Comment: Essence of intrinsic tunneling: Distinguishing intrinsic features from artifacts [Phys.Rev.B 72 (2005) 094503].

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In a recent paper V.Zavaritsky has argued that interlayer (c− axis) current-voltage characteristics of high temperature superconductors (HTSC) are Ohmic, and has claimed to disprove all findings of intrinsic tunnelling spectroscopy, as well as existence of the interlayer tunnelling and the intrinsic Josephson effect in HTSC, as such.

In this comment I demonstrate, that the genuine interlayer current-voltage characteristics are strongly non-Ohmic, which undermines the basic postulate and the logical construction of the criticized paper.

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Mobile charge carriers in strongly anisotropic high temperature superconductors (HTSC), such as Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ (Bi-2212), are confined in CuO$_2$ planes. The out-of-plane c−axis transport in those compounds is caused by interlayer tunnelling, which results in non-metallic behavior and leads to appearance at $T < T_c$ of the "intrinsic" Josephson effect between neighboring CuO$_2$ planes. At present all major fingerprints of the intrinsic Josephson effect were observed, including Fiske and Shapiro steps in Current-Voltage characteristics (IVC’s); the Josephson plasma resonance; thermal activation and macroscopic quantum tunnelling from the Josephson washboard potential; and the flux quantization. The latter experiments explicitly confirmed the correspondence between the stacking periodicity of intrinsic Josephson junctions (IJJ’s) and the crystallographic unit cell of Bi-2212. The interlayer tunnelling was also successfully employed for intrinsic tunnelling spectroscopy, which is unique in its ability to probe bulk phonon and quasiparticle spectra of HTSC.

However, in a recent paper V.Zavaritsky denies the existence of interlayer tunnelling in HTSC and speculates that all the non-linear features in c−axis IVC’s are artifacts of self-heating.

The two basic postulates of Refs. [22, 23] are:

1. That the intrinsic Josephson effect does not exist,
2. That the genuine, self-heating free c−axis IVC’s of HTSC are Ohmic.

The latter statement together with the assumption of semiconducting $T$−dependence of the Ohmic resistance leads in the presence of self-heating to non-linear IVC’s, which according to Ref. [22] provides both qualitative and quantitative description of all key findings of interlayer transport experiments in HTSC, proves that all the non-linear features of interlayer IVC’s are artifacts of self-heating and disproves all findings of intrinsic tunnelling spectroscopy.

The incorrectness of the first postulate in the face of overwhelming and unambiguous experimental evidence does not require extra comments, except that it demonstrates an obvious failure of the reviewing process in several scientific journals.

In this comment I demonstrate incorrectness of the second postulate. It is shown that the genuine interlayer IVC’s of Bi-2212 are strongly non-Ohmic and are represented by perfectly periodic, multibranch IVC’s, which are not affected by self-heating. The huge, two order of magnitude, genuine non-linearity of IVC’s represents the extent of irrelevance of the model advocated by Zavaritsky to the essence of intrinsic tunnelling in HTSC and undermines the logical construction of Ref. [22].

Intrinsic tunnelling characteristics of HTSC mesa structures exhibit a characteristic multi-branch structure due to one-by one switching of IJJ’s from the superconducting into the resistive state. 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 [22]:

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

where $P = VI$ is the total dissipation power and $R_{th}$ is the effective thermal resistance of the mesa, which depend on the sample geometry and temperature. 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.

Fig. 1 shows how the intrinsic IVC is distorted by extreme self-heating. It shows an IVC at the base temperature $T_0 = 4.2K$ for a large Pb-doped Bi-2212 mesa structure, containing $N \simeq 40$ IJJ’s. The IVC is measured in the four-probe configuration. The extremely
large \( P > 5 \text{mW} \) at the end of the multi-branch structure in the IVC is caused first of all by a very large critical current density \( J_c \sim 10^4 \text{A/cm}^2 \) in this Pb-doped Bi-2212 crystal. A similar distortion of intrinsic IVC’s at comparable \( P \) can be seen in Fig. 10 a) of Ref. [15], Fig. 1 of Ref. [26].

Fig. 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 \( J_c < 400 \text{A/cm}^2 \) [11] and approximately the same number of IJJ’s, \( N = 34 \), is shown. Properties of this mesa were studied in Refs. [11, 25]. A combination of small area and \( J_c \) results in a two order magnitude smaller \( P \) can be seen in Fig. 10 a) of Ref. [15], Fig. 1 of Ref. [26].

The separation between branches provides an independent test for the extent of self-heating, because \( \Delta V \) depends on \( T \), as shown in Fig. 2 c). From Fig. 2 c) it follows that branches can remain periodic only if the successive increase of \( T \) with branch number does not exceed \( \sim 15 \text{K} \). This is consistent with in-situ measured \( T = 10.8 \text{K} \) at \( P = 55.6 \mu \text{W} \) point A in the IVC from Fig. 2 a) [23]. Similarly, for the case of extreme self-heating shown in Fig. 1, we may conclude that the mesa is heated to \( T \approx 60 \text{K} \) at the end of the multi-branch structure at \( P \approx 5 \text{mW} \), again consistent with the measured self-heating \( \Delta T/P \sim 10 \text{K/mW} \) at \( T = 60 \text{K} \) [23]. Furthermore, atomic separation between IJJ’s in the mesa leads to uniform self-heating within the mesa, see Appendix-A.

Appendix-B presents a detailed comparison of intrinsic IVC’s with the self-heating model of Ref. [22], which, in contrast to claims of Ref. [22], demonstrates a severe contradiction between experimental data and the model. On the other hand, this failure is obvious already from the raw data in Figs. 1, 2. This data speaks for itself: The distorted periodicity of branches in Fig. 1 indicates significant self-heating. To 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. However, \( V/I \) changes by approximately two orders of magnitude in this voltage range.

Thus, observation of the periodic strongly non-Ohmic branches in interlayer IVC’s can only mean that:

i) the self-heating along the branches is negligible;

ii) those periodic branches represent the genuine self-heating free IVC’s of Bi-2212;

iii) The genuine interlayer IVC’s are strongly non-linear.

The latter statement is the main conclusion of this comment. It disproves the basic postulate of Ref. [22] and undermines the logical construction of that paper.
From Fig. 2 and a large collection of similar data reported in literature, it can be concluded that the genuine non-linearity of intrinsic IVC’s exceeds two orders of magnitude at low T, which also represents the degree of irrelevance of the model suggested in the criticized paper to the essence of intrinsic tunnelling in HTSC.

APPENDIX A

The author of Ref. 22 speculates 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.

Fig. 3 shows the schematics of heat flow in Bi-2212 mesa structure. The heat P = VI, produced in the mesa, can flow down to the crystal and upwards 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

\[ \Delta T = P R_{th} = \frac{P (R_1 + R_{el})(R_2 + R_{cr})}{R_1 + R_2 + R_{el} + R_{cr}}, \]

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

\[ R_{1,2} = \frac{s N_{1,2}}{A \kappa_c}, \]

where \( s = 15.5 \mu\text{m} \) is the interlayer spacing, \( N_{1,2} \) is the number of layers in top/bottom parts of the mesa, and \( \kappa_c \) is the c-axis thermal conductivity. For Bi-2212, \( \kappa_c \approx 0.5 W/Km \) at \( T = 30 K \). For the mesa with \( A = 10 \times 10 \mu m^2 \), the thermal resistance per layer \( R_1(N = 1) \approx 31 K/W \) is three orders of magnitude smaller than \( R_{th} \). In two extreme cases, \( R_{cr} \gg R_{el} \) and \( R_{cr} = R_{el} \), the ratios of temperature difference per junction in the mesa to the total self-heating of the mesa are \( R_1/R_{th} \approx 7.8 \times 10^{-4} \) and \( R_1/2R_{th} \approx 3.9 \times 10^{-4} \), 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, \( \Delta T_{mesa} \) is only \( \sim 0.3 K \).

Furthermore, this is a strongly overestimated value because: (i) \( \kappa_c \) 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 \( \kappa_c \) in the mesa is close to \( \kappa_{ab} \), 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 23 27. This will considerably reduce \( \Delta T_{mesa} \) 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.

APPENDIX B

One of the critical assumptions of Ref. 22 is that the semiconducting zero-bias resistance \( R_0(T) \) represents \( V/I \) at finite bias along the IVC’s. This a direct consequence of the second postulate, see above. A seeming matching between decaying \( V/I(P) \) and \( R_0(T) \) is demonstrated in Fig. 1 of Ref. 22 for some IVC, which, however, does not bear any resemblance with classical multi-branched interlayer characteristics 8 11 13 16. Below I will repeat the same fitting for the case of conventional intrinsic IVC’s.

Fig. 4 represents \( V/I(P) \) (left and top axes) for the IVC from Fig. 2 a). The IVC in full scale is shown in inset of Fig. 4. The decaying part of the curve represents the resistance of the last branch, while the linearly increasing part represents multiple branches in the IVC. The dashed and solid lines in Fig. 4 represent \( R_0(T) \) measured with a small ac-modulation current and the quasiparticle resistance with all \( N = 34 \) IJJ’s in the resistive state \( R_0^N(T) \) obtained from numerical differentiation of the IVC’s, respectively (left and bottom axes). On the first glance, a good match between \( V/I(P) \) and \( R_0(T) \), in a limited \( T \)−range, can be obtained if we allow an arbitrary offset and stretching along the \( T \)−axis of \( R_0(T) \). However,
Eq. (1) is non-linear due to \( V/I \). One should instead expect self-scaling of the heating model because the relation between \( R \) and \( P \) parameter, representing the power required to compensate for the same mesa at Fig. 2, replotted as \( V/I\) vs. \( P = VI \) (top axis). Dashed and solid lines represent the zero bias resistance \( R_0 \) and the quasiparticle resistance \( R'_0 \) vs. \( T \) (bottom axis), respectively. \( R_0 \) is matched to \( V/I \) using the procedure suggested in Ref. [22]. Inset shows the original \( I - V \) characteristics of a Bi-2212 mesa at \( T_0 = 5.6 K \). Major deviations between \( V/I \) and \( R_0 \) at low \( P \) and a huge offset \( T(P = 0) \approx 70 K \gg T_0 = 5.6 K \), indicated by an arrow, reveal severe contradiction between experimental data and the self-heating model of Ref. [22].

Several inconsistencies can be seen in such a "fit":

i) \( T \) - offset, required for matching, leads to \( T(P = 0) \approx 70 K \gg T_0 = 5.6 K \), as indicated by the arrow in Fig. 4. A similar offset can be seen in Fig. 1 of Ref. [22]. Therefore, such a "fit" simply does not make any sense. The seeming coincidence in Fig. 4 indicates simply that two smooth decaying functions can be matched in the limited interval using two fitting parameters.

ii) Major deviations of \( V/I\) and \( R_0 \) at low \( P \), where the main, almost 2-order of magnitude, drop of \( V/I \) occurs. The severe discrepancy between \( V/I\) and \( R_0 \) at low bias indicates that the IVC is non-linear in this bias range.

Strictly speaking, the scaling between \( V/I \) and \( R_0 \) should not be expected even within the self-heating model because the relation between \( T \) and \( P \) in Eq. (1) is non-linear due to \( T \) - dependence of \( R_0 \). One should instead expect self-scaling of \( V/I\) curves at different \( T_0 \), using the offset \( \Delta P \) as the only fitting parameter, representing the power required to compensate the difference in \( T_0 \) between different measurements. Such scaling does not require constant \( R_{th} \) and just implies that equal \( P \) would heat the mesa by the same \( \Delta T \), irrespective of how the mesa reached the initial temperature.

Fig. 5 shows the check for such a self-scaling for the optimally doped mesa \( T_c = 93 K \), \( A = 3.5 \times 7.5 \mu m^2 \), \( N = 10 \), studied in Ref. [16]. Fig. 5 a) shows a set of \( V/I\) curves at six \( T_0 \) from 4.9 to 220 K. For each curve the offset \( \Delta P \) was chosen in such a way that the initial point \( V/I\) would coincide with \( V/I\) of the nearest curve with lower \( T_0 \). Apparently, the self-scaling is not existing for conventional intrinsic IVC’s. Fig. 5 b) shows zoom-in of the high power part of the plot. Here self-heating should be the largest. It is seen that the IVC’s asymptotically approach some “normal” resistance \( R_n \). Experimental values of \( R_n \) and \( R_0 \) vs. \( T_0 \) are shown in Fig. 5 c). Comparison of \( R_n \) and \( R_0 \) shows that \( R_n \) is smaller than \( R_0 \) at any \( T \). This makes the fitting of \( V/I \) by \( R_0 \) technically impossible, indicating that the IVC’s have to be non-Ohmic.

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