Reply to "Comment on 'Intrinsic resistance fluctuations in mesoscopic superconducting wires' "

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We show that several essential assumptions used by Landau and Rinderer (see the preceding Comment) are in contradiction with available experimental data on mesoscopic superconducting wires. Therefore their model cannot be used for the interpretation of the anomalous $R(T)$ behavior in these samples.
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The Comment, written by Landau and Rinderer (LR),[1] is based on a well-known phenomenon: the existence of extra resistance at a normal-superconducting (NS) interface. This effect was discovered in bulk type-I superconductors by one of the authors of the Comment.[2] Of course we were aware of this paper and other publications on the same subject, but we did not consider them (and therefore did not cite the paper[2] in our publication[3]), since it was not possible to use that approach in its existing form to interpret our experimental data. Moreover, even a modified approach (see the preceding Comment) with several assumptions, used by LR in their description of the resistance anomaly, is still not applicable for our experiments with short mesoscopic superconducting wires.

The LR model[1] for the resistance anomaly is based on the following assumptions:

(1) The anomaly is observed when the NS boundary enters the space between potential probes and leads to the quasiparticle charge imbalance and to a discontinuity of the electric potential at the NS boundary.

(2) The charge imbalance phenomena cannot give resistance values higher than those in the normal state. Therefore the resistance anomaly should be attributed to the "step" of the electrical potential at the NS boundary and not to charge imbalance.

(3) To obtain any noticeable discontinuity of the electrical potential (to be comparable with the one needed to explain the experimentally observed resistance anomaly) for the NS boundary being normal to the current the mean free path of electrons l must be much greater than all other characteristic distances.

(4) For the situation with very short l's a strongly "tilted" NS boundary is needed between the potential probes. If the NS boundary is perpendicular to the current and the l value remains very small, then the potential step at the NS boundary is too small to explain the experimental data.

Now we show that these four assumptions, essential for the LR model,[1] are in a contradiction with available experimental data.[3–6]

(i) In experiments of Park, Isaacson, and Parpia[5] with the clearly defined (through etching) NS interface *the resistance anomaly was observed both for the NS interface between the voltage probes and for the probes not enclosing the interface.* In the caption to Fig. 2 in Ref. 5 we read, "...Note that the voltage probes need not span the etched-unetched (NS) interface to observe the (resistance) anomaly." Therefore the positioning of the NS boundary between the voltage probe is not a necessary condition for the observation of the resistance anomaly. This is clearly against the above-mentioned assumption (1) by LR.

(ii) *The resistance anomaly was manifested only if it was measured with superconducting voltage probes*.[5] With normal (etched) probes no resistance anomaly is observed whatever the position of the probes with respect to the NS boundary. Since the S and N probes measure the electrochemical potential of pairs and normal quasiparticles, respectively, within a nonequilibrium region, this implies that the charge imbalance of pairs is responsible for the appearance of the resistance anomaly. These observations are in contradiction with the assumption (2) that the main factor is the "step" of the electrical potential at the NS boundary.

(iii) In Refs. 3–6 and others the mean free path l is typically 10–20 nm, which is much less (and *not* much more) than the distance between the probes, the coherence length, the charge imbalance length, and other relevant parameters. Therefore, under these conditions no noticeable resistance anomaly can be expected in the framework of the LR model. By the way, this is also admitted by LR in their Comment.

(iv) To resolve this inconsistency, LR propose that the NS boundary is not perpendicular to the current. This may eventually happen, but on the other hand in Ref. 5 the resistance anomaly in wires with very short l has been observed for the NS boundary etched perpendicular to the current. This is in a contradiction with the assumption (4).

We would like to emphasize here that one of the main conclusions of the recent experimental observations[3–6] is that the resistance anomaly is related to the nonequilibrium charge imbalance around both phase slip centers (PSC's) and the NS boundary. Therefore, the discontinuity of the electrical potential at the NS interface[1] is not the dominant mechanism responsible for the appearance of the resistance anomaly.

The authors of the Comment[1] also criticize the concept of PSC, referring to four publications (Refs. 1–4 in Ref. 1; two of them, by the way, are by other groups, and therefore, we cannot be criticized for that). The authors of Ref. 1 give, without a proper context, a misleading presentation of the model proposed by us[3] to interpret an anomalous resistance peak in mesoscopic wires. The essence of our model is that we were considering *not only narrow* wires *but at the same time very short wires*, with a length being smaller than both the charge imbalance lengths λ_Q^* and the coherent lengths ξ. Therefore in this case the sample is much smaller than all characteristic scales for the decay of the nonequilibrium distribution of pairs and quasiparticles considered in theoretical papers, including the paper by Ivlev and Kopnin (Ref. 7). Only for extremely short mesoscopic wires did we assume that switching between normal and superconducting states might be eventually possible. This assumption was based on the well-known phenomenon of the formation of superconducting/normal domains in current carrying superconducting wires.[8] It seems then possible to expect that in very short wires temporal switching between normal and superconducting states could be realized, instead of forming coexisting moving N and S domains. In other words, we have made an attempt to consider mesoscopic samples smaller than the size of the phase slip center itself. This problem was not considered in theoretical papers on this subject (including Ref. 7) and therefore the statement of LR about an obvious contradiction is misleading. Moreover, never in our paper[3] did we mention that the anomalous resistance peak cannot be observed in other materials, including bulk type-I superconductors in the intermediate state.

The authors of the Comment[1] are summarizing the main conclusions of several previous experimental and theoretical papers on the interface resistance in bulk type-I superconductors (Refs. 9–16); they do not focus specifically on short mesoscopic wires. LR write in their ''Comment'', ''Our model has virtually nothing new.'' We agree with this statement. We do not agree, however, with the following statement that ''...it can explain rather well all features observed experimentally,'' since, contrary to Ref. 3, LR did not even try to fit the main experimental data: $R(T)$ curves demonstrating an anomalous resistance peak just below T_c, the magnetic field and current dependence, etc.

We would also like to remark here once again that we are convinced that the phase slip and charge imbalance phenomena are indeed relevant for explaining an anomalous $R(T)$ behavior in the vicinity of T_c in mesoscopic type-II superconductors. Recently[17] we have shown that PSC can also be induced by the radio-frequency radiation and Arutyunov[18] has presented a model where the $R(T)$ peak is also related to thermally induced phase-slip events. This author has confirmed the relevance of spin-flip events for the anomalous behavior of the $R(T)$ curves by comparing his calculations with the recent experimental observations.

Concluding, we think that the arguments given by the authors[1] are not directly relevant, since they are based on the model containing the four assumptions which seem to be not valid for our work on mesoscopic short wires; not new, since they are summarizing well-known published facts; and not conclusive, since besides handwaving arguments, no quantitative comparison with the existing experimental $R(T)$ data has been made.

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