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HOT-ELECTRON EFFECTS IN HIGH-RESISTIVITY InSb*

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We report that in the presence of random potential of the conduction band hot-electron transport can exhibit some novel features, some of which can be observed in dependencies of electric conductivity, mean electron energy and noise temperature on electric field strength.

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Standard treatment of electron transport in crystalline semiconductors assumes that an electron moves in a homogeneous electric field. However, in highly compensated materials, where the random fluctuations of conduction band exists, the motion of electron in electric field can be greatly affected by the random potential fields. In what follows we demonstrate experimentally some peculiarities of hot-electron transport in high-resistivity InSb⟨Cr⟩, observed in dc and microwave (MW) electric fields at the liquid nitrogen temperature.

The samples used in the experiment were prepared from the crystal of n-InSb grown by the Czochralski method. The concentration of doping impurities Cr (deep donor) and either Mn or Zn (shallow acceptors), introduced during the growth, was about 2×10^{15} cm^{-3}. Electron concentration and mobility at lattice temperature $T = 78$ K were $n = (10^{10} \div 10^{14})$ cm^{-3} and $\mu \approx 2.5 \times 10^{5}$ cm^2/(V s) respectively.

The first peculiarity of electron transport is related with quite different behaviour of electric conductivity σ in strong dc and MW electric fields [1]. As may be seen from Fig. 1, the dependence of σ on *dc electric field* strength is strongly influenced by electron concentration. When $n > 10^{13}$ cm^{-3}, the electric conductivity decreases with the increase in dc electric field strength E, meanwhile in high-resistivity samples the opposite picture is observed: the increase in σ with E. We associate this property with the presence of random potential of conduction band due to compensation. When electron concentration is high, the random potential is screened by free electrons. Quite a different situation is in high-resistivity samples, where random potential is too high to be neglected. Due to the applied dc electric field electron concentration above the percolation level increases analogically as in the Poole–Frenkel effect. Consequently, more electrons participate in electrical transport causing the increase in electric conductivity. We verified this

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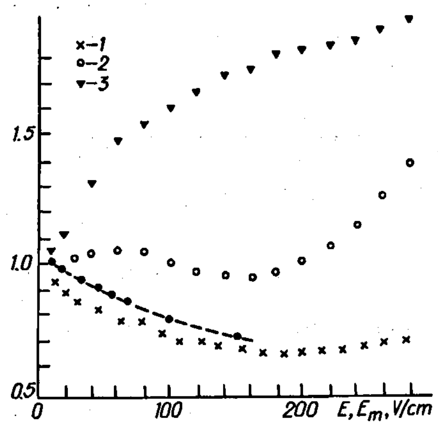

Fig. 1. Dependence of electric conductivity on electric field strength in dc (1, 2, 3) and MW electric fields. Dotted line — σ_m/σ_0 at 10 GHz. Electron concentrations (cm^{-3}): 1 — 1.2×10^{13}, 2 — 2.5×10^{12}, 3 and dotted line — 3×10^{11}.

model by measuring the current dependence on dc electric field strength. Shklovskii [2] obtained that within the framework of percolation theory the current can be described as

$$I = I_0 \exp(\alpha E^{1/2}/kT), \tag{1}$$

where I_0 is the current in weak electric field, k is the Boltzmann constant, α is the characteristic parameter of random potential.

We have observed the dependence (1) at the liquid nitrogen temperature in high-resistivity samples in dc electric fields. Moreover, the characteristic parameter of random potential, estimated by (1), was found to be close to the Poole–Frenkel constant.

Along with dc also conductivity σ_m in strong *MW electric fields* has been measured by the integral technique [3]. However, in this case only the decrease in electric conductivity σ_m has been observed both in low-resistivity and high-resistivity samples. It implies that the decrease in electron mobility is dominant and the influence of random potential on electric conductivity is smaller than in dc electric fields.

One more peculiarity observed in high-resistivity InSb was connected with mean electron energy. As predicted theoretically [4] and observed experimentally [5], at certain conditions the mean electron energy* ε in electric fields can be smaller than equilibrium value ε_0, i.e. electrons can be cooled by MW electric field (Fig. 2). The essence of this phenomenon can be described as follows: when an electron, accelerated by electric field, reaches the energy of optical phonon, it

*The mean electron energy was estimated from the measurements of the thermoelectromotive force of hot-electrons U_T which arises in graded n-n^+-junction placed in MW electric field of 10 GHz. Since in electric fields up to 50 V/cm electron mobility changes within 10%, then $1 + U_T/V_K \approx \varepsilon/\varepsilon_0$ [6] (where V_K is the height of potential barrier of n-n^+-junction).

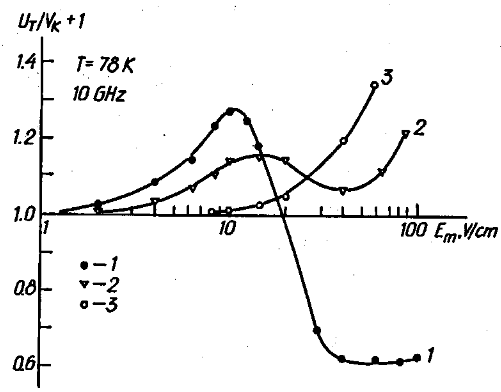

Fig. 2. Dependence of $U_T/V_K + 1$, which is proportional to the mean electron energy, on MW electric field strength. Electron concentration in n and n^+ regions respectively (cm^{-3}): 1 — 1.2×10^{11} and 4.4×10^{11}; 2 — 9×10^{11} and 8.5×10^{12}; 3 — 2.3×10^{13} and 8.1×10^{13}.

emits with high probability an optical phonon; as a result, the electron loses all its energy and finds itself in the potential valley. The electrons are localized here, since their mobility is low due to the scattering of electron on the complexes of ionized impurities. For that reason the mean energy of electron gas becomes smaller than the equilibrium value.

In order to verify this explanation we performed experiments in a transverse--to-current-flow magnetic field. Since the emission of optical phonon is necessary for electron-gas cooling, it is reasonable to expect that the strong magnetic field will destroy this effect. Indeed, in the experiment we have found that the electron-gas cooling vanishes in magnetic fields of induction $B > 0.05$ T ($\mu B > 1$), i.e. the suppression of optical phonon emission decreases the number of electrons which reach the potential valleys.

Thus, for existence of electron-gas cooling the following conditions must be fulfilled: the dominant mechanism of electron energy loss is a spontaneous emission of optical phonons, while that of momentum loss is ionized impurity scattering and electron concentration is low. As may be seen from Fig. 2, in low-resistivity samples electron-gas cooling vanishes.

Since the mean electron energy in electric fields can be smaller than the equilibrium value, it is of particular interest to obtain the information on the mean electron energy directly from noise temperature*. We measured longitudinal and transverse noise temperatures and established that with the decrease in electron concentration noise temperature decreases too, and in high-resistivity InSb ($n < 10^{11}$ cm^{-3}) noise temperature in electric fields up to 100 V/cm does not depend on electric field strength and is close to the lattice one [8]. One must note that such a dependence, as well as the increase in noise temperature with magnetic field

*Noise temperature was measured at 10 GHz frequency range by applying high field dc electrical pulses to samples placed in X-band guide [7].

induction is observed only in the samples where electron-gas cooling exists. These observations have led us to the conclusion that the reason of such behaviour of noise temperature could be attributed to the electron-gas cooling effect.

We thus conclude from our experimental facts that in high-resistivity InSb a number of peculiarities can be observed: (a) dc electric conductivity increases, while σ_m decreases with MW electric field strength; (b) mean electron energy, estimated from the thermoelectromotive force of hot electrons, is smaller in MW electric fields than the equilibrium value, (c) noise temperature in the electric fields up to 100 V/cm is close to that of the lattice.

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