Hopping conductivity in *n*-InSb

E. M. Gershenzon, V. A. Il'in, L. B. Litvak-Gorskaya, and S. R. Filonovich

Moscow State Pedagogical Institute
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It is shown that a new type of photoconductivity—hopping photoconductivity—is realized in maximally purified and compensated *n*-InSb.

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It is customarily assumed that the photoconductivity (PC) is always due to free carriers. Another mechanism of photoconductivity, wherein absorption of the photons facilitate hopping between localized states, is discussed in[1].

We have observed in *n*-InSb a new form of PC—hopping photoconductivity.

We investigated the PC induced in *n*-InSb samples with donor density $N_d \approx (1-2)\times 10^{14}$ cm^{-3} and with compensation $0.8<K<0.95$ by submillimeter and millimeter radiation ($\lambda=0.6-8$ mm). The measurements were performed by a standard modulation procedure at $T=4.2-1.7$ K in magnetic fields $H=0-5$ kOe using spectrometers with backward-wave tubes[2] and with klystrons[3]; the sample was shielded against short-wave radiation.

At $T\lesssim 10$ K, this material has a dark hopping conductivity with activation energy ϵ_3; this conductivity gives way at $T=4$ K to the Mott hopping conductivity.[4] Under these conditions, most electrons are concentrated on donor pairs, which are the analog of the molecular hydrogen ion H_2^+.[5] By way of example we present the results of an investigation of a sample with $N_d \approx 1.5\times 10^{14}$ cm^{-3}, $K=0.9$, and $\epsilon_3=0.7$ meV. In this sample, the characteristic dimension of the H_2^+ donor pairs is $R_D\approx 2a$ (a is the Bohr radius of the electron on the donor), and their ionization energy is $\epsilon_1=1.4$ meV.

The PC was excited by radiation with frequencies such that $\hbar\omega_1\leq\epsilon_1$ or $\hbar\omega \ll \epsilon_1$. Figure 1 shows plots of the PC signals $\Delta\sigma(H)/\Delta\sigma(0)=f(H)$ for different λ at $T=1.7$ K. On the basis of the quantum energy, λ_1 corresponds to photoionization, λ_2 to the $1s\sigma_g\to 1p\pi_u$ transition,[5] and λ_3 to ϵ_3. For λ_4 we have $\hbar\omega<\epsilon_3$. A sharp decrease of the signal with increasing H is observed for all λ, and the curves coincide at short wavelengths.

The cited experimental results cannot be attributed to PC of free electrons. In that case the decrease of the mobility with H, obtained from the change of

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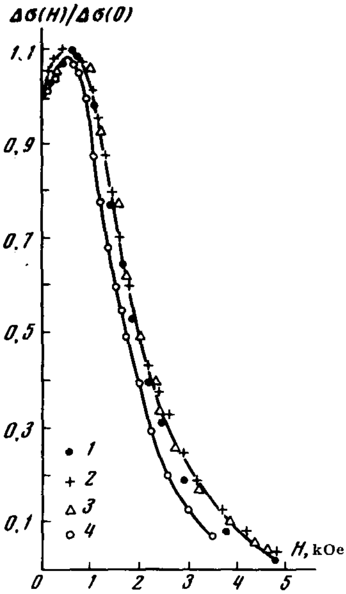

FIG. 1. Plots of $\Delta\sigma(H)/\Delta\sigma(0)$ against H at $T=1.7$ K: 1—$\lambda_1 = 0.87$ mm; 2—$\lambda_2=1.12$ mm; 3—$\lambda_3=1.74$ mm; 4—$\lambda_4=8$ mm.

the conductivity under the influence of the radiation $\Delta\sigma(H)$ at the known dependence of the absorption coefficient a on H, should be described by the relation $[\mu(0)-\mu(H)]/\mu(H)=\mathrm{const}H^2$; but this relation is not satisfied. We have assumed that PC of the hopping type takes place in the case under consideration. Then, if $\hbar\omega \gtrsim \epsilon_3$, then an electron that has absorbed a photon goes over to the excited state of the H_2^+ center and then, emitting a photon, goes to the percolation level; at $\hbar\omega<\epsilon_3$ the PC mechanism is similar to that described in[1]. In the case of hopping PC it is convenient to consider not the quantity μ, which has no clear physical meaning here, but the probability of electron hopping per unit time to a center located at a distance R from the starting point, $W_p \sim \exp(-2R/a)$. Then

$$\Delta\sigma \sim W_p a q \tau, \tag{1}$$

where q is the number of quanta incident per unit time on a unit surface of the sample, and τ is the time that the electron participates in the photoconductivity. In the case of ϵ_3 conductivity[6]

$$\frac{W_p(H)}{W_p} = \exp\left[-\frac{t_1 a e^2 H^2}{N_d c^2 \hbar^2}\right], \tag{2}$$

where τ is constant; in the case of Mott hopping conductivity[6,7] we have

$$\frac{W_p(H)}{W_p} = \exp\left[-\frac{1}{504}\,\frac{e^2 a^{*4} H^2}{c^2\hbar^2}\left(\frac{T_0}{T}\right)^{3/4}\right], \tag{3}$$

where T_0 is a constant connected with the density of states on the Fermi level,

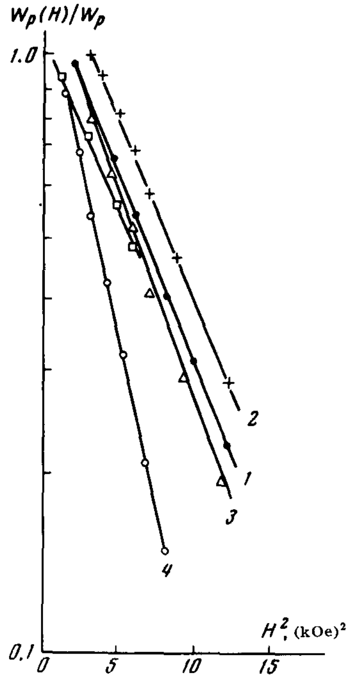

FIG. 2. Plots of $W_p(H)/W_p$ (curves 1—4) and of $\sigma(H)/\sigma(0)$ (curve 5) against H^2. The numbering of the curves is same as in Fig. 1.

and $a^* = \hbar/\sqrt{2m\epsilon_1}$ is the characteristic fall-off length of the wave function of the ground state of H_2^+. Since an independent experiment shows that $\tau(H)$ is constant at $H = 0$—4 kOe, it is easy to obtain for the current-generator regime at constant U

$$\frac{W_p(H)}{W_p} = \frac{\Delta U(H)}{\Delta U(0)}\,\frac{\sigma(H)}{\sigma(0)}\,\frac{a(0)}{a(H)}\,. \qquad (4)$$

The results of the corresponding calculation are shown in Fig. 2. It is seen that $\ln[W_p(H)/W_p] \sim H^2$. Figure 2 shows also a plot of the dark conductivity $H\sigma(H)/\sigma(0)$.

From the dependence of the dark conductivity on $H\sigma(H)/\sigma(0)$ we can estimate the radius of the states over which it is realized, namely $a \approx 680$ Å. A similar estimate can be obtained from (2) for the PC (λ_1, λ_2, λ_3); it yields $a \approx 610$ Å. The small difference between these quantities favors the assumption that the PC is realized over the same states as the dark conductivity, i.e., over the percolation level. At the same time, if $\hbar\omega < \epsilon_3$ ($\lambda_4 = 8$ mm), it appears that there is no more photo-ejection of electrons to the percolation level, and we have instead the photon-stimulated hopping conduction near the Fermi level, which was discussed in[1]. According to (3) we have here $a^* \approx 530$ Å, which is close to $a^* \approx 460$ Å calculated from ϵ_1.

It is assumed that n-InSb that has been purified and compensated to the utmost is the optimal material for the production of high-sensitivity receivers for submillimeter radiation.[8] Measurements specially performed by us show that this holds true only for $0.8 < K < 0.95$. Using the proposed PC model, we can calculate the voltage-power sensitivity S_u of such receivers. In the case of PC over the percolation level we have

$$\frac{\Delta\sigma}{\sigma} \; \frac{W_p\, a q \tau}{W_{\epsilon_3}(N_d - N_a)} \text{ and } S_u = \frac{aU\tau \exp(\epsilon_3/kT)}{S\hbar\omega(N_d - N_a)} \tag{5}$$

where $W_{\epsilon_3} = W_p \exp(-\epsilon_3/kT)$ and S is the area of the receiving element. For the sample considered, $\lambda = 1$ mm, $\alpha = 20$ cm^{-1}, $\tau = 3\times10^{-7}$ sec, $U = 0.1$ V, and $S = 0.24$ cm^2, the calculated value is $S_u = 10^4$ V/W. The experimentally obtained value was $S_u \gtrsim 3\times10^3$ V/W. The closeness of the theoretical and experimental values of S_u serves as additional evidence favoring the proposed PC mechanism.

Thus, in our opinion, photoconductivity of the hopping type is realized in n-InSb.

We note in conclusion that the hopping-photoconductivity mechanisms can probably be realized also in other disordered systems, such as amorphous semiconductors.

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