Comment on "Electronic Correlation Effects and the Coulomb Gap at Finite Temperature"

In a recent Letter [1] an observation of the Coulomb gap in doped semiconductors with the help of the break junction technique was reported. The authors studied current transport through the device fabricated from Si-doped Ge and observed strong nonlinearity of the I-V curve which was ascribed to the energy dependence of density of states (DOS) in the banks of the junction. It was suggested that the observation of DOS was possible due to the fact that the conductance was controlled by a single hop through the junction. Indeed, one notes that no spectroscopical measurements would be possible if the bias applied would be redistributed among many hopping sites. In this Comment we point out the factors that are essential for nonlinear hopping transport through a point contact which, in our opinion, were not taken into account in Ref. [1].

The standard tunneling spectroscopy of DOS (see, e.g., [2]) is based on the expression for the tunnel current

$$j \propto \int d\varepsilon g_l(\varepsilon) g_r(\varepsilon - eV) F_0(\varepsilon)[1 - F_0(\varepsilon - eV)]W, \quad (1)$$

where g_l and g_r are densities of states in the left and right bank, correspondingly, F_0 is the Fermi function, while W is the tunneling probability suggested *to be independent of* V. The latter fact implies resonant tunneling through the barrier between the states separated by the barrier. Indeed, only in this case the nonlinearity of the current-voltage curve would be controlled by the densities of states. Another assumption crucial for the DOS spectroscopy is that the size of the system is large enough since the concept of DOS implies a thermodynamical limit. In our opinion, both of these criteria do not hold for the transport controlled by a single hop.

First, in this case one cannot expect the hopping probability to be independent of V. Indeed, if one assumes that the bias is concentrated on the single pair of sites, i and j, where one of the sites is in equilibrium with the right bank while the other one is in equilibrium with the left bank, the energy difference for such a "critical pair" is equal to $\varepsilon_i - \varepsilon_j - eV$. In the low temperature regime ($T < |\varepsilon_i - \varepsilon_j|$) and for $eV > T$ one expects the choice of the critical pair, and, correspondingly, the hopping probability, to be crucially dependent on the bias. Note that the nonlinearity related to electric field dependence of the sites' energies was first considered for the bulk case by Shklovskii [3].

While we are going to consider the hopping conductivity through a point contact in more detail elsewhere, here we give semiqualitative arguments concerning the extreme situation $d < l$, l being the hopping length. It is this situation which was ascribed by the authors of [1] to their experiment. Considering the critical pair mentioned above one notes that the most probable pair with energy separation δE and spatial separation l corresponds to the relation $g(\delta E)\delta E l^3 \sim 1$. To ensure the lowest possible resistance, the values of l and of δE should be optimized in the way standard for the variable range hopping. Since the effect of activation on the resistance is different for different temperatures, the relation between l and δE is expected to be different for different temperatures. Therefore the pairs responsible for the critical hop are expected to be different for different T. The same conclusion is expected for the bias if $eV > \delta E(T)$. Estimating the value of l for $\delta E = eV$ and calculating the corresponding tunneling probability one obtains in average for $g = \text{const}$,

$$R \propto \exp\left(\frac{1}{geVa^3}\right)^{1/3}. \quad (2)$$

Thus a strong bias dependence of R is expected even for $g = \text{const}$. Since this effect is much stronger than the "spectroscopical" factor of Eq. (1), to our opinion it can hardly be ignored if the hopping transport is indeed dominated by a single "effective resistor."

Another important feature expected for the hopping transport controlled by a single hop is its "mesoscopic" character. Indeed, the choice of the optimal pair with a variation of T or V leads to large fluctuations of the hopping exponent with a magnitude of the order of the average value. (Note that qualitatively similar considerations concerning both nonlinear conductance and mesoscopic behavior were given for "point" tunnel junctions in Ref. [4].) In any case one can not expect that the corresponding device can give any information concerning DOS since the latter implies an average over plenty of realizations. It can rather give information concerning the (occasional) distribution of sites in the contact region.

At the same time the device reported in [1] exhibits no pronounced mesoscopic fluctuations. This fact as well as the large value of the conductance (of the order of $0.25e^2/h$) proves in our opinion that this device does not exhibit "single hop" transport. Correspondingly, the interpretation of the experimental results obtained in [1] still needs some further insight to the problem.

V. I. Kozub
A. F. Ioffe Physico-Technical Institute
194021, St. Petersburg, Russia

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