Comment on "Counterintuitive consequence of heating in strongly-driven intrinsic junctions of $Bi_2Sr_2CaCu_2O_{8+\delta}$ mesas"

V. M. Krasnov
Department of Physics, Stockholm University, AlbaNova University Center, SE-10691 Stockholm, Sweden
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In a recent paper, Kurter *et al.* [Phys. Rev. B **81**, 224518 (2010)] analyzed self-heating in strongly-driven $Bi_2Sr_2CaCu_2O_{8+\delta}$ mesa structures. They attributed observed peaks in conductance to heating of mesas up to the superconducting critical temperature T_c, extrapolated this statement to much smaller mesas, used in intrinsic tunneling spectroscopy (ITS), and called for reinterpretation of ITS data. They also suggested a universal figure of merit for the shape of tunneling characteristics. Here, I argue that the peak in c-axis conductance usually occurs well below T_c; that for small ITS mesas, it represents the superconducting gap; and that the genuine shape of tunneling characteristics for cuprates is not universal but depends on doping, uniformity, and geometry.

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I. INTRODUCTION

Self-heating in intrinsic tunneling spectroscopy (ITS) has actively been discussed for more than a decade because ITS appeared as a result of active obviation of self-heating.[1–8] Self-heating in mesa structures is well studied, primarily in microelectronics. It depends on materials parameters, temperature, bias, and geometry.[2,4] Size dependence allows unambiguous discrimination between heating and spectroscopic features.[4,7] This is the subject of this paper.[1] Unlike previous ITS studies, which were focused on small micrometer-to-submicrometer mesas,[4,5,7,9] Kurter *et al.* considered larger 10-μm mesas. Their main conclusion was: "... That the sharp peaks occur at fixed heating power per junction and the conductance data show no dip/hump features allow us to conclude directly, and unambiguously, that such peaks represent the transition of the mesa into the normal state." Here, I argue that their conclusions, based on numerical simulations, are not reliable; the peak in ITS characteristics of small mesas is not connected with T_c but represents the superconducting gap Δ and that tunneling characteristics of cuprates are not universal.

II. SELF-HEATING IN LOW- AND HIGH-T_c JUNCTIONS

To call to mind how self-heating affects current-voltage (I-V) characteristics of superconducting tunnel junctions, in Fig. 1(a), we show normalized I-V's of $Nb/AlAlO_x/Nb$ junctions with different sizes. Progressive backbending of the sum-gap knee develops with increasing junction area. Figure 1(b) shows sum-gap peaks at $V_p = 2\Delta/e$. They become infinitely sharp for the two largest junctions. The dip at $V > V_p$ is due to the proximity effect in Al.[10] It is also affected and becomes narrower and *deeper* as a result of self-heating. At larger bias, I-V's reach Ohmic T-independent tunnel resistance R_n.[11]

From Fig. 1, it is clear that, even though self-heating (infinitely) distorts the sum-gap peak, it practically does not affect the spectroscopic resolution because V_p is reduced only marginally, as seen from the inset of Fig. 1(a). A similar conclusion follows from numerical simulations for ITS on $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi-2212), taking into account the actual T and I dependencies of thermal resistance, for self-heating up to $\delta T \sim T_c/2$ at the peak (see Fig. 2 in Ref. 3). The robustness of spectroscopy with respect to self-heating is mainly due to flat $\Delta(T)$ at low T.[3,7]

The Ohmic behavior at $V > V_p$ is not due to heating above T_c but is the signature of tunneling characteristics. Because R_n is T independent, the eventual transition through T_c would be featureless and would not show up as a peak in dI/dV. Similarly, there is much direct experimental evidence that the dI/dV peak in Bi-2212 mesas is not connected with T_c:

(i) In large mesas, hysteretic quasiparticle (QP) branches are still present in the backbending region of I-V with infinite and negative dI/dV (see Fig. 1 in Ref. 6 and Fig. S2 in the supplement to Ref. 12), indicating that mesas remain well below T_c.

(ii) Electromagnetic wave emission, caused by the ac-Josephson effect, was observed not only at the onset of backbending ($IV \simeq 10$ mW) but also in the whole backbending region up to 25 mW (see Fig. 2 in Ref. 12).

(iii) Direct measurement of mesa temperatures showed that small ITS mesas remain well below T_c at the peak.[4] Recently, this was confirmed by intrinsic detection of T_m.[6,7] In this case, T-dependent characteristics of the mesa itself were used for determination of T_m, avoiding a possible lag between the mesa and the thermometer.

For small mesas, used in ITS, there is much evidence that the peak not only occurs well below T_c, but also represents the sum-gap singularity.

(iv) Clear evidence comes from observation of large magnetoresistance (which is the signature of superconductivity and disappears at $T > T_c$) not only at the peak, but also at the bias well above the peak.[8,11,13–15]

(v) Additional superconducting dips are observed at twice the peak voltage[7,16] and several times the power [see also Figs. 2(b) and 2(c) below].

(vi) Evolution of the peak with increasing self-heating in moderately large mesas is consistent with the sum-gap origin of the peak.[7]

(vii) Size independence of the peak voltage in small mesas was proven.[4,5]

(viii) Strong phonon resonances were observed up to the sharp peak, indicating the presence of the sum-gap Riedel singularity of the supercurrent.[17]

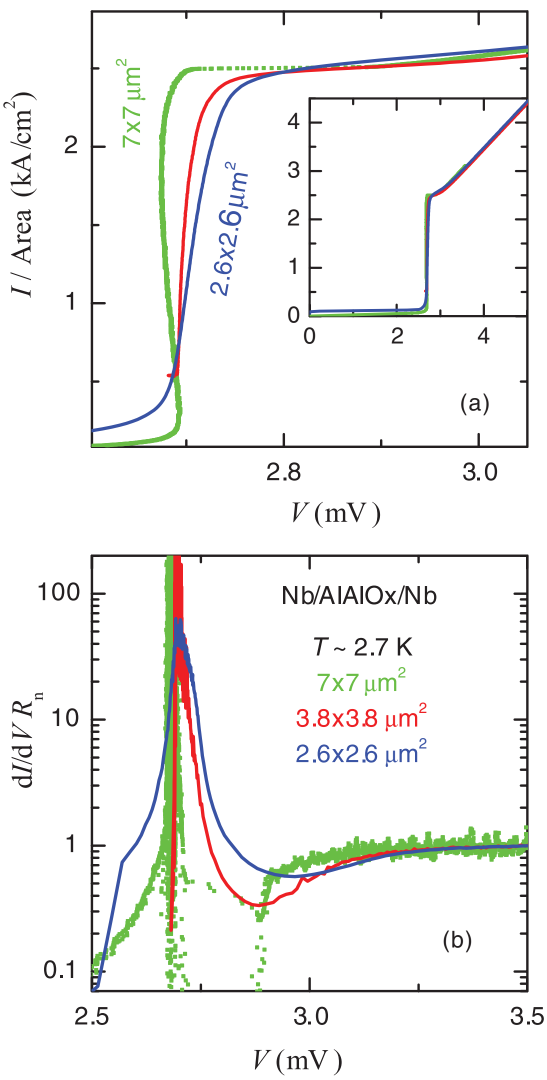

FIG. 1. (Color online) (a) Current density versus V curves for the Nb junctions with different sizes. The main panel shows development of backbending at the sum-gap knee as a result of self-heating in larger junctions. Full-scale I-V curves are shown in the inset. (b) Normalized $dI/dV(V)$ curves for the same junctions. The sum-gap peak becomes infinitely sharp for the two largest junctions, but the peak voltages are affected only marginally. The dip behind the peak is due to the proximity effect in Al. It becomes narrower and *deeper* as a result of self-heating.

III. SELF-HEATING IN LARGE BI-2212 MESAS

To support their conclusions, the authors perform numerical simulations (Figs. 5–7). The main parameter of simulations is the thermal resistance α, which depends on cooling conditions, mesa geometry,[2] heat-transport mechanism, T, and I.[4,7] Meaningful simulations require the knowledge of $\alpha(T,I)$ for studied 10×10-μm^2 intercalated mesas with a top mechanical contact 0.5 μm in diameter. Instead, the authors assumed a constant $\alpha = 70$ K/mW, obtained indirectly from ITS data on much smaller micrometer-size pure Bi-2212 mesas.[5]

To estimate α for similar size mesas as in Ref. 1, in Fig. 2(a), we show I-V's for Bi(Y)-2212 mesas $\sim 12 \times 17$ μm^2 with $N = 6$ junctions at $T = 4.2$ K. At point A, current exceeds the in-plane critical current of one CuO plane. This leads to switching of an additional junction just beneath the mesa.[18] Large mesas are prone to such instability because of a small perimeter-to-area ratio.[7] With a further increase in I, more bulk junctions switch into the resistive state. The QP branches of those junctions are hysteretic, and the spacing between them remains large at point B with $P = 13.7$ mW, implying that $T \lesssim T_c/2$.[6] At larger bias, the separation between branches decreases but is still visible at point C with $P = 33.5$ mW, implying that the structure is still below T_c. The corresponding $\alpha \sim 2.5$ K/mW is $\sim$30 times less than the value adopted in Ref. 1 (comparison is justified because of the same ascribed $T \sim T_c$). This raises questions about reliability of conclusions based on such simulations. Already, a factor 2 error in α would considerably change the conclusions.[3]

Large junctions may also exhibit a hot-spot instability in which a part of the junction is heated above T_c.[19] Nonuniform bias through a point contact in Ref. 1 may create hot spots in their mesas. On the contrary, small mesas with uniform bias and power distribution do not develop significant lateral T gradients due to the boundary condition $\partial T/\partial x = 0$ at the edge of the mesa (no heat flow through the sidewalls).[2] Typically, hot-spot formation leads to acute backbending, clearly distinct from tunneling I-V's [see curves (a) and (b) in Fig. 1 of Ref. 1]. Both types of instabilities prevent the spectroscopic analysis on large junctions and, therefore, do not allow explicit comparison with smaller junctions, which do not exhibit those instabilities.

IV. SELF-HEATING IN SMALL ITS MESAS

The authors of Ref. 1 ask for reinterpretation of ITS data. To facilitate an objective evaluation of the situation by the community, it is indeed instructive to reanalyze previous ITS results. Figure 2(b) shows $dI/dV(V)$ for a moderate size, 4×5 μm^2, underdoped mesa, $T_c \simeq 84.5$ K, with $N = 8$ junctions.[20] Comparison of curves at low T with that at $T = 84.1$ K $\simeq T_c$ indicates the appearance of the familiar peak-dip-hump structure in the superconducting state. A minor dip at $V \sim 2V_p$ also is seen. It was attributed to additional depairing at $V > 4\Delta/e$ due to reabsorption of nonequilibrium bosons.[21] The dip scales with the peak as a function of T (Ref. 16), and both are suppressed by the magnetic field.

Figure 2(c) shows $dI/dV(V)$ for a smaller 1.8×2 μm^2 near the optimally doped ($T_c \simeq 92$ K) mesa, containing $N = 9$ junctions.[7] Comparison with the normal-state curve at $T = 95$ K demonstrates a perfect-state conservation in dI/dV (30 K) $- dI/dV$ (95 K), as discussed in Ref. 11. Two minor superconducting features at higher bias are also seen: a small maximum at $V \simeq 0.8$ V and a double-gap dip at $V \simeq 2V_p$. Thermal properties of those mesas were summarized in Ref. 7.

Common, for the ITS data from Figs. 2(b) and 2(c), is the presence of superconducting double-gap dip at powers five and seven times larger than that at the peak. This unambiguously shows that the mesas are not heated to T_c at the peak. Both mesas exhibit large $\Delta \simeq 43$ and 34 meV, respectively, consistent with other reports and twice that in the criticized paper. This clearly indicates that the extracted gap values for small mesas are close to equilibrium, i.e., not affected by

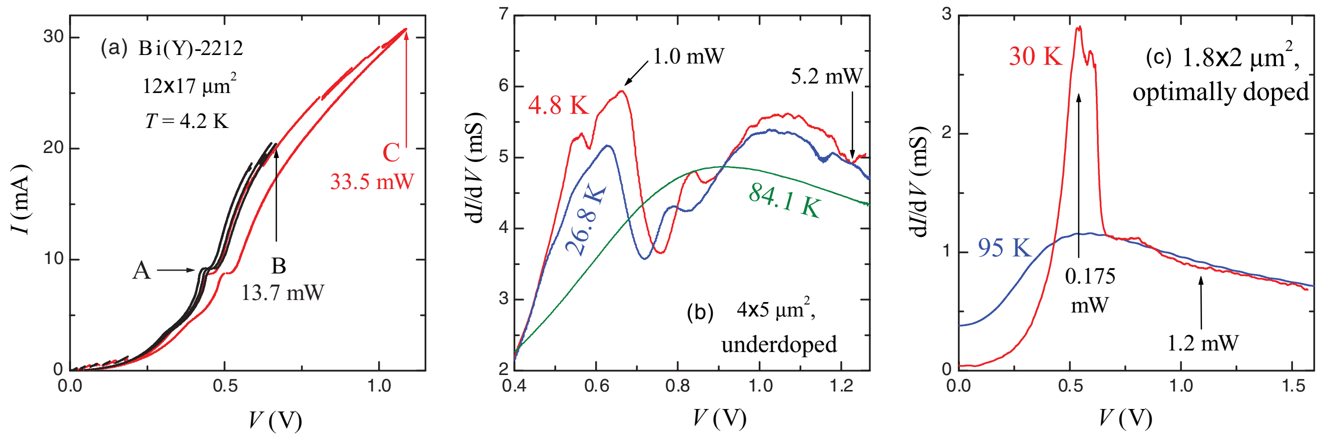

FIG. 2. (Color online) c-axis characteristics of Bi(Y)-2212 mesas of different sizes. (a) I-V's of large slightly overdoped mesas. Small perimeter-to-area ratio in large mesas leads to switching of additional bulk junctions beneath the mesa (point A). Hysteretic quasiparticle branches are visible up to $P = 33.5$ mW (point C). (b) $dI/dV(V)$ for a moderate-size underdoped mesa (data from Ref. 20), and (c) for a small optimally doped mesa at low T and close to T_c (data from Ref. 7). Powers at the sum-gap peak and the double-gap dip are noted. It is seen that the mesas remain superconducting, at least, up to the dip, corresponding to dissipation powers several times that at the peak.

self-heating and that interpretation of ITS peaks as sum-gap singularities withstands the scrutiny.

V. CORRECT SHAPE OF TUNNELING CHARACTERISTICS

The authors suggested a universal figure of merit for tunneling characteristics: Correct spectra should look like their mechanical contact (MCT) characteristics, i.e., have a nonsharp peak followed by a pronounced dip. In support, they claim that there is excellent agreement among MCT, scanning tunneling spectroscopy (STS), and angle-resolved photoemission (ARPES) spectroscopy with no significant discrepancies. However, discrepancies are noticeable both concerning T and concerning doping dependencies of the superconducting gap and the pseudogap.[7,22]

The authors put much weight on the claimed excessive sharpness of peaks and the lack of peak-dip-hump structure in ITS. This is confusing because the relative height $dI/dV(V_p)R_n$ of their MCT peaks[23] is similar to $\sim$4.5 from early ITS studies on moderate-size mesas.[24] The peaks in Figs. 2(b) and 2(c) are, in fact, *lower* than their peaks. Similarly, practically all ITS studies were discussing the pseudogap hump above the peak. This is only possible if there is a dip between them. From Figs. 2(b) and 2(c), it is clear that the appearance of the dip at low T does not depend on heating but on doping.[20] For optimal and slightly overdoped Bi-2212, the dip is seen only at elevated T, but for underdoped Bi-2212, it is observed at low T as well.

A useful insight into the influence of self-heating on the spectroscopic peak-dip structure is obtained from analysis of Nb/AlAlO$_x$/Nb data from Fig. 1(b). It is seen that self-heating exaggerates both the peak and the dip. This is the fundamental consequence of state conservation,[11] due to which R_n is T independent. Because of that, at large bias, $I = \int_0^V (\partial I/\partial V) dV = V/R_n$ is independent of heating, meaning that the higher peak must be compensated by the correspondingly deeper dip so that the total integral remains constant. Therefore, simultaneous lowering of the peak and deepening of the dip in very small mesas[5,23] is more consistent with progressive underdoping due to oxygen out-diffusion or surface passivation in small mesas with a large surface-to-volume ratio, rather than with trivial self-heating.

Observation of MCT-like spectra does not automatically mean that they are free from artifacts. Although the dips in spectra are commonly observed in cuprates, they are typically less pronounced[17,25–27] than those reported by MCT.[28] Intrinsic tunneling is one of the few techniques that could reproduce similar extraordinary large dips.[23,29] However, the "correct" behavior in that case is *an artifact* of switching of bulk junctions below the mesa, as in Fig. 2(a). The corresponding jump in I-V (point A) may even lead to a negative dI/dV, provided the measurement setup has a negative load line. Furthermore, not only one, but multiple dips could be observed due to consecutive switching of several bulk junctions,[18,30] just as in Fig. 2(a). The corresponding small sub-branches, in fact, can be seen in the dip region (Fig. 3 of Ref. 29 at $V \sim 800$ mV). Splitting of the dip in MCT also has been reported.[31]

Tunneling in cuprates crucially depends on QP momentum due to the d-wave symmetry of Δ,[32] strong momentum dependence of the tunneling matrix,[33] and on coherence (momentum conservation) of tunneling.[32,34] There are substantial variations in tunneling geometries for different spectroscopic techniques: For STS, this is [CuO/BiO-vacuum-normal metal] surface c-axis tunneling; for MCT, this is [CuO/BiO-vacuum-BiO/CuO] surface tunneling in an unknown direction; and for ITS, this is [CuO-BiO-CuO] c-axis tunneling in a bulk single crystal. Variation in electronic structure and doping level at the surface [CuO/BiO vacuum] may cause differences between surface and bulk characteristics.[7] Therefore, any universal shape for all tunneling characteristics, irrespective of experimental details, should not be expected. The lack of universality is reflected in a variety of characteristics reported in point contacts and break junctions on cuprates.[17,26,27,31]

Theoretically, very sharp sum-gap peaks are expected in the case of coherent QP tunneling.[34] This is supported by observation of large $I_c R_n \sim \Delta/e$ both in ITS (Ref. 20) and in MCT junctions.[28] For d-wave superconductors, this is only possible in the case of coherent tunneling.[32] Furthermore, it is known that the sharpness of QP peaks is crucially dependent on doping. From ITS and ARPES data, it follows that the peak is intrinsically sharp in overdoped Bi-2212 and rapidly loses sharpness with underdoping,[20] as seen from Fig. 2(b).

VI. CONCLUSION

To conclude, self-heating is *always present* in transport measurements; the main question is in its magnitude. The ITS technique is not neglecting self-heating[23] but quantifies it and utilizes methods for reduction[2–5,7–9] or compensation[7,14] of self-heating. For small enough mesas, used in recent ITS studies, the peak in dI/dV represents the superconducting gap. This conclusion was cross-checked in many ways as described above and does not need reinterpretation.[11]

The genuine shape of dI/dV characteristics remains an unsettled issue because the sharpness of the sum-gap peak can indeed be enhanced by self-heating, as shown in Fig. 1(b), or can be reduced by inhomogeneity of junctions.[3] In any case, it does strongly depend on doping and the tunneling geometry. Therefore, any universal shape for all types of cuprate tunnel junctions is not to be expected. More systematic studies on small mesas, that take all those factors into consideration, are needed.

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