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ACTIVATIONLESS HOPPING CONDUCTIVITY IN COMPENSATED GERMANIUM

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Submitted 10 August 1972
ZhETF Pis. Red. 16, No. 7, 374 - 377 (5 October 1972)

At low temperatures, the conductivity of doped semiconductors is produced, as is well known, by a hopping mechanism [1, 2], wherein the charge is transported via tunnel transitions (hopping) of the electrons from occupied to free impurity centers, the presence of which is ensured by the compensation. The presence of activation energy is connected with the scatter of the impurity levels in the random fields of the charged donors and acceptors, and as the electron moves it is quite likely to absorb or emit a phonon, on the average with equal frequency. The need for absorbing a phonon leads to an exponential dependence of the conductivity on the temperature. However, in a sufficiently strong field, the hopping conductivity can become in principle activationless [3]. To this end, it is necessary that the potential-energy drop over the length R of the hop, in an electric field eER, be comparable with the energy spread Δ of the impurity centers. In this case the electron hops will be accompanied only by the emission of phonons, and the conductivity ceases to depend on the temperature. Simple estimates show, however, that in the region of the classical hopping conductivity over shallow impurities it is impossible to observe this effect, since impact ionization of the impurity centers occurs in much weaker fields. More favorable possibilities are uncovered by further lowering of the temperature, when the conductivity is due to the hopping of the electrons not over the nearest impurities, but over states located in a narrow energy band near the Fermi level. In this region, the conductivity σ decrease with temperature in accordance with the formula [4]

$$\sigma = \sigma_0 \exp\left(-\frac{T_0}{T}\right)^{1/4}, \quad T_0 \sim \frac{1}{g(\mu)a^3}, \tag{1}$$

where g(μ) is the density of states at the Fermi level and a is the Bohr radius. The value of the critical field needed to observe activationless hopping conductivity is in this case greatly reduced, for Δ decreases and R increases with decreasing temperature. In strongly doped and strongly compensated germanium, a conductivity of the "$T^{-1/4}$" type (1) was observed in the experimentally convenient region of nitrogen - helium temperatures [5], and in addition the strong compensation leads to a lowering of the Fermi level into the forbidden band and to an increase of the impact-ionization field. These circumstances governed the choice of the object of the investigation. The experiments were performed on samples of germanium strongly doped with phosphorus ($N_0 \approx 10^{19}$ cm^{-3}) and simultaneously strongly compensated with gallium. The degree of compensation was of the order of 80%.[1)]

Owing to the strong compensation, the samples were not homogeneous and their Hall coefficient was not measured. The current-voltage characteristics of the samples were nonlinear and accompanied by breakdown under stationary

1) We are sincerely grateful to R.L. Korchazhkina for preparing the strongly-compensated germanium samples.

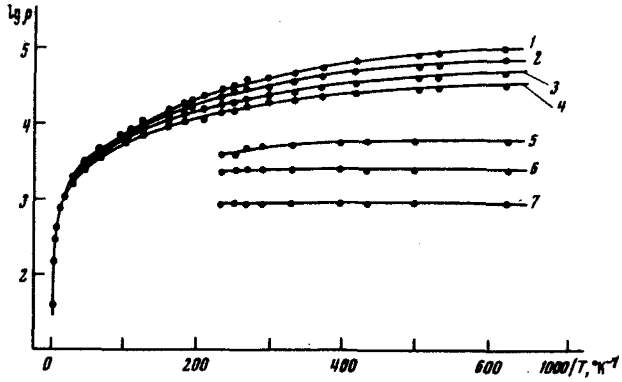

Fig. 1

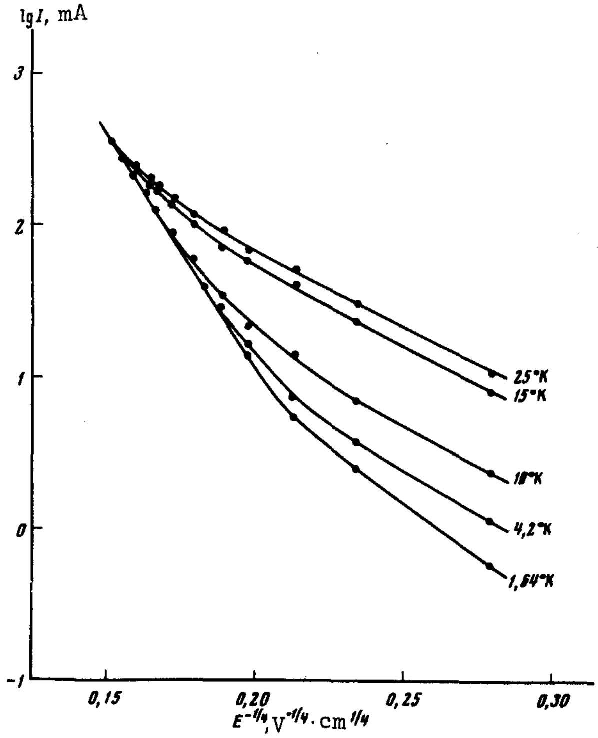

Fig. 2

Fig. 1. Temperature dependence of the conductivity of strongly-compensated germanium at different electric field intensities (V/cm): 1) 2, 2) 10, 3) 30, 4) 50, 5) 100, 6) 200, 7) 800.

Fig. 2. Dependence of the current on the intensity for strongly compensated germanium at different temperatures.

conditions [5]. The use of a pulse procedure made it possible to avoid breakdown; to exclude thermal phenomena, the experiments were performed under conditions such that the current was independent of the pulse duration and of the off-duty cycle.

Figure 1 shows the temperature dependences of the conductivity on one of the samples in different fields. At the very lowest temperatures one can see clearly the effect of the activationless hopping conductivity, where the conductivity ceases to depend on the temperature and depends only on the applied field. A temperature-independent conductivity was observed also in amorphous germanium [6], but it was attributed there to tunneling of the carrier, in a strong field, from a localized state into the allowed band.

In our case the experimental data (relatively weak fields far from the breakdown field) allow us to state that the activationless conductivity is realized by localized carriers in accordance with the model described above, i.e., in essence hopping conductivity. In this case, as shown in [7], the dependence of the conduction current on the electric field should be given by

$$I(E) \sim \exp\left(-\frac{E_0}{E}\right)^{1/4}, \quad E_0 \approx \frac{T_0}{ea}. \tag{2}$$

Figure 2 shows a plot of log I against $E^{-1/4}$ for different temperatures. It is seen from the figure that under conditions when the current is independent of the temperature the experimental points fit well a straight line, in agreement with (2).

Thus, the activationless hopping conductivity observed in germanium can apparently ensure a finite resistance of doped semiconductors at T = 0.

In conclusion, the authors thank S.M. Ryvkin for a useful discussion of the problems involved, B.I. Shklovskii for a preprint of [7], and A.G. Zabrodskii for help with the experiment.

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SELF FOCUSING OF LIGHT IN A PLASMA AND SUPERSONIC IONIZATION WAVE IN A LASER BEAM

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Submitted 21 August 1972
ZhETF Pis. Red. 16, No. 7, 378 - 382 (5 October 1972)

With developed evaporation of a bismuth target in a helium atmosphere of pressure P_0 = 2.5 - 5 atm by a laser beam (λ = 1.06 μ) of intensity $I_0 \approx 10^7$ W/cm^2 in a millisecond pulse, we obtained a plasma flare regime that is new for metals (in comparison with [1]), with almost complete absorption of the laser radiation passing through the flare.

The presence of strong absorption in the flare was demonstrated by passing through it a beam inclined 5° to its axis. It was found that at P_0 = 4 atm, a light energy E = 2.3 - 3.6 kJ in a pulse of τ = 0.8 msec, at a focusing-region dimension $d_0 \approx 0.8$ cm on the target, and a traversed flare length ℓ = 4 - 6 cm, the beam was attenuated by a factor 5 - 10. This corresponds to an absorption coefficient averaged over time and length α = 0.4 - 0.6 cm^{-1}.

The figure shows a time scan of the flare. At the start of the process (Nos. 3 and 11), a detachment and drift of the flare from the target is observed [2]. The detachment of the plasma from the target indicates by itself that the target is strongly screened from the incident radiation by the flare[1]. From the fact that the transverse dimension of the flare becomes stable in time it follows that a pressure P, equal to the external pressure P_0, is established in it as a result of expansion.

The condition $P = P_0$ is the key to the understanding of the investigated processes. It enables us to estimate the temperature T and the electron density n_e of the plasma from the measured bremsstrahlung absorption coefficient $\alpha \approx 0.4$ cm^{-1}. A calculation at P_0 = 4 atm yields a value of T in the interval (1.7 - 2.3) × 10^4 °K and $n_e \approx 10^{18}$ cm^{-3}. The degree of the first ionization of bismuth is equal to unity in this case, and the degree of second ionization ranges from 0.09 to 0.75.

[1] The detachment of the plasma from the target and its connection with the screening of the target by the flare was reported by us in 1969 to the First All-union Conference on the Physics of the Effect of Optical Radiation on Condensed Media, at the Vavilov State Optical Institute. This was the first communication of the possibility of obtaining an absorbing plasma in the vapor of a solid target.