Anomalously narrow Coulomb gap

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(Submitted 29 September 1993)
Pis'ma Zh. Eksp. Teor. Fiz. **58**, No. 10, 809–813 (25 November 1993)

Many-electron correlations are likely in the hopping motion of localized charge carriers when the impurity band is approximately half-filled. These correlations should make the Coulomb gap narrower than in the Éfros–Shklovskiĭ one-electron limit. A narrowing of this sort, by about an order of magnitude, has been observed experimentally in a "K=0.3" lot of samples of neutron-transmutation-doped Ge:Ga.

Studies of an N series of samples—heavily doped and compensated GaAs:Si, Ge:P, Ge:As, and Ge:Ga with a fixed concentration (N) of the primary dopant and a variable compensation K (Refs. 1–5)—and also a $K=0.2$ series—of 6H SiC:N samples (Refs. 6 and 7) in which the value of N was varied—have furnished an empirical law for the activated low-temperature conductivity:

$$\sigma=\sigma_0 \exp[(T_0/T)^x], \tag{1}$$

where $x = 1/2$, and the values of T_0 vanish at the metal–insulator junction.

The interpretation of (1) in the model of a hopping conductivity with a variable hopping range (VRH), without any additional assumptions, led to the conclusion[2–7] that a parabolic gap exists at the Fermi level when the density of states satisfies

$$g=g_0(E-E_F)^2. \tag{2}$$

According to the Pollak–Hamilton formula,[8,9] we have

$$T_0=A/g_0^{1/3}a, \tag{3}$$

where A = const, and a is a localization radius.

It turns out[3,5] that the values found experimentally for the coefficient g_0 in the N series in the limit $K \to 0$ are close to the prediction of the Éfros–Shklovskiĭ model for a Coulomb gap:[10]

$$g_0\simeq\kappa^3/e^6, \tag{4}$$

where κ is the permittivity. It was on this basis that the gap which was detected was identified in Refs. 3-5 as the Coulomb gap of Éfros and Shklovskiĭ. This was also the basis for the establishment of a correspondence between (on the one hand) the empirical divergence of the coefficient g_0 and the closing of the gap at the metal–insulator junction and (on the other) the divergence of the constant κ.

In the theory (see the paper by Pollak and Ortuno[11] and the papers cited there), however, there have been repeated discussions of the idea that the regime of one-electron hops might be less probable than one of correlated many-electron hops.

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Unfortunately, for the latter case there are no analytic expressions like (2) and (4) which would make it possible to describe a macroscopic hopping conductivity under VRH conditions by analogy with Eqs. (1) and (3). For this reason, the observation of many-electron correlations experimentally in the course of a hopping motion of charge carriers is by no means a simple problem. This problem is the subject of the present letter.

We first note that many-electron correlations should be sensitive to the extent to which the impurity band is filled (compensation). In the limit $K \to 1$, there are few charge carriers, while in the limit $K \to 0$ there are few vacant states in the band. In both cases, conditions are unfavorable for the correlations in which we are interested here. Incidentally, this circumstance verifies the result[3,5] cited above: the experimental confirmation of a one-electron Coulomb gap in the limit $K \to 1$. Moderate compensation levels, not greatly different from 1/2, are most favorable for many-electron correlations. One might attempt to detect such correlations experimentally on the basis of a deviation of the density of states in the Coulomb gap from the prediction of the one-electron model[10] [see (2) and (4)]: If many-electron transitions are predominant, the density of states for these transitions will be greater than (2), while the corresponding Coulomb gap will, on the contrary, be narrower. Here we need to recall the dynamics of both gaps on the insulator side of the metal–insulator junction due to the divergence of the dielectric constant κ. It is therefore correct to make the comparison (as mentioned above) of the density of states in the gap in the "insulator limit": far from the metal-insulator junction, where the parameter κ can be regarded as constant.

For some of the experiments we selected a "$K = 0.3$" series of neutron-transmutation-doped Ge:Ga. At a fixed value of the compensation, these samples differed from each other in doping level, which was proportional to the neutron flux. (The reader interested in the procedure for preparing the material and in the parameters characterizing it is referred to Ref. 12.) Low-temperature measurements were carried out in a cryostat with He^3 evacuation.

A first series of experiments was devoted to testing law (1) with $x = 1/2$ over the entire range of concentrations (N) of the main dopant,[1)] Ga, which we studied: $2 \times 10^{16} \lesssim N < 2 \times 10^{17}$ cm^{-3}. The temperature dependence of the hopping conductivity was studied through an analysis of the behavior of the corresponding activation energy divided by the temperature (Ref. 5, for example):

$$w = \epsilon/kT = -\partial \log \rho / \partial \log T. \quad (5)$$

We used both a graphical differentiation procedure and numerical methods. Figure 1 shows some results for some typical Ge:Ga samples found by the graphical procedure. We see that at temperatures $T \leqslant T_V \lesssim 1$ K the hopping conductivity (VRH) obeys law (1) with the parameter value $x \approx 1/2$; this value is essentially independent of the doping level. Approximately the same values of x are found by a numerical fit of expression (1) at temperatures $T \leqslant T_V$. We used the same procedure to find values of T_0 and ρ_0. Figure 1 shows a corresponding family of curves.

As can be seen from the behavior of the reduced activation energy in the inset in Fig. 1, the high-temperature boundary (T_V) of the VRH regime is not defined clearly

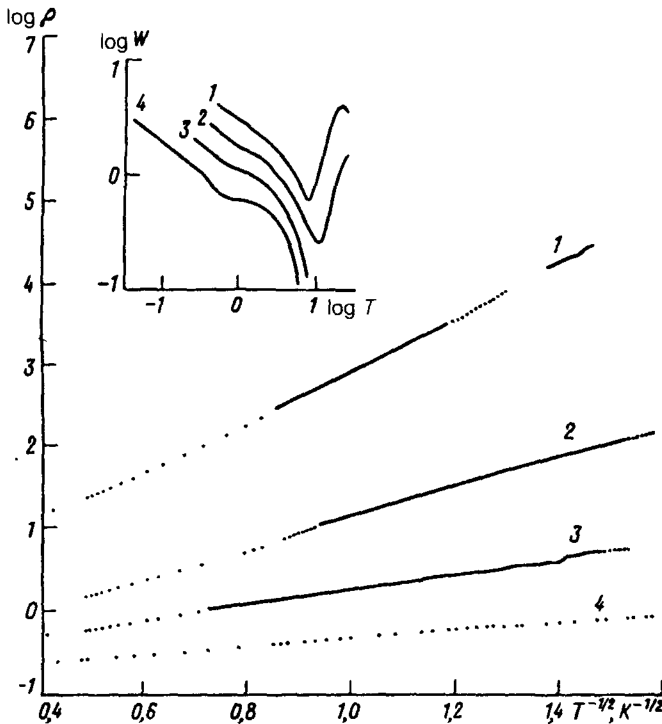

FIG. 1. Resistivity of neutron-transmutation-doped Ge:Ga in the region of a variable-range hopping. *1*—The gallium concentration N is (in units of 10^{16} cm^{-3}) 4.74; *2*—9.62; *3*—12.8; *4*—16.8. The inset shows the reduced activation energy over a broad temperature range.

enough that we could, by analogy with Refs. 3–5 and 7, use Zabrodskiĭ's idea[3] of directly determining the width of the parabolic Coulomb gap from T_V measurements and then subtracting the coefficient g_0 and the behavior of the density of states in it. (The "blame" for the poor definition of this high-temperature boundary is the region of saturation of the hopping conductivity.[12]) We will therefore attempt to derive the necessary estimates on the basis of expression (3) for the coefficient T_0 and an independent determination of the localization radius a.

Figure 2 shows values of T_0 found by a fitting procedure. The values vanish near the metal–insulator junction. Far from the junction, the concentration dependence $T_0(N)$ weakens, with the result that near the so-called boundary of the region of intermediate doping,[12] $N \simeq N_I = 2 \times 10^{16}$ cm^{-3}, we have

$$T_0 = 7.5 \pm 0.5 \text{ meV}. \quad (6)$$

According to data[12] from a study of the region of saturation of the nearest-neighbor hopping conductivity of neutron-transmutation-doped Ge:Ga, the hopping transport in this material at $N \leqslant N_I$ is determined by the first Bohr radius of a light hole, $a = a_0 = 90$ Å. Toward the point $N = N_c$ of the metal–insulator junction, the

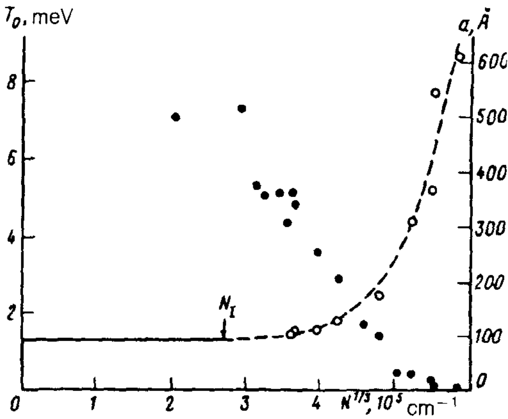

FIG. 2. Behavior of the parameter T_0 (●) and a (○) for variable-range hopping in NTD Ge:Ga.

values of the localization radius a diverge,[5,7] in accordance with the divergence of the correlation length in the scaling theory. To see a picture of the entire concentration dependence of a, we used an idea from Shklovskiĭ to determine the localization radius, as we did in Ref. 7. That idea is based on parallel measurements of the positive magnetoresistance under VRH conditions and was first implemented in Ref. 15. The results are shown in Fig. 2. We see that the values measured for a by this method do indeed diverge at the point of the metal–insulator junction. As we move away from the junction, toward the boundary ($N=N_I$) of the region of intermediate doping, the values asymptotically approach a_0 at $N \leqslant N_I$.

A study of the variable-range hopping at concentrations close to the value $N \simeq N_I$ thus yields $a = a_0$. Working from (6) and (3), we thus find the estimate

$$(g_0^{1/3}/A)_{\text{exper}} = 1.5 \times 10^8 \text{ cm}^{-1} \cdot \text{eV}^{-1}. \tag{7}$$

On the other hand, for the Efros–Shklovskiĭ Coulomb gap, with g_0 from (4) and[10] $A = 2.8$, we find

$$g_0^{1/3}/A = 4 \times 10^7 \text{cm}^{-1} \cdot \text{eV}^{-1}. \tag{8}$$

Since the quantity A in (3) is independent of the parameters a and g_0 , the difference between our result in (7) and the theoretical prediction in (8) stems from the circumstance that in neutron-transmutation-doped Ge the value of $g_0^{1/3}$ is about four times that predicted by the one-electron theory, (4). Correspondingly, the gap is narrower by a factor of $4^{3/2} = 8$. A similar estimate of the gap width follows from an analysis of the values of T_V, which are proportional to the width of the Coulomb gap.[3-5,7]

This "insulator limit" of the Coulomb gap in neutron-transmutation-doped Ge:Ga, for which the value $g \simeq C(\kappa^3/e^6)(E-E_F)^2$ with $C \simeq 64$ is found, differs from the $K \to 1$ limit for highly compensated semiconductors,[3,5] with $C \simeq 1$ (Fig. 3). We explain this anomalously narrow Coulomb gap in the $K=0.3$ series of samples of neutron-transmutation-doped Ge:Ga on the basis of the idea of correlated many-

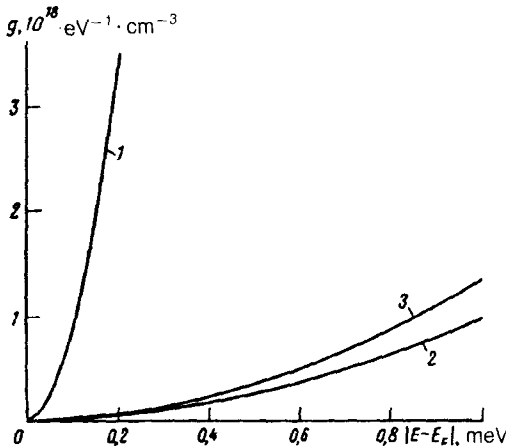

FIG. 3. Density of states in the Coulomb gap for Ge in the "insulator limit," *1*—Data of the present study on NTD Ge:Ga ($K=0 \times 3$, $N \approx N_I \approx 0.1 N_c$); *2*—data of Ref. 6 on Ge:As [$K=0.98, n=N(1-K)=1.4 \times 10^{16}$ cm^{-3} $\approx 0.035 N_c$]; *3*—according to the Efros–Shklovskiĭ- model,[10] (4) with $\kappa=16$.

electron hops. Experiment shows that a many-electron nature of the situation causes a narrowing of the Coulomb gap, while leaving it parabolic. The effect is equivalent to a reduction of the effective charges in the one-electron model.

This decrease in the parameter T_0 for VRH implies that the activation energy for the hops is roughly half that predicted by the one-electron theory. It is interesting to note that there is a corresponding discrepancy for the NNH regime.[12]

We wish to thank D. V. Shamshur for cooperation in the low-temperature measurements.

[1)]According to the data of Ref. 13, the parameter $x=x(N)$ in neutron-transmutation-doped Ge:Ga runs through the values 3/4, 1/2, and 1/4 rapidly with distance away from the metal–insulator junction. According to data from a study[14] of the sensitive elements of deeply cooled bolometers of neutron-transmutation-doped Ge:Ga with $N=4 \times 10^{16}$ cm^{-3}, on the other hand, the value is $x \simeq 1/2$. This result contradicts the value of 1/4 from Ref. 13 which we just cited. According to the data of Ref. 12, the value is $x \simeq 1/2$ for neutron-transmutation-doped Ge:Ga samples in which the doping is not heavy.

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Translated by D. Parsons