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

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The main criticism raised in the preceding Comment concerns our suggestion that sharp conduction peaks in $Bi_2Sr_2CaCu_2O_{8+\delta}$ mesas, along with absent dip-hump features, may, in general, be a result of self-heating. The author points to the variety of experimental configurations, matrix-element effects, and doping dependencies that might allow a diversity of conductance spectra. We argue that numerous mesa studies (with fixed matrix elements) firmly establish the systematic development of sharp conductance peaks with increased self-heating, and thus, the issue of nonuniversality of tunneling characteristics is not relevant. The author mentions a number of studies that show that the mesa is superconducting near the conductance peak voltage. This is not in dispute and indicates a misinterpretation of our analysis that is clarified here. To address further comments on the technical details of our heating model, we reiterate that our conclusions are independent of our model but rather are based solely on experimental data that are not in dispute.

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I. INTRODUCTION

We first summarize the conclusions and observations in our paper[1] and the relation of the Comment[2] to them. We then address the points raised in the Comment and their relation to our paper.

In Ref. 1, we experimentally demonstrated the evolution in the shape of the conductance spectra of intercalated $Bi_2Sr_2CaCu_2O_y$ (Bi2212) mesas with the degree of self-heating. Our shortest mesa with six junctions had minimal self-heating and exhibited a relatively broad conductance peak and a pronounced dip-hump feature (DHF), quite similar to spectra found by us in break junctions resulting from mechanical contact tunneling (MCT) on similar crystals. As self-heating increased, with an increasing number of junctions N, the conductance peaks shifted to lower voltages, sharpened abruptly, and grew in height while the DHF disappeared. We were able to show, based on the experimental data alone, that the sharp peaks found for larger self-heating no longer measured the superconducting gap. The absent DHF indicated the entire mesa had entered the normal state at (or below) the voltage where this feature normally would be seen. It was clearly stated that all these conclusions were based purely on experimental data, and none of these are disputed in the preceding Comment.[2]

Independent of these conclusions, we presented numerical simulations to show: (a) that *uniform* heating could not explain sharp peaks since, in our experiments, the peaks move to a lower voltage with greater self-heating rather than exhibit backbending (Fig. 5 of Ref. 1); and (b) that a model, based on a thermal gradient across the mesa, might plausibly explain such an N independence of our peak's shift and sharpness (Fig. 6 of Ref. 1). But any approximations or inadequacies of our models cannot tarnish our experimentally derived conclusions. In regard to (b), note that an inhomogeneous temperature profile is surely stable. The extremely high normal-state anisotropy of Bi2212 guarantees a uniform voltage across the entire mesa so local regions with higher temperatures will carry more current and, thus, will dissipate more heat [Fig. 5(a) of Ref. 1]. Furthermore, because of its inherent stability, the initiation of a thermal gradient may require only slightly nonuniform cooling across the mesa area. In other words, it might be commonly expected (e.g., see Ref. 3).

Finally, in Sec. VI of Ref. 1, we observed: "The extreme difficulty of eliminating heating may imply the need to reinterpret some recent IJJ studies that generally exhibit small or nonexistent DHF in dI/dV and β values of 0.03–0.15." This implication, that self-heating may be more general and may apply to all mesa data displaying high sharp conductance peaks and absent DHF, is the focus of the Comment. At this point, it is necessary to clarify an ambiguity in the opening sentence of our abstract:[1] "Anomalously high and sharp peaks in the conductance of intrinsic Josephson junctions in $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi2212) mesas commonly have been interpreted as superconducting energy gaps, but here, we show they are a result of strong self-heating." Although we intended "they" to refer to "Anomalously high and sharp peaks in the conductance," it is ambiguous, and one could conclude that "they" referred to all existing literature interpreting these sharp peaks as the superconducting energy gap. Whether the latter is true or not is beyond the scope of our paper; however, as that latter interpretation was not our intention, this present clarification is needed. Evidence, it was not our intention, is found in the phrase "may imply the need to reinterpret" in the above summary sentence. That sentence in our summary[1] expresses an idea that any practitioner in this field would formulate given our empirical results and the intrinsic tunneling spectroscopy (ITS) studies referred to in Ref. 2. The Comment text agrees with this, stating, "*To facilitate 'an objective evaluation of the situation by the community,' it is indeed instructive to reanalyze previous ITS results.*" Thus, the Comment[2] and this Reply are the beginning of a reanalysis and possible reinterpretation of previous ITS data that display high sharp peaks and no DHF.

We now address points raised in the Comment regarding: (1) matrix-element and (2) doping effects on the shape of tunneling data, (3) the mesa temperature at the peak of conductance, and (4) three sets of new data in Figs. 1, 2(a), and 2(c) of the Comment. We will show that point (1) is irrelevant to comparative mesa studies. Although point (2) will not affect our data in Ref. 1, we comment on it below. Point (3) results from a misconception of our model that is clarified here. With regard to point (4), Figs. 1 and 2(a) are consistent with our models, and Fig. 2(c) shows consistency with our experimental conclusions. It is unclear how Fig. 2(b), which is unlike any mesa data we have seen in the literature, can affect the issues at hand, so we make no comment.

II. UNIVERSALITY OF TUNNELING IN CUPRATES

Several statements address the shape of the tunneling characteristics (points 1 and 2 above). The first is "*The genuine shape of tunneling characteristics for cuprates is not universal but depends on doping, uniformity, and geometry.*" The Comment author correctly states that the shape of the tunneling characteristic, e.g., due to momentum selectivity, is not universal for the various spectroscopy *methods* used. However, in the present context, it is only necessary to point out that the momentum selectivity of the tunneling matrix element cannot vary from one mesa to another. Thus, matrix-element effects cannot explain the evolution from broad peaks with DHF for small mesas to the absence of a DHF and the development of sharp peaks in large mesas. In other words, the variations, with power dissipation, of the width of the conductance peak and the appearance of the dip (e.g., our data for $N = 6$ compared to $N > 12$) cannot be a result of momentum selectivity. Similarly, the independent mesa studies of Zhu *et al.*[4] and Benseman *et al.*[5] show a strong consistent evolution as a function of self-heating that agrees with our paper.[1] Thus, three other independent groups,[2,4,5] including new data in Fig. 2(c) of the Comment, have reproduced our experimental data on which our conclusion was based. These four results do show that the gradual disappearance of DHF and the development of sharp peaks are empirically consistent with self-heating. There is also a clear doping dependence of the tunneling characteristics, work that our group has pioneered using MCT over the past 20 years (see Ref. 6 and references therein). For all doping from heavily underdoped ($\Delta \sim 70$ meV) to heavily overdoped ($\Delta \sim 10$ meV) Bi2212, none of our MCT data bears any resemblance to the sharp peaks reported in mesa studies with $\beta < 0.15$. Also, our results on intercalated Bi2212 are unaffected, as T_c and doping are the same for all these mesas.

The second statement ascribes to us that the *"correct" spectra should look like their mechanical contact (MCT) characteristics. . . .*" The statement in Ref. 1 was "Our shortest mesa ($N = 6$) exhibits the least heating and most closely resembles the superconductor-insulator-superconductor (SIS) junction from MCT, with a relatively broader conductance peak as well as dip/hump features." There are small differences, but the relative width of the peak and the dip remain robust features. Both measurements are for *c*-axis tunneling, but heating in the MCT data is significantly reduced. We tacitly assume that there exists an electronic density of states in Bi2212, which is probed by tunneling and reflects the interactions that are responsible for superconductivity. Most of the *c*-axis tunneling spectroscopy studies, in which heating is minimal [e.g., scanning tunneling spectroscopy (STS) Ref. 7, MCT (Ref. 6), and even some intrinsic junctions],[1,2,4,5,8] reveal a DHF consistent with electronic self-energy effects observed in angle-resolved photoemission (ARPES) Ref. 9 and optical conductivity.[10] This feature is found for all doping from heavily underdoped ($\Delta \sim 70$ meV) to heavily overdoped ($\Delta \sim 10$ meV) Bi2212. Thus, while the word universal is too strong to describe Bi2212 tunneling, the remarkable similarity among STS, MCT, and mesas with minimal heating cannot be ignored. It is for this reason that the absence of a DHF in many mesa studies, along with sharp peaks, leads us to speculate that self-heating is still a problem. It is not a proof, but rather an indication.

The final statement on tunneling characteristics is that "*the authors suggested a universal 'figure of merit' for tunneling characteristics*." Our measure of sharpness of a peak, β, is traditional and consistent with other spectroscopy methods. We used the full width at half maximum divided by the centroid voltage as a figure of merit and plotted its empirical dependence on self-heating. For example, it might vary with the momentum selectivity in other tunneling or spectroscopy methods, but we found no evidence for very sharp peaks ($\beta < 0.15$) for any spectroscopy with demonstrated minimal self-heating.

III. CONDUCTANCE PEAK AND MESA TEMPERATURE

Next, we address point (3), the mesa temperature at the peak of conductance. The Comment states: "*Similarly, there is much direct experimental evidence that the dI/dV peak in Bi-2212 mesas is not connected with T_c. . . .*" This implied criticism is based on a misconception—that, in our analysis, the *peak value of conductance dI/dV* represented "heating of mesas up to the superconducting critical temperature T_c." First, such an assumption would contradict our $N = 6$ mesa data that exhibit a residual DHF, which is an unmistakable indication of superconductivity, so the entire mesa area does not reach T_c even at the *end* of the peak. Second, our thermal gradient analysis places no special emphasis on the peak value of conductance. Here, we clarify that, when we used the term "conductance peak," we meant the entire feature that has a beginning, its highest point, and an end. Our use of the terms "sharp" and "broad" only has meaning for the entire peak feature, not simply the voltage of the conductance maximum.

Furthermore, there must be some superconductivity in the mesa throughout the peak, since otherwise one would only measure the smaller normal-state conductance. In modeling our sharp conductance peaks where self-heating is strong, we suggest the fraction of the mesa area in the normal state ($T > T_c$) grows from the beginning to the end of the peak feature, as the dissipation (voltage times current) increases. Here, it is instructive to look at the current-voltage curve $I(V)$—[e.g., see Figs. 1(c) and 3 of Ref. 1 the rapid increase in I with increasing V tracks the increase in the fractional normal area of the mesa and, clearly, the peak in dI/dV, somewhere in the middle, has no special meaning. Furthermore, any occurrence of a dip beyond the end of the conductance-peak feature demonstrates that the mesa is not entirely normal at that voltage (our $N = 6$ and $N = 12$ mesas). For our mesas with $N > 12$, there is no evidence of a dip, and thus, one can conclude that the entire mesa has reached the normal state for the voltage at the *end* of the peak feature since then the conductance joins the universal normal-state conductance found for all our mesas (see Fig. 2 of Ref. 1).

In this regard, the Comment also presents evidence from the literature [items (i)–(viii)] that the conductance maximum does not correspond to the entire mesa being at T_c. We reiterate that we agree: This contention is a strict necessary feature of our thermal gradient model. Nevertheless, we comment on some of these references. Josephson switching events (i), as well as phenomena tied to the ac-Josephson effect [e.g., electromagnetic wave emission (ii) and phonon resonances (viii)], merely require that a superconducting state still exists somewhere in a mesa under self-heating conditions. The observation of such effects near the conductance maximum in no way contradicts our interpretation and, thus, is not proof that the conductance peak is itself a measure of the superconducting gap. For item (iii) in the Comment, we argue that a second adjacent mesa is a poor thermometer to probe a primary mesa under high-power conditions (see Ref. 11 for details). The best measure of the degree of self-heating of a mesa is its own $I(V)$.

With regard to (v), the peculiar multiple structures beyond the conductance peaks in Fig. 2(b) of the Comment do not resemble the dip features others and we have seen and have discussed. On the other hand, the small-area mesa in Fig. 2(c) displays a broader conductance peak, and the slight dip near 700 mV may represent an emerging DHF of the type discussed here and in our paper.[1] The evolution with heating that we reported in Ref. 1 was also seen by Zhu *et al.*[4] with unintercalated Bi2212 mesas. Their mesas with areas $\leqslant 1$ μm^2 have minimal heating, and the conductance peak becomes relatively broad with a pronounced DHF.[4] Benseman *et al.*[5] have recently reproduced the results of Ref. 4. The new data of Fig. 2(c) on a smaller area mesa also mimic the evolution others and we have reported and, therefore, with regard to points (vi) and (vii), we would suggest that, if Krasnov's mesas were reduced further (to ~ 1 μm^2), he would start to see a well-developed DHF, similar to that found in Refs. 4 and 5.

IV. NEW DATA IN THE COMMENT

We now address the new data in the Comment starting with the niobium tunneling data of Fig. 1. These data implicitly suggest that the sharp peak could be found near the equilibrium $2\Delta_{\text{eq}}$ due to moderate uniform heating and the temperature dependence of Δ_{eq}. However, here, we point out that, at low reduced temperature, there is negligible current (and dissipation) in junctions of s-wave superconductors, such as Nb until pair breaking occurs at $V \sim 2\Delta_{\text{eq}}$, where Δ_{eq} is the gap value without self-heating. Thus, the initial upturn in I at $V \sim 2\Delta_{\text{eq}}$ is little affected by heating at the lowest bath temperatures. In a d-wave superconductor, the nodal quasiparticles cause dissipation starting at $V = 0$ for all temperatures so that heating can reduce Δ long before V reaches $\sim 2\Delta_{\text{eq}}$. Thus, these Nb data cannot predict what will happen in d-wave high-T_c superconductors.

Furthermore, these Nb data replicate the results of our numerical simulation of Fig. 5 of Ref. 1 that was presented to show that *uniform* heating could not explain sharp peaks in dI/dV since, with greater heating in our experiments, the peaks move to a lower voltage rather than exhibit backbending. A sharp peak would only occur for a special value of uniform self-heating and for slightly greater self-heating, backbending must be seen (as in Fig. 1 of the Comment). That such sharp peaks would be rare, indeed, precludes *uniform* self-heating from explaining the wealth of mesa data in the literature, including ours, that show sharp peaks but no cases of backbending.

Next, we consider Fig. 2(a) in which the Comment author quotes a small value of α (2.5 K/mW) from his data. Of course, the important point is the temperature rise. At point B, the increase in voltage, associated with an additional junction below the mesa, is $\sim$35 mV, whereas, the voltage across the six junctions of the mesa is twice that, i.e., at least 70 mV each, for the corresponding current, i.e., near point A. To interpret the temperature at point B, we note that the measured gap feature in Bi2212 by STS (Ref. 7) [and ARPES (Ref. 9)] drops slowly compared to a BCS superconductor, and at T_c in Ref. 7, the gap drops to values between 45% and 75% of the zero-temperature values. Thus, the 50% reduction in the mesa gap feature (associated with 2Δ) in Fig. 2(a), from 70 to 35 meV, would imply the temperature at point B is fairly close to T_c. Thus, the junction under the mesa would exhibit $T \sim T_c$ near the *end* of the conductance peak in Fig. 2(a) (i.e., where the current bends over to the linear normal-state behavior). This result would be completely consistent with the temperature rise in our model of a thermal gradient in cases with no DHF. Note that, opposed to the equilibrium gap from STS (Ref. 7), any sharp conductance peak due to heating would necessarily close to zero as the bath T approaches T_c, since transitions to the normal state are then impossible.

Finally, Fig. 2(c) of the Comment provides an additional example of the broadening of the conductance peak and possible DHF when heating is reduced compared to previous mesas of the Comment's author. Its figure of merit, $\beta \sim 0.25$, is consistent with the nascent emergence of a DHF (see also the inset of Fig. 2 in Ref. 1).

V. SUMMARY

To summarize, our primary conclusion, that sharp conductance peaks of Ref. 1 are *not* a measure of a superconducting gap Δ, is not challenged. Rather, the Comment challenges our suggestion that mesas, which exhibit high sharp peaks and absent DHF, in general, may need re-interpretation. The additional experimental evidence in the Comment and Ref. 5 provide further empirical confirmation of the evolution from sharp peaks without dip features to relatively broader peaks and well-resolved dip features as self-heating is systematically reduced. This conclusion is purely based on experimental data and, thus, is independent from our model. That is, if we had never conceived of the inhomogeneous temperature model, the validity of the primary conclusion would remain true, and the additional experimental confirmations[2,4,5] attest to its robustness. The Comment's criticism of *our model* is based on a misconception that was outlined above. Although the Comment correctly points out the variable momentum selectivity of various tunneling methods, in the present context, it is only necessary to realize that the momentum selectivity of the tunneling matrix element cannot vary from one mesa to another. Thus, the wide variation of $I(V)$ across the entire mesa literature cannot be a result of momentum selectivity, and the sharp peaks are more likely due to self-heating.

Our responses to other issues in this Comment[2] and those of a considerably different earlier version of this Comment[12] can be found elsewhere.[11]

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