Study of hopping conductivity in GaSb⟨Te⟩

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The density-of-state function and the impurity-band conductivity, which was split off from the L extremum, were investigated concurrently in GaSb⟨Te⟩. A transition from Mott's law, which occurs over a broad temperature range 0.38 K $< T <$ 50 K, to a power-law dependence $\rho \sim 1/T^{a}$ (0.08 K $< T <$ 0.38 K), which was predicted by Pollak [J. Non-Cryst. Solids **35–36**, 83 (1980)] for a cascade, many-electron, hopping conductivity, was detected.

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1. The study of hopping conductivity (HC) in disordered systems continues to generate a great interest. A hopping conductivity with a variable hopping length, which is described by Mott's law if the density of states near the Fermi level is constant $\epsilon_F g\,(\epsilon_F \pm \Delta\epsilon/2) = \text{const}$, can occur at sufficiently low temperatures[2]

$$\rho \sim \exp\,(T_0/T)^{p}, \tag{1}$$

where the exponent $p = \frac{1}{4}$. Allowance for electron-electron interaction[3] leads to the formation of a "Coulomb gap" in the density of states $g(\epsilon)$ and to a breakdown of the condition $g(\epsilon_F \pm \Delta\epsilon/2) = \text{const}$. The exponential dependence (1) of the resistivity ρ on the temperature T in this case remains, but the exponent changes to $p = 1/2$.[4] Pollak[1] has recently analyzed the contribution to HC from cascade single-electron jumps. Since this process can become dominant at extremely low temperatures, its contribution to transport phenomena is greater than that from single-electron jumps. A characteristic feature of cascade excitations is the power-law temperature dependence of the resistivity

$$\rho \sim 1/T^{\alpha}. \tag{2}$$

Here $\alpha = (2\ln d_0)\bar{r}/a$, $\bar{r}$ is the average length of the jump, and d_0 is the $\bar{r}$-dependent constant; $d_0 \sim 6$ for $\bar{r} \sim a$ (a is the localization radius).[1] The exponential dependence (1), therefore, becomes a power-law dependence (2) as a result of lowering the temperature. As far as we know, such a transition has not been observed until now.[5]

2. In this letter we report the results of an investigation of HC in an impurity band (an impurity band, which has been split off from the L extremum, is considered here) of GaSb ⟨Te⟩ in the temperature range 0.08–300 K at pressures up to 15 kbar. Under a pressure we were able to vary the population of an impurity band within certain limits (Fig. 1) and to obtain reliable information on the structure of the $g(\epsilon)$ density-of-states function in it, without which the results could not be interpreted unambiguously.

3. The method of oscillation and galvanomagnetic measurements at helium temperatures and pressures up to 15 kbar was described in detail elsewhere.[6] Superlow temperatures down to 80 mK were obtained by an He^3-He^4 dissolution refrigerator.

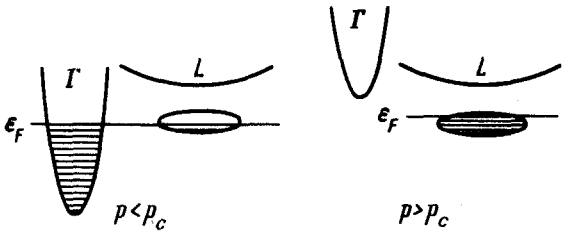

FIG. 1. Reconstruction of the energy spectrum of GaSb ⟨Te⟩ under pressure. Critical pressure p_c corresponds to a total depopulation of the Γ band.

The experiments were carried out using GaSb ⟨Te⟩ single crystals with a Te concentration $(2\text{–}3)\times 10^{17}$ cm^{-3} at which only the Γ band can be doped heavily, whereas the doping of an impurity band, which was split off from the L extremum, was slight. Since the quality of surface treatment can affect the $\rho(T)$ dependences,[5] the samples under study were etched thoroughly in a polishing etching agent $5HNO_3$: $3HF{:}3CH_3COOH$.

4. The structure of the band spectrum of GaSb is such that the relative location of the Γ band and of the impurity level near the Γ band can be varied under a pressure. This allows the Γ electrons to move across to this level (Fig. 1).[6,7] The population of the Γ band at different pressures, which can be accurately determined from the oscillation measurements,[6] in this case can be used to determine the number of

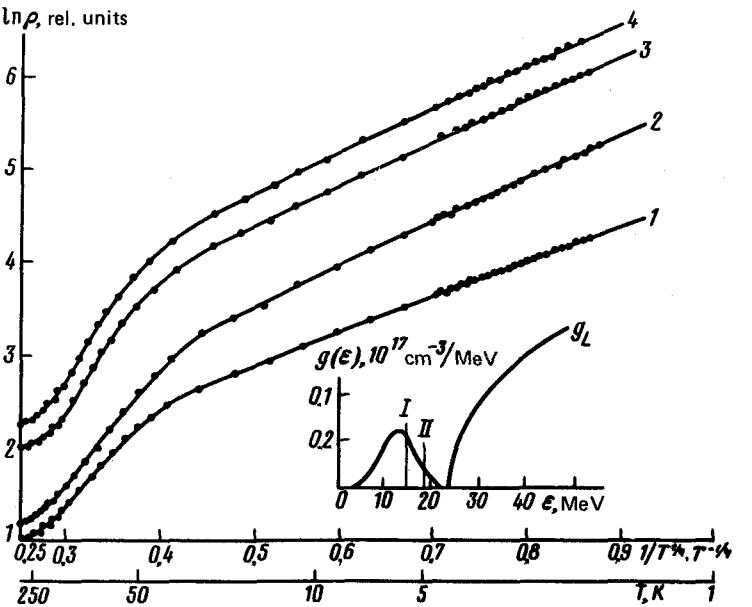

FIG. 2. $\rho(T)$ dependences for different pressures (kbar). 1, 8.55; 2, 9.8; 3, 13.3; 4, 14.7. The curve for the density of states $g(\epsilon)$ near the L extremum and the location (shown schematically) of the Fermi level in the impurity band at $p = 8.55$ kbar (I) and at $p \gtrsim 9.8$ kbar (II) are illustrated in the inset.

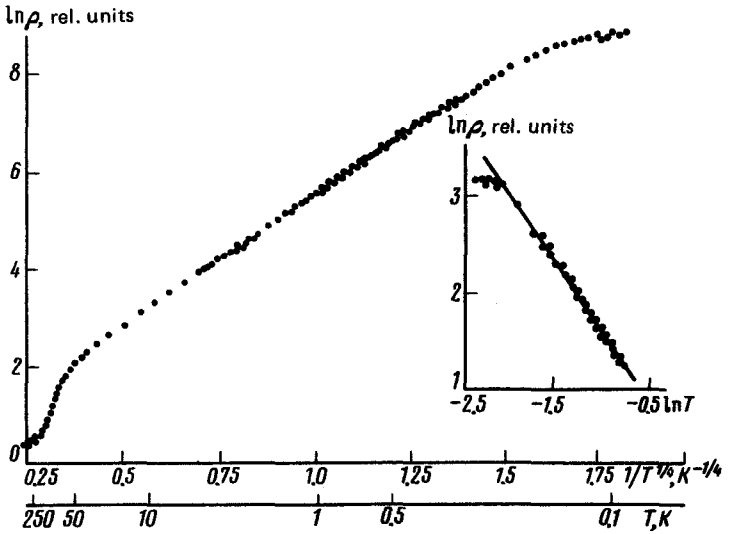

FIG. 3. $\rho(T)$ dependence at $p = 9.8$ kbar. The straight line plotted in the inset corresponds to the power law $\rho \sim 1/T^{1/4}$.

Γ electrons that move to the impurity band and to reconstruct the density-of-states curve for it (see inset in Fig. 2). There was no evidence of a local decrease of $g(\epsilon)$ near the Fermi level, which is associated with the formation of a Coulomb gap. The Γ band was almost empty and the impurity band was more than half populated in the pressure range $8.55 \lesssim p \lesssim 9.8$ kbar; this population was varied by transferring the electrons from the "tail" of the Γ band. At $p \gtrsim 9.8$ kbar the electron transfer stopped and the Fermi level was located in the impurity band (see inset in Fig. 2).

5. The characteristic temperature dependences $\rho(T)$ for different locations of the Fermi level in the impurity band are shown in Figs. 2 and 3. Distinct linear sections corresponding to Mott's law can be seen on all the curves $\ln\rho = f(T^{-1/4})$. The slope of these sections increases with decreasing density of states at the Fermi level as the pressure increases from 8.55 to 9.8 kbar. The value of T_0 in Eq. (1) is constant and equal to 1680 K in the range $p \gtrsim 9.8$ kbar.

It is interesting to note that agreement with the Mott's law has been observed for the first time in such a broad temperature range (see Fig. 3)—from 50 K to 0.38 K—in which the temperature varies by a factor of approximately 130. Because the dependence $\ln\rho = f(T^{-1/4})$ is linear in such a broad range, it cannot be regarded as a transitional region between one type of ρ dependence on T and another, as suggested by Ootuka *et al.*[5]

The radius r_0 of localized states can be estimated from the T_0 slope (Figs. 2 and 3) by substituting in the formula $r_0^3 = \beta[T_0 k_B g(\epsilon_F)]^{-1}$ the values of T_0 and $g(\epsilon_F)$ measured in the experiment. At $p \gtrsim 9.8$ kbar the radius r_0, calculated for $\beta \approx 20$ (Ref. 8), is equal to $\sim 10\, a_B^L$ (a_B^L is the Bohr radius of the L extremum: $a_B^L \approx 20$ Å).

In the temperature region below 0.38 K Mott's law becomes a power-law depen-

dence $\rho \sim 1/T^{1/4}$ (see inset in Fig. 3), which can be interpreted as the power-law dependence (2) predicted by Pollak[1] for the cascade, many-electron, hopping-conductivity mechanism.

In conclusion, we would like to take this opportunity to thank R. V. Parfen'ev (A. I. Ioffe Physicotechnical Institute, Leningrad) for providing GaSb⟨Te⟩ single-crystal samples.

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