Critical behavior of n-Ge parameters in the region of compensation-induced Anderson transition

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The critical behavior of low-temperature electrical conductivity of n-Ge and the parameters that determine it are investigated in the region of the compensation-induced metal-insulator transition.

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1. The recent scaling theory of the metal-insulator transition (see, for example, Refs. 1–3) describes the critical behavior of the properties of a system in analogy with phase transitions in the form of power-law functions Φ of the coherence length ξ:

$$\Phi(\xi) = \Phi^* \, |1 - n/n_c|^{\nu_\Phi}, \tag{1}$$

where $\xi = \xi^*|1 - n/n_c|^{\nu_\xi}$, while Φ^*, ξ^*, ν_Φ and $\nu_\xi (\nu_\xi \cong -1)$ are coefficients that are independent of the ratio of uncompensated charge carrier density n to the critical value n_c.

The scaling approach was used in Ref. 4, in the case of the metal-insulator transition in a compensated semiconductor, to describe the vanishing of the metallic conductivity. We report the main results obtained in an investigation of the critical behavior of low-temperature conductivity and the parameters that determine it on both sides of the transition for compensated germanium.

2. A series of n-Ge specimens close to a transition with a main impurity concentration $N \cong (6–7) \times 10^{17}$ cm^{-3} and compensations $0.7 \gtrsim K \gtrsim 0$ was obtained in analogy with Ref. 5 by compensating n-Ge: As with an admixture of Ge during neutron doping. The electrical conductivity was also measured at constant current and at temperatures $T \lesssim 1$ K with a S-72D bridge at a frequency 237 Hz. The results of measurements of the resistivity $\rho(T)$ of typical specimens are shown in Fig. 1.

On the insulator side of the transition, for sufficiently low temperatures $T \lesssim T_v$ $\rho(T)$ has an exponential behavior with variable activation energy:

$$\rho(T) = \rho_0 \exp(T_0/T)^x. \tag{2}$$

Excluding the vicinity of the transition, we have $x \cong 0.5$ to within several percent. In the hopping conductivity model with variable hopping length [so-called variable range hopping (VRH)], Eq. (2) corresponds to the presence of a parabolic quasigap $g(E) = g_0(E - E_F)^2$ in the density of localized states in the vicinity of the Fermi level E_F. Far from the transition the constant g_0, estimated experimentally in Ref. 5, corresponds to the predictions of the theory of Éfros and Shklovskiĭ.[6] For $n \to n_c$ the index x decreases slightly ($x \cong 0.4$ in No. 4), which could be a result of the fact that the para-

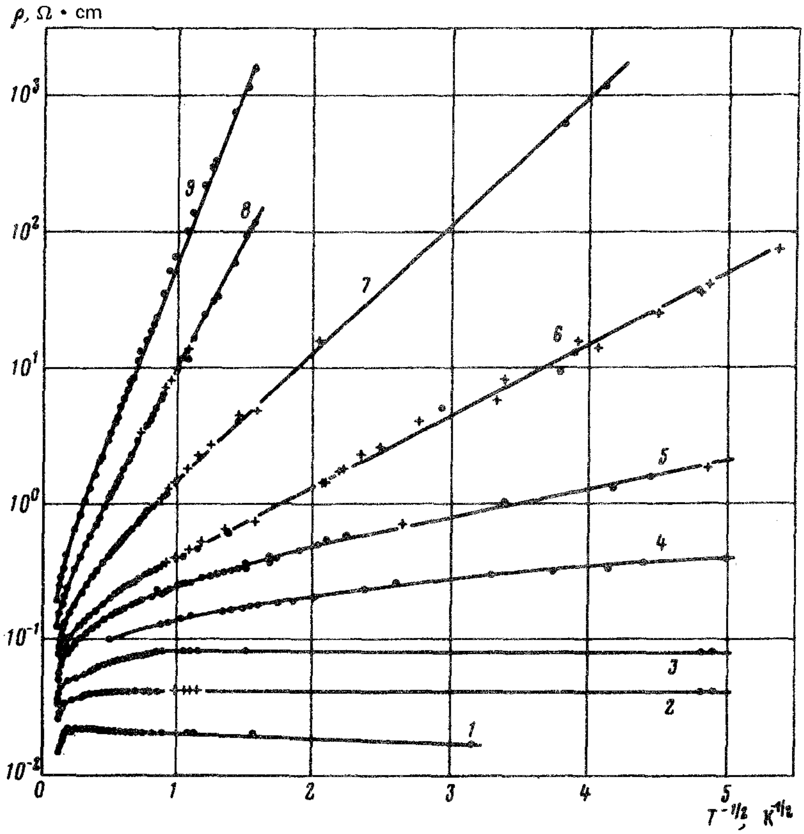

FIG. 1. Resistivity at constant current (●) and at a frequency of 237 Hz (+). The concentration n 10^{17} cm^{-3} 1—5.7; 2—4.5; 3—4.1; 4—3.8; 5—3.6, 6—3.3; 7—2.66; 8—2.24; 9—1.9.

bolic quasigap on the insulator side continuously transforms with the transition the Al'tshuler and Aronov square-root singularity.[7]

In the critical region, we have a certain temperature range (on the insulator side, they precede VRH)

$$\rho(T) \propto T^{-m}. \tag{3}$$

The index m on the insulator side decreases continuously from values $\lesssim 1$ (Nos. 8 and 9), vanishing on the metal side and then changes sign (No. 1).

3. From the condition that the activation energy of VRH vanish, it was found that the transition occurs with $n_c = 4.0\times 10^{17}$ cm^{-3} and $K_c \equiv 1 - n_c/N \cong 0.3$.

The critical behavior of the metallic conductivity $\sigma(0) \equiv \lim_{T\to 0}\sigma(T)$ is shown in Fig. 2. In accordance with (1), $\sigma(0) = A\sigma_M$, where $A \cong 13$, and $\sigma_M \cong 0.05(e^2/\hbar)n_c^{1/3} \cong 9$ (Ω cm^{-1}) is the computed value of the Mott minimum metallic conductivity, while the index $\nu_{\sigma(0)} \cong 0.80 \pm 0.15$. The latter corresponds to the data in Ref. 4 for compensated

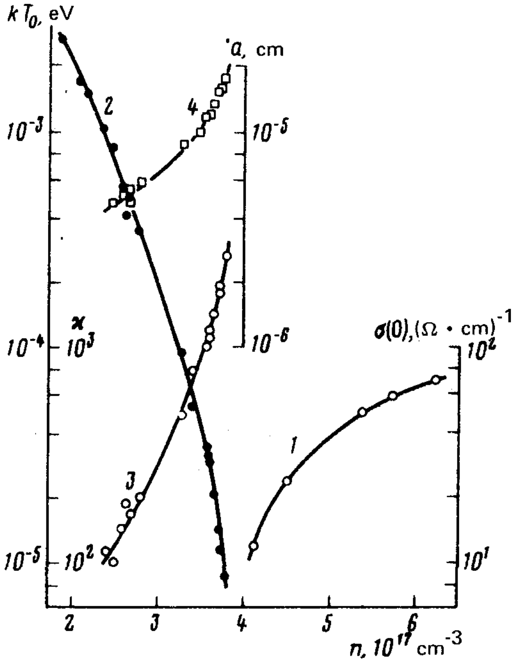

FIG. 2. Critical behavior of $\sigma(0)$ (1), T_0 (2), κ (3), and a (4).

Ge:Sb, while the quantity A is several times higher and coincides with its value in uncompensated Si:P.[8]

On the insulator side, the critical behavior of T_0 and T_v is identical: $T_0^* \cong 30$ K, $T_v^* \cong 20$ K, and $\nu_{T_0, T_v} \cong 2.0 \pm 0.2$ (see Fig. 2). Since the width of the Coulomb gap Δ is of the order of kT_v (k is the Boltzmann's constant), its collapse is described by analogous parameters. In particular, Δ^* has a reasonable magnitude of the order of the width of the impurity band.

The pre-exponential VRH factor does not have a singularity at the transition, so that the following limit exists:

$$\lim_{n \to n_c - 0} \rho_0 \equiv \rho_0^{min} \equiv (\sigma_a^{max})^{-1}, \tag{4}$$

where $\sigma_a^{\max} \cong 10$ $(\Omega\text{·cm})^{-1}$ is the upper limit for the activation conductivity, which represents the temperature independent, i.e., metallic, conductivity, since $\lim_{n \to n_c - 0} T_0 = 0$. If there also exists a Mott σ_M, conductivity in the system, then our conductivity $\sigma_a^{\max} = \sigma_M$.

4. This part of the paper is concerned with an analysis of data on the insulator side of the transition within the scope of the VRH model in order to clarify the critical behavior of the localization radius a and the static dielectric constant κ. First, as in Ref. 5, by equating the densities of states in the Coulomb gap and in the impurity band, the coefficient g_0 and its divergence were determined.

This divergence is primarily due to the weakening of the Coulomb interaction due to the divergence of κ. To estimate the latter, we used the theory of Éfros and Shklovskiĭ,[6] according to which

$$\kappa \cong e^2 g_0^{1/3}. \tag{5}$$

It turned out that $\kappa^* = 3\kappa_0$, where $\kappa_0 \cong 16$ is the static dielectric constant of Ge in the case of isolated impurity states, i.e., far from the transition on its insulator side, while $\nu_\kappa = -(1.3 \pm 0.2)$. Our index ν_κ is close to the result in Ref. 10, obtained from direct measurements of κ in uncompensated Si:P.

The quantity a was determined from the well-known ratio for VRH in a parabolic quasigap:

$$a = \beta / g_0^{1/3} k T_0 , \tag{6}$$

where $\beta \cong 2.8$.[9] For the divergence of a obtained from here (Fig. 2), $a^* \cong 3 \times 10^{-6}$ cm and $\nu_a = -(0.70 \pm 0.15)$. The relation $|\nu_a| \cong \nu_\sigma \cong |\nu_\xi|$ following from our data agrees with the scaling theory. As follows from this work, this theory adequately describes the Anderson transition in a compensated semiconductor if the correlation effects leading to the Coulomb gap are included (see, for example, Ref. 3). We also call attention to the fact that the critical indices found above slightly exceed the indices which determine the metal-insulator transition in a uncompensated semiconductor.[8,10] This means that introduction of a disordering factor (compensation) washes out the transition, making it less abrupt.

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