Reply to "Comment on 'Essence of intrinsic tunneling: Distinguishing intrinsic features from artifacts' "

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The recent paper of Zavaritsky [Phys. Rev. B **72**, 094503 (2005)] experimentally resolves the intrinsic shape of the *c*-axis current-voltage characteristics (IVCs) of HTSC and demonstrates that at sufficiently high heat loads the heating-induced IVC nonlinearities exceed the intrinsic ones so radically that the latter might be safely ignored. The author of the Comment fails to take into account the experimental findings by Zavaritsky [Phys. Rev. B **72**, 094503 (2005)] and seeks to cast doubt on all its conclusions through reference to a brushlike IVC, which is claimed to be free of heating. I will show that this claim lacks substantiation; indeed, it can be stated with certainty that the IVC is not free from heating. I will further show that the data selected for this Comment make it possible to explore the effect of temperature on a range of loads where the genuine response is not hidden by heating and to demonstrate that $R(T)$ of the same sample is responsible for a rich variety of IVC behaviors taken above and below T_c at bath temperatures spanned over 180 K. Thus these data, in fact, provide strong evidence in favor of the major conclusions by Zavaritsky [Phys. Rev. B **72**, 094503 (2005)], in particular, the extrinsic cause of the key findings by intrinsic tunneling spectroscopy.

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Heat W, dissipated in a sample, escapes through its surface area A and causes significant heating if the heat load $P=W/A$ exceeds the critical value P_c, which depends on the experimental environment. Notably, P_c depends on the coolant medium; it is close to 1 W/cm^2 for liquid helium and is significantly smaller for helium vapor at a comparable temperature. Heating is probably the most common problem in low-temperature research and a particularly harsh limiting factor for the study of current-voltage characteristics (IVCs). Self-heating of superconductors is particularly well studied; notably, it is known to cause IVC nonlinearities and transform a single-valued IVC into a multivalued characteristic with regularly spaced branches (see Ref. 1 for a comprehensive review).

The findings in Ref. 1 are particularly relevant to high-temperature superconductors (HTSCs) because the exceptionally poor thermal and electrical conductivities of HTSC make them particularly prone to local heating. However, unlike other studies of HTSC, the heating issues in "intrinsic tunneling" devoted to the brushlike IVC were misinterpreted or ignored until recently. Particularly, confusing claims arise from "intrinsic tunneling spectroscopy" (IJT), which postulates (i) that HTSCs *factually* represent natural stacks of atomic-scale intrinsic superconductor-insulator-superconductor Josephson junctions and (ii) an intrinsic cause for the IVC features built by the heat loads in excess of kilowatts per cm^2 which exceed the corresponding P_c by 4–6 orders (Refs. 2 and 3).

Central to the resolution of this confusion are the systematic experimental studies summarised in Ref. 2, which suggest that the true IVC is Ohmic above T_c, while the brushlike part is reasonably described by

$$|V_{\#}| = R_{\#}|(I - I^{*})|, \tag{1}$$

where the differential resistance of a resistive branch $R_{\#}$ is proportional to its number # and represents a fraction of the normal-state resistance $R_N(T_B)$ of the same sample measured under conditions of complete suppression of its superconductivity. The behavior in Eq. (1) is compatible with Josephson-based explanations albeit ruling out the basic IJT postulate, (see Ref. 2).

Heating masks the genuine response, which could be seen at $P<P_c$ only. Furthermore, the experiments summarized in Ref. 2 show that at sufficiently high heat loads, the heating-induced IVC nonlinearities exceed the intrinsic ones so radically that the latter might be safely ignored. The experimental IVC in such circumstances is primarily determined by $R_N(T)$, while the mean temperature T of the self-heated sample is appropriately described by Newton's law of cooling (1701),

$$T = T_B + P/h, \tag{2}$$

where T_B is the temperature of the coolant medium (liquid or gas) and h is the heat transfer coefficient, which depends neither on A nor on T, (see Refs. 2 and 4 for details). The consistency of this parameter-free description (which suggests the extrinsic cause of the key IJT findings, see Refs. 2 and 4–6) was reaffirmed by independent measurements in Ref. 7. The area independence of heating effects observed in Ref. 2 was strongly supported by Ref. 6, which addressed the heating cause of IJT spectra by Ref. 8 and discovered that practically the same heat loads ($P\sim 10$ kW/cm^2) build the IJT gap in Bi2212 structures of vastly different area $1<A<30\ \mu\text{m}^2$.

As is shown below, the data selected for the Comment provide evidence in favor of the major conclusions in Ref. 2 and allow resolution of important issues which were not covered in Ref. 2. In particular, I will provide a demonstration of the fact that (i) the model in Ref. 2 describes quantitatively the whole set of IJT IVC taken at T_B above and below T_c, (ii) the genuine parts of these IVCs agree reasonably with Eq.

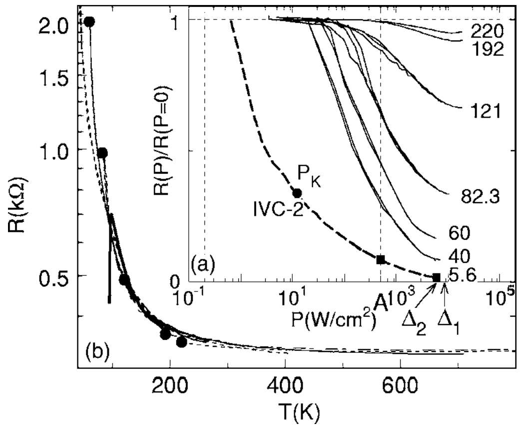

FIG. 1. (a): The solid lines represent the nonlinear IVCs, measured in Ref. 9 at different T_B above and below T_c=93 K, replotted as a sample resistance, $R=V/I$, normalized by its value at $P \to 0$, versus the heat load, $P=IV/A$; A=26 μm^2. T_B are shown in the figure at the corresponding curves. The solid dots in (b) represent $R(P\to 0)$ vs T_B. The thick broken line shows $R(P)$ for IVC-2; The characteristic heat loads which build the IJT gaps and the point "A" in the Comment's IVC are shown by the solid dots and the axis labels; P_K marks the typical heat load of a domestic kettle. (b) Compares the measured $R(T)$ shown by the thick solid line with the ones calculated with Eq. (1) from the nonlinear IVCs using one and the same heat transfer coefficient h=32 W cm^{-2} K^{-1} for the data taken at T_B spanned over 180 K.

(1), and (iii) P_c drops with temperature so radically that at low T the extrinsic features dominate almost throughout the range of loads.

The set of drastically different IVCs of the same "mesa" at various T_B (promoted by Ref. 9) provides a harsh consistency check for the parameter-free description in Ref. 2 and hence is particularly pertinent to the subject under discussion. Besides, this set is worth considering as it allows exploration of the effect of temperature on a range of loads where the genuine response is not hidden by heating. To allow intrinsic features to be distinguished from extrinsic ones, it is appropriate to consider $R=V/I$ as a function of the heat load, $P=VI/A$, rather than I-V only (see above and also Refs. 2 and 3). This is illustrated in Fig. 1(a), which shows the set of accordingly replotted IVCs mentioned above. As seen in Fig. 1(a), all curves exhibit a similar shape: there is a well defined threshold level P_c below which $R(P)$ is flat, while it drops rapidly at $P>P_c$. According to Refs. 2, 4, and 5, the $R(P)$ curves in the latter case are caused by Joule self-heating and hence must obey Eq. (2). Indeed, as is seen from Fig. 1(b), the parameter-free Eq. (2) collapses all IVCs, obtained at T_B spanned over 180 K, into a single curve which reproduces quantitatively the $R(T)$ of the same mesa and allows an estimate of the heat transfer coefficient h =32 W cm^{-2} K^{-1}, typical for this type of measurements. Thus, Fig. 1 confirms the heating origin of the IVC nonlinearity and suggests that the IVC in Ref. 9 will be almost linear above and below T_c=93 K if the heating artifacts are removed. So, these findings suggest that Eqs. (1) and (2) correctly describe both the IJT spectra and a genuine IVC hidden by heating artifacts, hence demonstrating the unfoundedness of the principal claim by the author of the Comment.

Figure 1(b) strongly suggests that h does not depend on temperature. This conclusion agrees well with the earlier experimental findings summarized in Ref. 2 and similar, albeit less reliable, conclusions could be drawn from the row data in Ref. 7. However, it contradicts radically the findings in Ref. 8. A resolution of this dichotomy is possible by taking into account the actual experimental arrangement of Ref. 8, where the thermometer and the overheated sample are individually heat sinked to the bath through metal electrodes of enhanced area and thermal conductivity. Such an arrangement makes unavoidable a thermal lag between the thermometer and the overheated sample. This lag depends on P and T_B and, for this reason, the data of Ref. 8 are not beyond dispute (see Ref. 6 for more details).

As seen from Fig. 1(a), the critical load drops with temperature radically, as does the range of loads where intrinsic features dominate. However, the heat loads of the characteristic IVC points demonstrate the opposite trend, as both the switching current I_J and IJT gap increase as the temperature becomes lower. So, a study of intrinsic response, feasible at temperatures slightly below T_c and above (see Ref. 2), becomes enormously complicated at helium temperatures, where the extrinsic features dominate almost throughout the range of loads where the brushlike IVC exists. This common case is illustrated by the appropriately replotted IVC-2 (T_B =5.6 K) from Fig. 2 of the Comment. As is seen in Fig. 1(a), the entire IVC-2 belongs to the falling part of $R(P)$ and so is most likely caused by heating. This conclusion is additionally supported by (i) the qualitative similarity of the falling parts of $R(P)$ taken at vastly different T_B and (ii) the reasonable correlation between the coarse estimate of P_c(5.6 K) for IVC-2, the value [shown by the unlabeled grid line in Fig. 1(a)] obtained from the measurements of the local heating in another mesa (see Refs. 2 and 3 for details) and the extrapolation of $P_c(T_B)$ from Fig. 1(a).

Thus, the IVC-2 supports neither the claim that "the self-heating along the branches is negligible" nor the claim that "the genuine interlayer IVCs are strongly nonlinear." The last major claim of the Comment, that the branches in the brush "are perfectly periodic," is also at odds with the experiment because neither the genuine branches described by Eq. (1) nor the nonlinear ones, advocated by the author of the Comment, obey the definition of periodicity:

$$F(x+a)=F(x), \quad a=\text{const}. \tag{3}$$

As far as the heating in the samples of different A is concerned, neither the critical current I_c nor the heat W=IV (confusingly denoted as P in the Comment) fit the comparison (see above). Furthermore, I_J depends on ambient factors (e.g., it is easily suppressed by a small magnetic field) which leave unaffected both the overall shape of IVC and the IJT gap. For this reason and because of the unknown cause of I_J, it is more appropriate to compare the heat loads Δ which build the IJT gap. A and Δ are estimated accordingly: A_1 ≅60 μm^2 and Δ_1≅8.6 kW/cm^2 are taken from the figure assuming that the author alleges I_J with I_c; A_2=13.5 μm^2

and $\Delta_2 \cong 6$ kW/cm^2 are taken from the source article (Ref. 8). As Δ_1 and Δ_2 are practically the same [see Fig. 1(a)], there are no valid reasons to expect the self-heating to be radically different in these samples, one of which is declared to represent "the case of extreme self-heating" by the author of the Comment (see Ref. 10). This conclusion is consistent with the earlier studies which suggest the extrinsic cause of all known shapes of IJT gaps, hence rendering irrelevant the association of the IVC "backbending" with the signature of extreme self-heating (see Ref. 2 for details).

To conclude, it is demonstrated, using exclusively the data selected for the present Comment by its author, that neither the argumentation nor the conclusions of the Comment by Krasnov *et al.* are borne out by experiment. Contrary to the Comment's claims, Ref. 2 addresses the genuine IVC experimentally and shows that at sufficiently high heat loads the heating-induced IVC nonlinearities exceed the plausible intrinsic ones, e.g., of Eq. (1), so radically that the latter might be safely ignored. Moreover, the data selected for this Comment make it possible to explore the effect of temperature on the range of loads where the genuine response is not hidden by heating. Furthermore, it is shown that the whole set of experimental IVCs taken above and below T_c at vastly different T_B spanned over 180 K are described quantitatively by Newton's law of cooling and Ohm's law using the normal-state resistance of the same sample only. This finding confirms the heating origin of the IVC nonlinearity, which was originally claimed as "evidence for coexistence of the superconducting gap and the pseudogap" in Ref. 9 and suggests that unlike conventional spectroscopy,[11] the heating in IJT is not a small perturbation but a principal cause of IVC nonlinearity.

Our conclusions do not rule out worthwhile IJT experiments, some of which were proposed in Ref. 2. Moreover, the feasibility of macroscopic quantum tunneling (MQT) was recently discussed by the authors of Refs. 12 and 13. Such studies might be virtually unaffected by heating as long as they appropriately address the statistics of stochastic switching from a zero-P state. However, heating can spoil MQT, and indeed the authors of Ref. 14 discovered that the escape process from the first resistive branch is most likely governed by heating even in the bridgelike samples, which reveal a noticeably higher P_c than the mesas considered above, (see Ref. 2). The findings in Ref. 14 thus provide independent evidence in support of our conclusions. However, the range of heat loads where MQT still exists remains to be explored, e.g., by an *in situ* suppression of the switching current by magnetic field.

I am grateful to the authors of Ref. 13 for their explanation of their belief that IVC of HTSC bridge taken at milli-Kelvin temperatures remains unaffected by heating even at $P \sim 1$ kW/cm^2.

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