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Nonlinear carrier transport within gigahertz-terahertz frequencies in spatially non-uniform InSb

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Abstract. Influence of a dc electric field, microwave and terahertz (up to 1.63 THz) excitation on the carrier transport in moderately compensated $n$-InSb$\text{<Cr>}$ containing graded $n/n^+$ junction is investigated. Hot electron thermo-electromotive force and field dependences of the dc-conductivity were measured within 10-110 K. Peculiarities of electron gas heating and low-temperature electron transport can be attributed to the potential fluctuation effects due to random spatial distribution of impurity density in high-resistivity InSb$\text{<Cr>}$ crystal.

1. Introduction
Non-equilibrium carrier transport phenomena caused by external illumination in $n$-type indium antimonide, can serve in many applications, for instance, in hot-electron bolometers, widely employed in a terahertz sensing systems. As a rule, a key-component of such detector is uniform InSb, which exhibits high carrier mobility at low temperatures allowing thus effective electron gas heating above the lattice temperature.

In a present communication, we concentrated our attention into compensated InSb containing graded $n/n^+$ junction along the crystal investigating an influence of a gigahertz (GHz) and terahertz (THz) excitation on the carrier nonlinear transport. The compensated InSb due to the electron gas cooling effect in strong electric fields [1,2] exhibits low-level noise properties [3] and thus can be an attractive option in optimizing sensitivity of high-frequency devices. The structures with electron density of $10^{12}$–$10^{13}$ cm$^{-3}$ were studied measuring dc-current-voltage characteristics, thermo-electromotive force of hot carriers at different temperatures and its exposition characteristic at GHz- and THz-frequency excitation. The experiment were carried out within the temperature range of 10-110 K using magnetron as a source of GHz frequency radiation and an optically-pumped molecular laser as THz emitter.

2. The sample and experimental set-up
2.1. Compensated $n$-type indium antimonide
The sample was cut from single crystals of $n$-type indium antimonide doped with Cr and Zn. The crystal carrier mobility is of about $3.5 \times 10^5$ cm$^2$/Vs at 78 K. A dumb-bell shape of the sample was made by polishing the crystal. After all sample preparation processes the length $l$, width $w$ and height $h$ of active sample part were of about 3.3 mm, 0.4 mm, and 0.4 mm, respectively. Ohmic contacts were prepared using In + 2%Te alloy. The sample was then soldered to a copper frame and placed in a
closed cycle cryostat having an optical port to admit the THz radiation. The sample temperature was controlled by a thermocouple at the point of sample attachment to the frame. The distribution of carrier density along the sample was monitored using four contacts attached stationary to the sample at different temperatures (up to 4 K). More detailed carrier distribution was probed using a mobile probe at liquid nitrogen temperature.

2.2. An experimental set-up

An optically-pumped molecular laser was used as a THz radiation source. The laser was tuned to emit at 0.762 THz or 1.63 THz frequency. The spherical mirror was used to focus THz radiation to the sample placed behind the high pressure polyethylene window. The spot size diameter of the laser beam was of about 2 mm. The laser beam has linear polarization and the orientation of the electric field vector was along the length axis of the sample. For experiments at 9.4 GHz frequency the same sample was placed in the rectangular waveguide perpendicularly to its broad wall.

The sample dc-conductance is measured using a digitally controlled source-meter applying voltage below 1 V and dc-pulse technique generating up to 200 V, i.e. providing the electric fields higher than the one needed to start impact ionization process in InSb. The signal of the thermo-electromotive force (thermo-emf) was recorded by means of 350 MHz bandwidth oscilloscope and the lock-in amplifier.

3. Experimental Results and Discussions

The conductance of the sample measured in wide temperatures range is shown in Fig. 1. The conductance change reflects different processes related with change in carrier density and the mobility. The area of interest is in the range 50-10 K, where the sample dc-conductivity governed by mobility decreases with temperature due to grown electrons scattering on ionized impurities. Also, it is worth noting that the impact of potential fluctuation due to random inhomogeneities in the impurity density increases [4].

![Figure 1](image1.png)

**Figure 1.** The sample conductance dependence on temperature at dc-current of about 10 μA. Inset: voltage distribution along the sample measured at fixed points at four temperatures under dc-voltage of about 1 V. A two-grey-tone outline drawing illustrates the contour of the sample with different $\sigma_1$ and $\sigma_2$ conductivity regions.

![Figure 2](image2.png)

**Figure 2.** Variation of the sample conductivity with applied dc-voltage at 10 K and 78 K temperatures. The dc-conductivity is normalized to its value obtained at low bias voltage.
The amplitude of the potential barrier arising due to \( n/n^+ \) junction presence is estimated at 78 K measuring the voltage distribution along the sample. It was found that the dc-conductivity of differently doped sample parts schematically shown in the inset of Fig. 1 is: \( \sigma_1 = 1.7 \) S/cm and \( \sigma_2 = 0.83 \) S/cm. The height of potential barrier is determined using the formula:

\[
V_k = \frac{kT}{e} \ln \left( \frac{\sigma_1}{\sigma_2} \right),
\]

\( k \) is Boltzmann constant, \( T \) is temperature. The value of the potential barrier of about 4.7 meV is found. The dependence of the potential barrier on temperature is tested up to liquid helium temperature. The data is shown in the inset of Fig. 1. It is seen that the voltage distribution along the sample remains unchanged varying the temperature in 4-80 K. Therefore, it allows to assume that the ratio between \( \sigma_1 \) and \( \sigma_2 \) values remains the same within all above indicated temperatures.

The electric field dependence of sample dc-conductivity studied at different temperatures and electric field regions are shown in Fig. 2 (strong fields). At 10 K temperature, the conductivity increases because of increase in the mobility [4]. Later, within the voltage range of 10-80 V, the conductivity decreases due to electrons interaction with optical phonon and, finally, conductivity starts to increase once again due to impact ionization process. One can note that at temperature of 78 K and voltage below of 100 V, the conductivity modulation with electric field is weaker due to strengthened electron-electron interaction.

The sample conductance under condition of low dc-fields was studied at different temperatures. The result is shown in Fig. 3. It is seen that the conductance change with the electric field becomes evident if the sample temperature is reduced to 30 K. Further lowering of the temperature leads to more pronounced nonlinear current-voltage characteristic showing up at lower dc-voltage values.

The results of thermo-\textit{emf} signal on temperature are shown in Fig. 4. The signal sign corresponds to the \textit{emf} induced by hot electron effects. Within the temperature range of 20-50 K the signal change is almost linear in a log-log plot scale and its value is changed nearly by 3 orders of magnitude. It is worth indicating that 2 mW power of the THz laser generates thermo-\textit{emf} signal value of about 0.6 mV at 10 K. Although the sample temperature was varied from 10 K up to 120 K, however, the \textit{emf} signal induced with THz frequency radiation is observed only at temperatures below 50 K.

![Figure 3. Variation of the sample conductance with applied dc-voltage at different temperatures.](image1)

![Figure 4. The thermo-\textit{emf} signal dependence on sample temperature at 0.762 THz excitation frequency.](image2)
The measured thermo-emf signal exposition characteristics in GHz and THz range are shown in Fig. 5. The results show that signal vs. power of high frequency radiation has linear dependence in log-log scale. The functional behaviour can be understood in terms of warm electron physics, e.g., if electron energy relaxation time $\tau_e$ is large ($\omega \tau_e >> 1$) and an ac-electric field amplitude $E_m$ is sufficiently small (hot electron distribution function is close to the distribution function in a steady state) then the thermo-emf signal $U_T$ is [1]:

$$\frac{U_T}{V_k} = \frac{1}{3} \frac{e \overline{\mu}}{kT} \frac{E_m^2 \tau_e}{e},$$

(2)

where $\overline{\mu}$ is differential mobility averaged over the ac-electric field period, other notations are as in previous formula.

### 4. Conclusions

Hot electron thermo-electromotive force induced by GHz and THz radiation and the field dependences of the dc-conductivity have been studied experimentally within wide temperature range. Conditions of formation of the thermo-electromotive force signal in THz range are determined; peculiarities of the low-temperature transport and electron heating effects are explained to be associated with significant influence of the random potential fluctuations on the ionized impurity scattering mechanisms in high-resistivity InSb.

### References