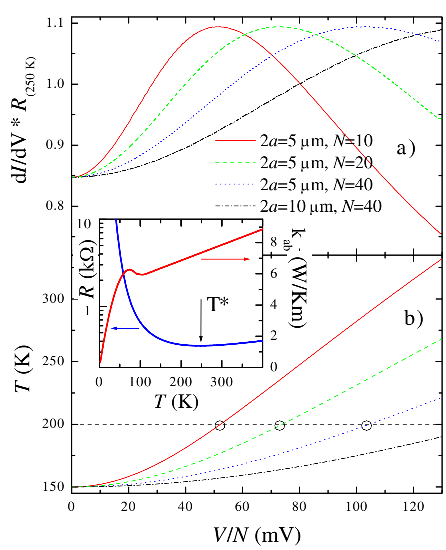

FIG. 1 (color online). Simulations for the self-heating model: (a) $dI/dV(V)$ and (b) corresponding $T(V)$ curves for four mesas with different geometry at $T_0 = 150$ K. A pronounced hump in dI/dV is seen for three largest mesas. Circles in (b) indicate positions of the humps. Irrespective of the sample geometry the hump occurs at the same $T \simeq 200$ K, even though the hump shape and voltage are different. Inset shows $R(T)$ and $\kappa(T)$ dependencies used in simulations.

$$v_{\mathrm{ball}} = V/N = K_2/\sqrt{a^2N} \propto N^{-1/2}A^{-1/2}. \tag{6}$$

Here A is the mesa area and $K_{1,2}(T_0)$ are material constants. The dependence (5) can be clearly traced from Fig. 1. This provides an unambiguous way to discriminate electronic spectra from self-heating artifacts: *Self-heating depends on the sample geometry in contrast to the electronic spectrum, which is a material property.*

So far there was no systematic size-dependent ITS study. Since self-heating depends on $R(T)$ and $\kappa(T)$, comparison should be made for mesas at the same crystal. Figure 2 shows $dI/dV(V)$ curves at $T_0 = 16.5$ K and 105 K for mesas with different area fabricated at the same optimally doped Bi-2212 single crystal, $T_c \simeq 93$ K. All mesas contained $N = 9$ IJJ's. Clearly distinguishable, a peak at $T_0 < T_c$ and a hump at $T_0 > T_c$ are seen, previously attributed to the superconducting gap (SG) and the pseudogap (PG), respectively, [3,4]. Figure 2(c) shows the peak, V_p, and the hump, V_h, voltages vs mesa area. It is seen that for small mesas V_p is independent of area, but for $A > 16\ \mu\mathrm{m}^2$, V_p becomes slightly smaller due to self-heating. This happens at $P(V_p) > 1$ mW. A stronger size dependence is seen for the hump. For $A > 10\ \mu\mathrm{m}^2$, V_h is well described by the ballistic self-heating (6), as indicated by the dashed line. However, for $A < 10\ \mu\mathrm{m}^2$, V_h also shows a tendency for saturation. Here $P(V_h) < 1.5$ mW. Note that scattering of data for small mesas is caused by flattening of the hump; see Fig. 2(b). It is not clear if the residual flat hump

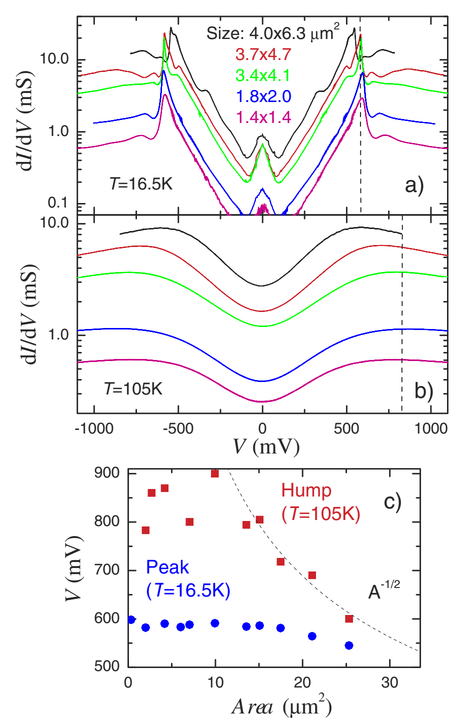

FIG. 2 (color online). Experimental characteristics at (a) $T_0 = 16.5$ K and (b) $T_0 = 105$ K for mesas with different area fabricated on the same Bi-2212 single crystal. (c) Size dependence of the peak voltage at $T_0 = 16.5$ K and the hump voltage at $T_0 = 105$ K. Dashed line shows the fit for ballistic heating.

represents the DOS, even though STM data [15] and short-pulse experiments [9], which are less prone to self-heating, would imply so. Nevertheless, for such a flat hump it is more instructive to consider the characteristic slope of the V-shape $dI/dV(V)$ at small bias, rather than V_h.

From Fig. 2 it is seen that experimental ITS characteristics retain the same V-shape and slope below the peak and the hump, irrespective of the mesa size. Such behavior is in stark contrast to self-heating artifacts shown in Fig. 1(a), for which both the slope and the voltage of the hump exhibited strong and correlated size dependence. Size independence of the shape of ITS characteristics together with saturation of peak and hump voltages at $A \to 0$ implies that those indeed represent gaps in DOS, rather than artifacts of self-heating. Such a conclusion is consistent with reported strong suppression of the peak by a magnetic field [5], which is hard to explain in terms of self-heating, since κ decreases with the field [13].

The ultimate judgment about the extent of self-heating can be made only by direct measurement of the mesa temperature. This requires fabrication of an *in situ* thermometer situated in an intimate vicinity and having good thermal coupling to the mesa, and allowing independent calibration. So far there were no measurements which would satisfy all those requirements, even though several attempts has been made [7,11]. To facilitate such measurements we developed a new method for fabrication of nanoscale multiterminal arrays of IJJ's: first a mesa was made on top of a Bi-2212 crystal by self-alignment cross-bar photolithography. Then a small portion of the initial mesa was cut using FIB. The bias current was applied through the larger mesa (the heater) and the $R(T)$ dependence of the nearby smaller mesa (the thermometer) was used for *in situ* measurement of T [7]. Typically we stopped the FIB cut within the height of the initial mesa so that both the heater and the thermometer mesas were sitting on a common pedestal—the bottom part of the initial mesa. The sketch of the sample geometry is shown in the inset of Fig. 3(a). Nanoscale separation between the heater and the thermometer mesas and small ∇T in the pedestal [6] facilitated accurate measurement of self-heating.

Figure 3(a) shows $R(T_0)$ of the thermometer for a set of dc currents through the heater mesa, I_{heat}, for an underdoped Bi-2212 crystal, $T_c \simeq 81$ K. It is seen that R decreases with I_{heat} as a result of heating. The ΔT can be obtained by subtracting T_0 vs R curves at certain I_{heat} from that without heating, $I_{\text{heat}} = 0$. Corresponding self-heating characteristics, normalized by the dissipation power are shown in Fig. 3(b). It is seen that, at low T_0, $\Delta T/P$ decreases with I_{heat}. This is due to a strong $\kappa(T)$ dependence at low T; see inset in Fig. 1. At higher $T_0 >$ 40–50 K, $\Delta T/P$ curves for different I_{heat} approach each other, indicating flattening of $\kappa(T)$ dependence.

The inset in Fig. 3(b) shows the I-V characteristics of the heater mesa at $T_0 = 5.6$ K. The actual T along the I-V characteristics is indicated. It is seen that at the end of the sum-gap knee (above the peak) the mesa is heated by

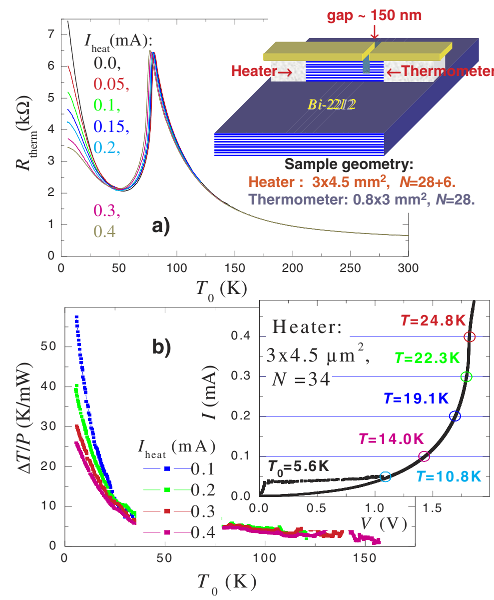

FIG. 3 (color online). (a) Thermometer mesa resistance as a function of the base temperature for several currents through the heater mesa. Inset shows the sample geometry. (b) Normalized self-heating characteristics for several heating currents. Inset shows the I-V characteristics of the heater mesa at $T_0 = 5.6$ K. The actual temperature along the I-V characteristics is indicated.

19.2 K, i.e., considerably smaller than T_c. The peak voltage is not affected by such heating [8] since the SG has a flat dependence in this T range [3].

Sample geometry used in this work is also interesting because it facilitates true four-probe measurements of IJJ's in the pedestal, removing questions about the influence of contact resistance between the mesa and the electrode and improving ITS resolution. Figure 4 shows four-probe characteristics from 90 to 302 K. Here we can clearly observe the peak just few K below $T_c \simeq 93$ K as well as some, presumably strong-coupling phonon features above the SG, which disappear at T_c. The inset in Fig. 4 shows *in situ* measured self-heating $\Delta T/P$ for this mesa, which is similar to that in Fig. 3(b) and all other measured samples. In Fig. 4 it is indicated that self-heating at the peak at $T_0 = 90$ K is small $\Delta T \sim 0.5$ K even despite a large number of IJJ's, $N = 90$ in total. Thus, the influence of self-heating on the peak vanishes at $T_0 \to T_c$ because both $\Delta T/P$ decreases with T and the power at the peak vanishes together with the SG at $T_0 \to T_c$ [3]. The realistic simulation of how self-heating affects T dependence of the SG can be found in Ref. [8].

From Fig. 4 it is seen that $dI/dV(V)$ are V-shaped at $T > T_c$ with a pronounced dip at $V = 0$. Whether or not the dip is a self-heating artifact can be understood from *in situ* T measurements, shown in inset. In Fig. 4 it is indicated that at $T_0 = 90$ K the mesa is heated to $\sim$100 K at $V = 200$ mV. On the other hand, at $T_0 =$ 100 K the self-heating free $dI/dV(V = 0) \simeq 4.0$ mS is considerably smaller than $dI/dV(V = 200\text{ mV}) \simeq$ 14.8 mS. Therefore, self-heating is insufficient to explain

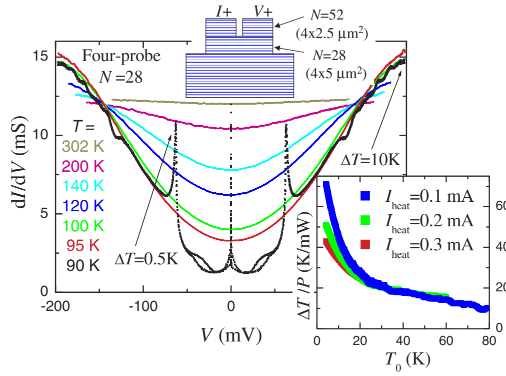

FIG. 4 (color online). Four-probe ITS characteristics at T_0 slightly below and above $T_c \simeq 93$ K. Sample geometry is shown in the top inset. Bottom inset shows *in situ* measured self-heating.

such a large increase of conductance from $V = 0$ to 200 mV and the V-shape characteristics must be attributed to the PG in DOS.

Now we can reanalyze one of the most important results of previous ITS studies, evidence for coexistence of the SG and the PG [3–5], which favors different origins of the two gaps. When the peak and the hump are observed simultaneously, the hump occurs at larger V and, therefore, at higher T than the peak. From Fig. 2 it is seen that for large mesas the hump is affected by self-heating and is exaggerated due to progressive back-bending of $dI/dV(V)$ at large V. In most of the previous ITS experiments dealing with larger mesas, humps were affected by self-heating. This is particularly true for the Bi-2201 [11], which has a similar $\Delta T/P$ as Bi-2212, but considerably lower T_c and, thus, more prone to self-heating. So, does the PG exists at $T < T_c$? The answer can be obtained from Fig. 4. It is seen that the $dI/dV(V)$ curve at $T_0 = 90$ K acquires the characteristic V-shape right after the peak, where self-heating is still small. Thus, the PG does coexist with superconductivity at $T < T_c$. Such a conclusion is also supported by observation of the V-shape PG characteristics at $T < T_c$ in magnetic fields $H > H_{c2}$ [5] and in the vortex core [15].

In summary, we performed a comprehensive analysis of self-heating in Bi-2212 mesas, which allowed unambiguous discrimination of gaps in electronic spectra from artifacts of self-heating. This was achieved via systematic size-dependent study and *in situ* measurement of self-heating using a nanopatterned part of the mesa as the *in situ* thermometer. We observed that for small mesas both shapes and voltages of the peak and the hump (or rather V-shaped suppression of conductance at $V = 0$) are independent of the mesa size and appear at T considerably smaller than T_c and T^*, respectively. Therefore, they are not due to self-heating [10], but represent the superconducting gap and the normal state pseudogap in electronic DOS, respectively. Such a confident spectroscopic information for a HTSC not affected by self-heating or surface deterioration was obtained here for the first time. On the other hand, ITS characteristics of larger mesas can be strongly affected by self-heating. The reported threshold mesa size and dissipation power, at which self-heating becomes insignificant, as well as the measured values of self-heating $\Delta T/P$, are typical for our mesas, but not universal. They depend on the sample geometry, materials, and experimental setup. Thus, it is important to carefully design samples for ITS: decrease mesa sizes, the number of junctions, avoid suspended structures, and, in particular, employ the top heat spreading layer, which is the most important heat sinking channel in mesas [6,12].

Finally we want to note that derived expressions and formulated principles of self-heating are general and valid for any material. Similarly, the developed experimental method, in which a small portion of the sample is used as the *in situ* detector, can be used for analysis of self-heating in a large variety of materials. The only requirement is that the resistance of material or the contact between electrode and material should have considerable T dependence, while a layered structure and HTSC is not essential. For example, our method can be directly applied for studying self-heating in small mesalike semiconducting transistors [12].

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