Heating and cooling of electron gas in electric fields in a compensated indium antimonide

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"Absolute" cooling of electron gas, which was previously predicted by Gribnikov and Kochelap [Sov. Phys. JETP **58**, 1046 (1970)], has been observed experimentally in high-resistance, compensated InSb at $T_0 = 78$ K in warming electric fields. The cooling effect of electron gas vanishes in a classical, strong magnetic field orthogonal to the electric field.

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A theoretical study conducted by Gribnikov and Kochelap[1] showed that at low temperatures the average energy of electron gas in high-resistance semiconductors can decrease in comparison with the equilibrium value $\epsilon_0 = 3/2\, kT_0$ in a certain range of electric fields with increasing field when the dominating mechanism of electron energy loss is spontaneous emission of optical phonons and that of momentum loss are the ionized impurities. An "absolute" cooling of electron gas in strong electric fields, however, has not been confirmed experimentally.

A compensated InSb with a chromium impurity (InSb ⟨Cr⟩),[2] which has a smooth $n - n^+$ transition at $T_0 = 78$ K, was investigated by us. The field dependences of the average energy of electron gas were determined from the thermoelectromotive force of hot electrons U_T, which was produced as a result of an $n - n^+$ transition in high-resistance n-InSb ⟨Cr⟩ samples due to the influence of a microwave electric field in the 3-cm wave range, using the relation

$$\frac{\overline{\epsilon \mu_d}}{\epsilon_0 \bar{\mu}_d} = 1 + \frac{U_T}{V_{k0}}, \tag{1}$$

where $eV_{k0} = kT_0 \ln(n^+/n)$ is the height of the potential barrier of the $n - n^+$ transition, and $\bar{\epsilon}$ and μ_d are the energy and differential mobility of electron gas averaged over the microwave period [the relation (1) was determined from the expression for U_T (Ref. 3) by using a modified Einstein relation[4]].

The field dependences of the thermoelectromotive force of hot electrons (see Fig. 1) showed that at $T_0 = 78$ K U_T increases nonmonotonically with increasing microwave amplitude of the electric field E_m in n-InSb ⟨Cr⟩ samples with an electron density $n^+ \leqslant 1.5 \times 10^{13}$ cm^{-3} in the n^+ region and U_T reverses its sign in samples with the highest resistance ($n^+ \leqslant 1.5 \times 10^{12}$ cm^{-3}) in the field range $20 \leqslant E_m \leqslant 200$ (V/cm). Since at $E_m < 50$ V/cm the ratio μ_0/μ_d in a high-resistance n-InSb ⟨Cr⟩

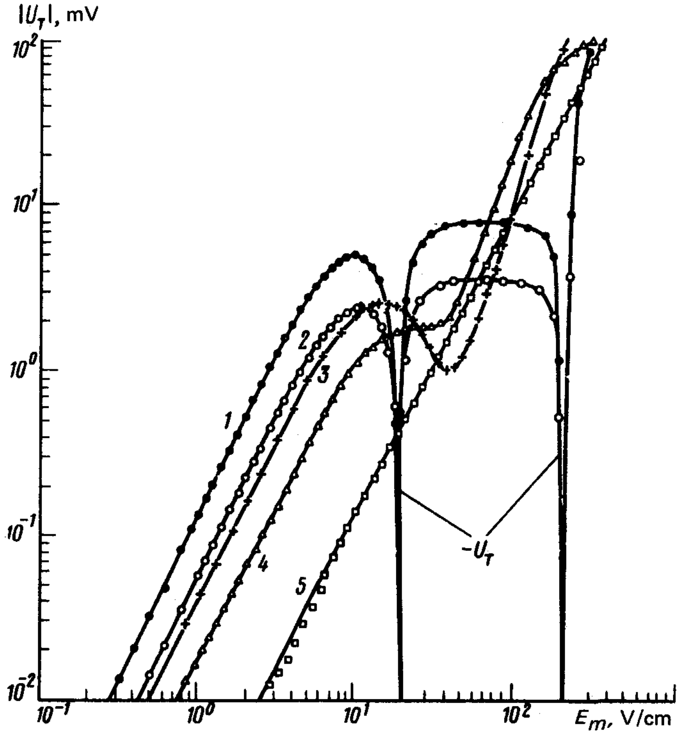

FIG. 1. Dependences of the thermoelectromotive force of hot electrons on the amplitude of the microwave electric field at $T_0 = 78$ K. The electron density in the n and n^+ regions, cm^{-3}. 1, 9.0×10^{10} and 1.5×10^{12}; 2, 1.2×10^{11} and 4.4×10^{11}; 3, 9.0×10^{11} and 8.5×10^{12}; 4, 3.0×10^{12} and 1.5×10^{13}; 5, 2.3×10^{13} and 8.1×10^{13}.

sample does not exceed 1.1 (Ref. 5) (μ_0 is the mobility of electrons in a weak field), it is reasonable to assume that $\overline{\epsilon}\mu_d/\epsilon_0\overline{\mu}_d \approx \overline{\epsilon}/\epsilon_0$ and hence, according to Eq. (1), the sign reversal of U_T in warming fields can be attributed to a reduction of the average energy of electron gas below the equilibrium value. We have determined that the minimum value of $\overline{\epsilon}/\epsilon_0$ is equal to ≈ 0.6.

On the basis of a comparison of the obtained results with theory,[1] the cooling of electron gas in warming fields can be accounted for by the localization of electrons in the neighborhood of the conduction-band bottom on which they impinge after emitting an optical phonon and in which their mobility is low. In fact, $\mu_0 \approx 2.5 \times 10^5$ cm^2/V • sec in the samples used by us. This indicates that the ionized centers play a dominant role in the dissipation of electron momentum.[6] Since the electron density in high-resistance samples in which U_T reverses its sign does not exceed 1.5×10^{12} cm^{-3}, the smallness condition of n,[1] for which the interelectronic interactions are negligible, is also satisfied. A reversal of the U_T sign because of "absolute" cooling of electron gas by an electric field is also indicated by the fact that first the U_T sign reversal and then the kink on the U_T vs E_m curve vanish as the electron density increases because of the increase in the intensity of interelectronic interactions.

"Absolute" cooling of samples with extremely low electron density in a field $E_m > 200$ V/cm (see Fig. 1) vanished because the electron penetrates deeply into the active region during the characteristic emission time of an optical phonon and it also retains sufficiently large energy even after the emission of an optical phonon.

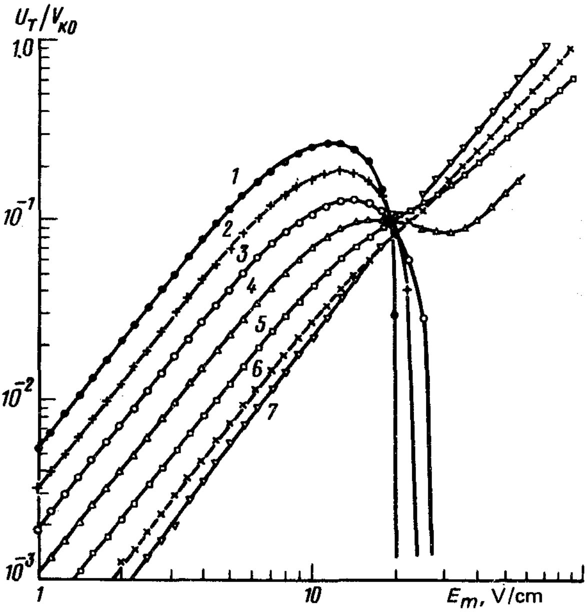

FIG. 2. Field dependences of the thermoelectromotive force of hot electrons of a high-resistance n-InSb ⟨Cr⟩ sample with $V_{k_0} = 20$ mV for different values of the magnetic field B, T. 1, 0.00; 2, 0.01; 3, 0.015; 4, 0.02; 5, 0.03; 6, 0.05; 7, 0.01

The cooling effect of electron gas also disappears as a result of application of a magnetic field at right angles to the vector of the warming microwave electric field $\mathbf{B} \perp \mathbf{E}_m$. We have found that at $B > 0.05T$ U_T does not reverse its sign, and at $B > 0.05T$, when $\mu_0 B > 1$, the kink on the U_T vs E_m curve vanishes (see Fig. 2). This can be explained by the fact that the motion of nonlocalized electrons is bent severely in the passive region of the phase space due to the influence of the Lorentz force. Therefore, the energy gain by electrons from the electric field decreases in the magnetic field, and the suppression of the emission of optical phonons decreases the number of electrons that reach the bottom of the conduction band after emitting optical phonons.

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