Quantum localization of electrons in the metal-insulator transition region in GaSb ⟨Se⟩

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As the electron density in the Γ band is reduced in Se-doped GaSb single crystals, the quantum corrections to the conductivity cause a pronounced localization of electrons. This localization sets in at the Fermi energy, ~25 meV, reckoned from the bottom of the undistorted Γ band.

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1. Of fundamental importance to the theory of the metal-insulator transition in the impurity band of doped semiconductors are the mobility threshold $\mathscr{E}_c$ and its position with respect to the unperturbed boundary ($\mathscr{E}_c^0$) of the conduction band in the undoped semiconductor matrix.

In the classical percolation approach[1] to this problem, the mobility threshold $\mathscr{E}_c^{c1}$ is associated with the level of the percolation of metallic-conductivity regions through the system. According to Zallen and Scher,[1] the percolation level must be below $\mathscr{E}_c^0$ in this problem in the three-dimensional case (Figs. 1a and 1b).

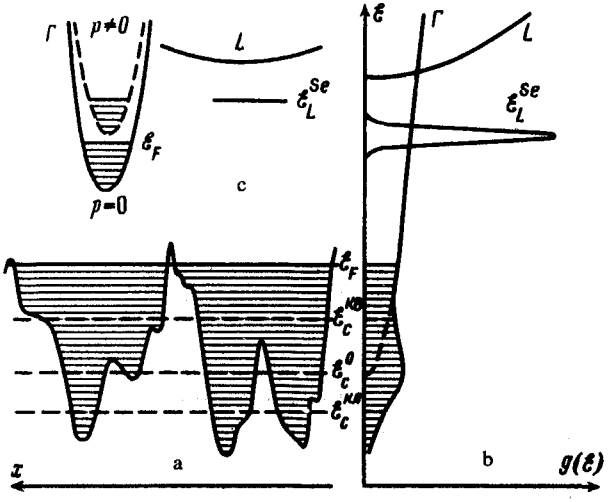

FIG. 1. a—Distortion of the relief of the bottom of the Γ band caused by the random impurity potential; b—state density $g(\mathscr{E})$ in the GaSb ⟨Se⟩ conduction band; c—pressure-induced changes in the GaSb ⟨Se⟩ spectrum.

As we approach the metal-insulator transition from the side of the metal in a quantum-mechanical analysis, we should consider effects such as above-barrier reflection from the potential relief of the bottom of the band—effects ignored in the classical determination of $\mathscr{E}_c$. In the theory of the quantum corrections to the conductivity,[2,3] the interference of the wave functions of the electrons which results from the above-barrier reflection intensifies as the Fermi level $\mathscr{E}_F$ approaches $\mathscr{E}_c^0$, and at a certain value $\mathscr{E}_F = \mathscr{E}_c^{qu} > \mathscr{E}_c^0$ this interference can cause a localization of electrons. In the three-dimensional case the quantum corrections to the conductivity near the metal-insulator transition may be so large that they in fact determine the mobility threshold.

To the best of our knowledge, however, no reliable experimental data have been reported on the position of the $\mathscr{E}_c$ level with respect to $\mathscr{E}_c^0$. In this letter we report a study of this question.

2. We selected Se-doped GaSb for the experiments. In GaSb ⟨Se⟩ single-crystal samples with a selenium concentration $n_{Se} = 3\times10^{17}$–10^{18} cm^{-3} the condition for strong doping for the Γ band and that for weak doping for the L band (Fig. 1c) can be satisfied simultaneously. The reason lies in a difference in Bohr radius, $a_B^\Gamma \gg a_B^L$, which leads to

$$(a_B^\Gamma)^{-3} << n_{Se} << (a_B^L)^{-3} \tag{1}$$

Under a pressure p the energy distance between the Γ and L bands, 93 meV at $p=0$ (Ref. 4), decreases at a rate[4] $\sim$10 meV/kbar, and at a certain p_0 electrons from the Γ band begin to move to the impurity level $\mathscr{E}_L^{Se}$ (Fig. 1c). As a result, at $p<p_0$ the concentration of Γ electrons does not change, and we have $\mathscr{E}_F(p)\approx$const (Fig. 2). At $p>p_0$, the value of $\mathscr{E}_F(p)$ decreases. Since the current flow through the $\mathscr{E}_L^{Se}$ band is

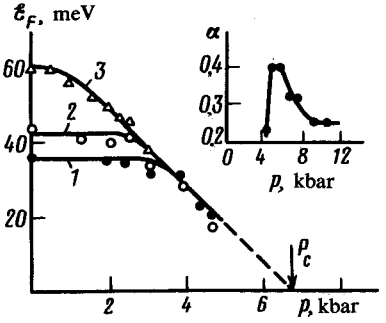

FIG. 2. Pressure dependence of the Fermi energy, reckoned from $\mathscr{E}_c^0$, for various GaSb ⟨Se⟩ samples ($p_c \approx 6.7$ kbar). The values of $\mathscr{E}_F$ are calculated from the period of the Shubnikov–de Haas quantum oscillations of the magnetoresistance at $T = 4.2$ K. The parameters of the spectrum used for the calculation are given in Ref. 4. The inset shows the pressure dependence $\alpha(p)$ for sample No. 1.

negligible in these GaSb ⟨Se⟩ samples over the entire pressure and temperature ranges,[5,6] the application of pressure makes it possible to work from oscillation and galvanomagnetic effects to study the Γ-band conductivity as $\mathscr{E}_F$ moves smoothly from $\mathscr{E}_F(p=0)$ through $\mathscr{E}_c$ and ultimately becomes completely emptied at $\mathscr{E}_F \ll \mathscr{E}_c$ (Fig. 1). Another reason for choosing GaSb ⟨Se⟩ is the significant region of localized states in the tail of the Γ band in this compound.[5,6]

3. The position of the unperturbed boundary of the Γ band, $\mathscr{E}_c^0$, can be found from the critical pressure p_c corresponding to the point at which $\mathscr{E}_F$ crosses $\mathscr{E}_c^0$ (Fig. 2). The pressure p_c can be determined by extrapolating the curve of $\mathscr{E}_F(p)$ to the value $\mathscr{E}_F = 0$, since condition (1) makes the change in the electron dispersion law negligible far from $\mathscr{E}_c$ in the Γ band.

As the pressure is raised, the temperature dependence of the resistivity, $\rho(T)$, changes qualitatively (Fig. 3): The metallic behavior $\rho(T)$ at $p \lesssim 2$ kbar (curve 1) gives way at $p \sim 3$ kbar to a power-law dependence $\rho \sim 1/T^{\beta}$ with $\beta = 0.28$ (curve 2); then, at $p \gtrsim 4$ kbar, the behavior becomes exponential,

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

It is convenient to plot expression (2) in the coordinates $\ln\ln\rho = f(\ln T)$. In these coordinates, under the condition $\ln\rho_0 \ll (T_0/T)^{\alpha}$—which always holds at sufficiently low temperatures—the linear regions correspond to an exponential dependence $\rho(T)$, and their slopes give us the exponent α.

The value of α varies nonmonotonically with the pressure (see the inset in Fig. 2): There is a maximum, $\alpha = 0.4$, at $p \sim 5$ kbar, and a tendency toward the Mott value $\alpha = 0.25$ at $p \gtrsim 9$ kbar. This behavior of $\alpha(p)$ agrees qualitatively with the predictions of the scaling theory of the metal-insulator transition,[2,3,7] according to which the conductivity σ in the insulating phase has a temperature dependence $\sigma \sim \exp(-\gamma L_T)$, where γ^{-1} is the localization radius, and L_T is a characteristic length, related to the temperature by $L_T \propto T^{-1/2}$ (Ref. 7).

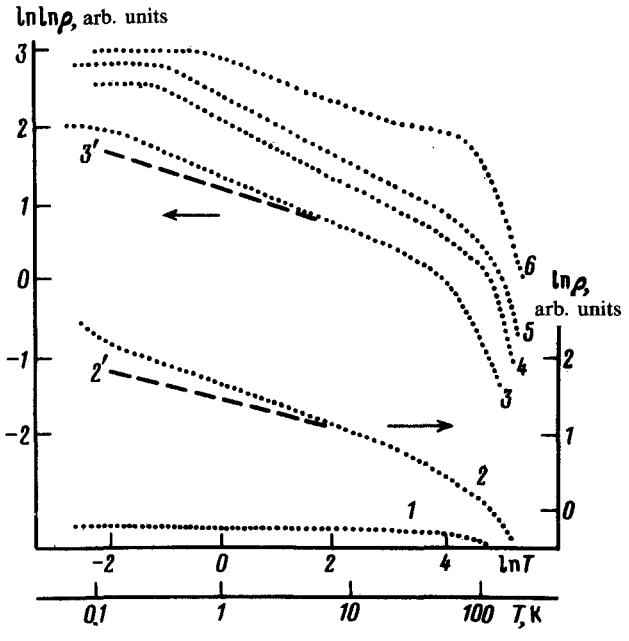

FIG. 3. Temperature dependence of the resistivity, $\rho(T)$, for various pressures (kbar): 1—$p = 0$; 2—2.8; 3—3.7; 4—5.0; 5—5.7; 6—9.0. For curves 3–6 the values of the parameter α in expression (2) are as follows: 3—$\alpha = 0.32$; 4,5—$\alpha = 0.4$; 6—$\alpha = 0.33$. Curves 2′ and 3′ were obtained in a magnetic field of 50 kOe and correspond to the same pressures as curves 2 and 3. For curve 2′, we have $\beta = 0.18$, while for curve 3′ we have $\alpha = 0.24$.

Interestingly, the exponential dependence $\rho(T)$ appears at pressures considerably (about 2.5 kbar) lower than p_c, i.e., when $\mathscr{E}_F$ lies ~ 25 meV from $\mathscr{E}_c^0$ and the carrier concentration in the Γ band is $\sim 2\times 10^{17}$ cm^{-3}.

Since $\mathscr{E}_c^{cl} < \mathscr{E}_c^0$, the appearance of an exponential temperature dependence of ρ at $\mathscr{E}_F < \mathscr{E}_c$ could not result from the crossing of the classical percolation level by $\mathscr{E}_F$; it is apparently caused by a quantum localization of electrons in the Γ band because of above-barrier reflection. This conclusion is also supported by the power-law dependence $\rho \sim T^{-\beta}$ near $\mathscr{E}_c$ (preceding the appearance of the exponential behavior) with $\beta = 0.28$, in agreement with the value $\beta = 1/3$ predicted in Ref. 3.

The suggestion that quantum corrections play a dominant role in the conductivity near the metal-insulator transition is also supported by the behavior of the magnetoresistence: At $\mathscr{E}_F \sim \mathscr{E}_c$ we see a negative magnetoresistance (curves 2′ and 3′ in Fig. 3), with a power-law temperature dependence in the metallic phase (curve 2′ in Fig. 3) and an exponential dependence in the insulating phase (curve 3′ in Fig. 3).

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