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

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In a recent paper, Zavaritsky [Phys. Rev. B **72**, 094503 (2005)] has argued that interlayer (c axis) current-voltage characteristics of high-temperature superconductors (HTSC) are Ohmic and that a simple self-heating model based on this assumption "provides a qualitative and quantitative description of key finding of intrinsic tunneling spectroscopy." In this Comment, I demonstrate that the genuine interlayer current-voltage characteristics are strongly non-Ohmic. Therefore, the self-heating model, advocated by Zavaritsky, can hardly provide correct explanation of nonlinearities observed in intrinsic tunneling spectra of HTSC.

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Mobile charge carriers in strongly anisotropic high-temperature superconductors (HTSC), such as $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi-2212), are confined in CuO_2 planes. The out-of-plane c-axis transport in those compounds is caused by interlayer tunneling,[1] which results in nonmetallic behavior[2–4] and leads to the appearance at $T<T_c$ of the "intrinsic" Josephson effect[5] between CuO_2 planes. At present, all major fingerprints of the intrinsic Josephson effect are observed, including Fiske[6–8] and Shapiro[7,9] steps in current-voltage characteristics (IVCs); the Josephson plasma resonance;[10] thermal activation,[11] as well as macroscopic quantum tunneling,[12] of phase in the periodic Josephson potential; and flux quantization.[6–8,13,14] The latter explicitly confirms correspondence between the stacking periodicity of intrinsic Josephson junctions (IJJs) and the crystallographic unit cell of Bi-2212. The interlayer tunneling was also successfully employed for intrinsic tunneling spectroscopy, which is unique due to its ability to probe bulk phonon[15] and quasiparticle[13,16–21] spectra of HTSC.

However, in a recent paper[22] and a series of other publications,[23] Zavaritsky has questioned the existence of interlayer tunneling in HTSC and has speculated that the genuine self-heating free c-axis IVCs of HTSC are Ohmic, implying that all the nonlinear features in c-axis IVCs are artifacts of self-heating.

In this Comment, I demonstrate that the genuine interlayer IVCs of Bi-2212 are strongly non-Ohmic and are represented by perfectly periodic, multibranch IVCs, which are not affected by self-heating. At low temperature, this periodicity and nonlinearity stretches over 2 orders of magnitude in resistance. Therefore, the self-heating model, advocated by Zavaritsky, can hardly provide correct explanation of nonlinearities observed in intrinsic tunneling spectra of HTSC.

IVCs of HTSC mesas exhibit a characteristic multibranch structure due to one-by-one switching of IJJs from the superconducting into the resistive state.[5] Each time a new junction is switched into the resistive state, the dissipation power within the mesa increases and the effective temperature of the mesa rises as a result of self-heating:[24]

$$\Delta T = PR_{th}. \quad (1)$$

Here, $P=VI$ is the total dissipation power and R_{th} is the effective thermal resistance of the mesa, which depend on the sample geometry and temperature.[24,25] The progressive self-heating with the branch number may result in a systematic distortion of the IVC in the way shown in Fig. 1. Namely, the critical current and the separation between branches decrease with the branch number. At large P, significant self-heating is indicated by progressive back-bending of the branches.

Figure 1 shows the IVC at the base temperature T_0 $=4.2$ K for a large Pb-doped Bi-2212 mesa, containing N $\simeq 40$ IJJs. The IVC is measured in the four-probe configuration. The large $P>5$ mW at the end of the multibranch structure in the IVC is caused, first of all, by the large critical current density $J_c \sim 10^4$ A/cm^2 in this Pb-doped Bi-2212 crystal. A similar distortion of intrinsic IVCs at comparable P can be seen in Fig. 10(a), of Ref. 15 and Fig. 1 of Ref. 26.

Figure 2 shows an opposite example of a small self-heating. In Fig. 2(a), the IVC of a small underdoped Bi-2212 mesa with a small $J_c<400$ A/cm^2 (Ref. 19) and $N=34$ IJJs is shown. The properties of this mesa were studied in Refs. 11 and 25. A combination of small area and J_c results in a 2 order of magnitude smaller P at the end of the multibranch structure, point A in Fig. 2(a), than at the similar point in Fig. 1. Thin lines in Fig. 2(a) represent multiple integers of the

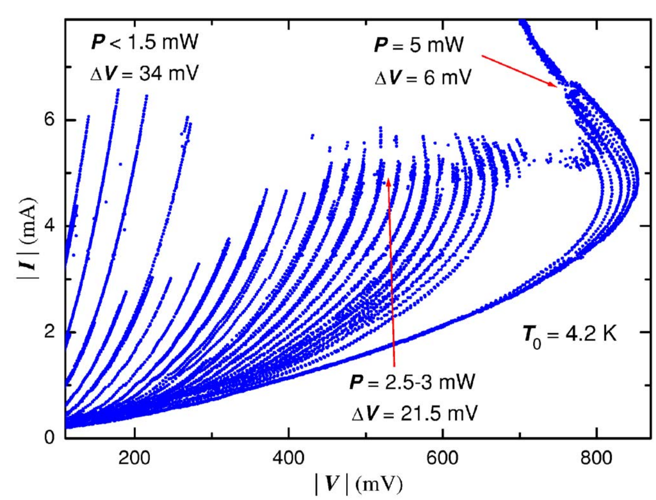

FIG. 1. (Color online) Superimposed positive and negative parts of the IVC of a large Pb-doped Bi-2212 mesa at T_0=4.2 K. It is seen how the IVC is distorted by self-heating: the critical current and the separation between branches decrease with the branch number due to progressive self-heating. Significant self-heating at large dissipation power is indicated by back-bending of the branches.

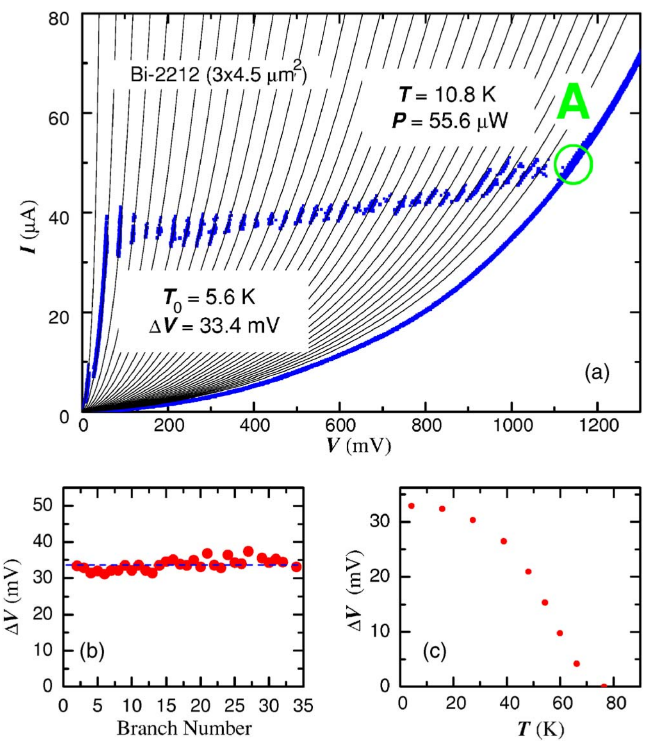

FIG. 2. (Color online) (a) The IVC of a small underdoped Bi-2212 mesa at T_0=5.6 K. Thin lines are multiple integers of the last branch divided by N=34. They demonstrate perfect periodicity of the branches. Panels (b) and (c) show voltage jumps between branches as a function of the branch number and the base temperature, respectively.

last branch divided by $N=34$, indicating perfect periodicity of the branches, typical for interlayer IVCs of Bi-2212 mesas.[9,11,15,16] Figure 2(b) shows voltage jumps ΔV between the branches as a function of the branch number. It is seen that ΔV is independent of the branch number. Small deviations from the mean ΔV are caused by thermal fluctuations of the switching current.[11,12]

Separation between branches provides an independent test for the extent of self-heating, because ΔV depends on T, as shown in Fig. 2(c). From Fig. 2(c), it follows that branches can remain periodic only if successive increase of T with the branch number does not exceed $\sim$15 K. This is consistent with *in situ* measured $T=10.8$ K at point A in Fig. 2(a).[25] Similarly, for the case of large self-heating shown in Fig. 1, we may conclude that the mesa is heated to $T \simeq 60$ K at the end of the multibranch structure at $P \simeq 5$ mW, again consistent with the measured self-heating $\Delta T/P \sim 10$ K/mW at $T=60$ K.[25] It should be emphasized that atomic separation between IJJs in the mesa leads to uniform self-heating within the mesa, as shown in the Appendix.

The raw data in Figs. 1 and 2 speak for itself: the distorted periodicity of branches in Fig. 1 indicates significant self-heating. On the contrary, the undistorted perfect periodicity of branches in Fig. 2(a) implies that the shape of the branches is not affected by self-heating. Yet, V/I of the branches changes by 2 orders of magnitude in this voltage range. Therefore, observation of periodic strongly non-Ohmic branches in the IVCs can only mean that (i) self-heating along the branches is negligible; (ii) those periodic branches represent the genuine self-heating free IVCs of Bi-2212; and (iii) the genuine interlayer IVCs are strongly nonlinear.

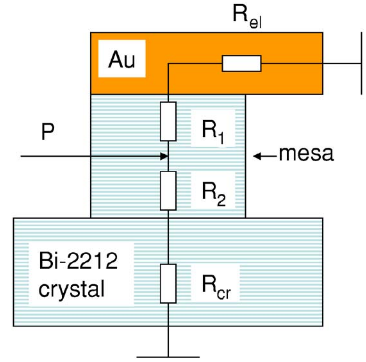

FIG. 3. (Color online) Schematics of heat flow from the mesa structure.

The latter statement is the main conclusion of this Comment. From Fig. 2 and similar data reported in literature, it can be concluded that the genuine nonlinearity of intrinsic IVCs exceeds 2 orders of magnitude in resistance, in contradiction with the assumption of bias independent resistance made in Ref. 22. Therefore, the self-heating model proposed in the criticized paper can hardly provide correct explanation of intrinsic tunneling spectra of HTSC.

I am grateful to A. B. Kulakov for providing Pb-doped Bi-2212 crystals.

APPENDIX

The author of Ref. 22 speculated about "peculiar temperature distribution along the sample." However, T distribution within the mesa can be easily estimated, without making any assumptions about heat-flow mechanism outside the mesa or dissipation mechanism inside the mesa.

Figure 3 shows schematics of heat flow in the mesa. The heat $P=VI$ can flow down to the crystal and upward into the contact electrode, characterized by heat resistances R_{cr} and R_{el}, respectively. $R_{1,2}$ represent heat resistances of top and bottom parts of the mesa. The total self-heating is

$$\Delta T = PR_{th} = P\frac{(R_1 + R_{el})(R_2 + R_{cr})}{R_1 + R_2 + R_{el} + R_{cr}}, \tag{2}$$

where R_{th} is the effective thermal resistance of the sample, which, according to Ref. 22, is $R_{th}=(Ah)^{-1} \simeq 4 \times 10^4$ K/W. One-dimensional nature of heat flow within the mesa allows straightforward estimation:

$$R_{1,2} = \frac{sN_{1,2}}{A\kappa_c}, \tag{3}$$

where $s=15.5$ Å is the interlayer spacing, $N_{1,2}$ is the number of layers in top and/or bottom parts of the mesa, and κ_c is the c-axis thermal conductivity. For Bi-2212, $\kappa_c \sim 0.5$ W/K m at $T=30$ K.[27] For the mesa with $A=10 \times 10$ μm^2, the thermal resistance per layer, $R_1(N=1) \simeq 31$ K/W, is 3 orders of magnitude smaller than R_{th}. For the cases $R_{cr} \gg R_{el}$ and $R_{cr} = R_{el}$, the ratios of temperature difference per junction to the total self-heating are $R_1/R_{th} \simeq 7.8 \times 10^{-4}$ and $R_1/2R_{th} \simeq 3.9 \times 10^{-4}$, respectively.

For the mesa with $N=10$ and $P=1$ mW [note that $P < 0.06$ mW at point A in the IVC of Fig. 2(a)], the maximum temperature difference within the mesa, ΔT_{mesa}, is only ~ 0.3 K. Furthermore, this is a strongly overestimated value because (i) κ_c measured in Ref. 27 was limited by stacking faults in large Bi-2212 crystals, which are absent in our mesas. The pure phononic thermal conductivity is expected to be almost isotropic, which would imply that the actual κ_c in the mesa is close to κ_{ab}, i.e., eight times higher. (ii) The estimation was obtained for the case of heat diffusion within the mesa. In reality, the c-axis heat transport in Bi-2212 is predominantly phononic and ballistic at the atomic scale.[25,27] This will considerably reduce ΔT_{mesa} for mesas with the total height less than the phononic mean free path, i.e., for $N \lesssim 1000$.

Therefore, for typical mesas, all layers within the mesa are heated uniformly, irrespective of where exactly within the mesa the dissipation takes place.

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