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On the Electron Gas Energy Relaxation Mechanisms in n-Type InSb at Helium Temperatures

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The relaxation time of the electrical conductivity and the non-linearity coefficient β in n-type InSb in the temperature range from 1.8 to 4.1 °K are studied as a function of power supplied to the sample from a d.c. source. The results are interpreted by considering energy losses by acoustic piezoelectric and deformation-potential scattering and by optical polar scattering. The constants of piezoelectric and deformation potentials are estimated.

Die Relaxationszeit der elektrischen Leitfähigkeit und der Koeffizient der Nichtlinearität β werden in n-leitendem InSb als Funktion der angelegten Gleichspannung im Temperaturbereich von 1.8 bis 4.2 °K untersucht. Die Ergebnisse werden durch Energieverluste infolge akustischer piezoelektrischer und Deformationspotentialstreuung sowie infolge optischer polarer Streuung gedeutet. Die Konstanten des piezoelektrischen Potentials und des Deformationspotentials werden abgeschätzt.

1. Introduction

The mechanism of electron energy transfer to the crystal lattice in n-type InSb at low temperatures has been studied originally by Sladek [1]. He pointed out two mechanisms of energy dissipation in n-type InSb: via the piezoelectric potential of acoustic phonons at helium temperatures and via optical phonons at higher temperatures. Kogan [2] has analyzed theoretically the energy dissipation via acoustic phonons. Particularly he has pointed out that in the case of energy dissipation via the piezoelectric potential the current-voltage characteristic of a semiconductor may have S-type shape.

In [3] some pecularities of non-linear d.c. i–V characteristics of n-type InSb have been investigated and qualitatively explained by energy dissipation via the piezoelectric and deformation potentials of acoustic phonons.

However, the relative contribution of each of the suggested dissipation mechanisms as well as its variation with heating of the electron gas remained obscure. The present paper makes an attempt to supplement the studies in these directions by an investigation of the relaxation time of electrical conductivity in n-type InSb which is more directly connected with the energy dissipation mechanism.

2. Experimental Procedure

We have studied the electrical conductivity relaxation time τ and the non-linearity coefficient $\beta = \frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}(E^2)}$ (see reference [4]) by measuring the active and reactive components of the complex semiconductor conductivity. This method allows one to use resonance amplifiers and bridge circuits and can therefore give the desired accuracy of measurements.

Let us consider a small deviation of the conductivity $\Delta\sigma_t(t)$ from the steady-state value σ_{t0}. Suppose that the time dependence of the total semiconductor

conductivity $\sigma_t(t)$ is defined by the equation

$$\frac{\mathrm{d}\Delta\sigma_t(t)}{\mathrm{d}t} + \frac{\Delta\sigma_t(t)}{\tau_E} = \frac{1}{\tau_E}\frac{\mathrm{d}\sigma_t(V)}{\mathrm{d}V}\bigg|_{V_0}\Delta V\,, \tag{1}$$

where $\sigma_t(V)$ is the dependence of the d.c. conductivity on the voltage V across the sample, V_0 is the steady-state value of V, and τ_E has the meaning of a relaxation time for constant voltage (the equation is of course valid under arbitrary circuit conditions)[1]. Then the complex conductivity of the sample is in the linear approximation

$$G(\omega) = \frac{I(\omega)}{V(\omega)} = g + i\,Y = \sigma_{t0}\left(1 + \frac{2\,\beta\,E^2}{1 + i\,\omega\,\tau_E}\right), \tag{2}$$

where $\sigma_{t0} = \sigma_t(V_0)$.

Thus, by measuring the active and reactive components of the complex conductivity of the sample we can determine separately τ_E and β which are of interest for us.

The process of establishing a stationary state in a circuit containing a non-linear semiconductor after the application of an external disturbance depends on the relationship between the semiconductor resistance and the load which determines the operating circuit conditions. This is a consequence of the pumping effect of the battery [4]. The voltage across the sample in an arbitrary circuit depends on the sample conductivity and other circuit parameters α (battery voltage, circuit resistances e.t.c.), i.e. $V = f(\sigma_t, \alpha)$. Thus,

$$\Delta V = \frac{\partial f}{\partial \sigma}\Delta\sigma_t + \frac{\partial f}{\partial \alpha}\Delta\alpha = \Delta V_{\text{reaction}} + \Delta V_{\text{external}}\,, \tag{3}$$

and therefore the relaxation equation (1) can be represented in the form

$$\frac{\mathrm{d}\Delta\sigma_t(t)}{\mathrm{d}t} + \frac{\Delta\sigma_t(t)}{\tau} = 2\,\tilde{\beta}\,\frac{\Delta V_{\text{ext}}}{V_0}\,\frac{\sigma_{t0}}{\tau}\,. \tag{4}$$

Here τ is the relaxation time of the electrical conductivity (obviously τ is related to the time τ_E), and $\tilde{\beta}$ is the dimensionless non-linearity coefficient of a semiconductor in an arbitrary circuit. $\tilde{\beta}$ enters, for example, into the expression for photosensitivity due to the electron gas heating (see (14) in [4]). In particular, if a sample with resistance $r_0 = \sigma_{t0}^{-1}$ is switched into the circuit in series with a battery and load resistance r_1, we obtain

$$\tau = \frac{\tau_E}{1 + 2\,\beta\,E^2\,\dfrac{r_1}{r_1 + r_0}}\,, \qquad \tilde{\beta} = \frac{\beta\,E^2}{1 + 2\,\beta\,E^2\,\dfrac{r_1}{r_1 + r_0}}\,. \tag{5}$$

Further we shall consider, in addition to τ_E, also the relaxation time τ_p of the electrical conductivity under the condition where the power P dissipated in the sample does not depend on $\Delta\sigma_t(t)$. In the circuit under discussion this case corresponds to the condition $r_1 = r_0$.

The experimental set-up for measuring the complex conductivity of the sample is schematically shown in Fig. 1. The measurements were carried out by the compensation method. A resonance amplifier of the approximate sensitivity $\sim 1\ \mu\mathrm{V}$ was used as a balance indicator. Operating frequencies of 250 and

[1]) If the i–V characteristic of a semiconductor is of the S-type then the region corresponding to $\sigma_{\text{diff}} < 0$ should be considered after substituting $r(t)$ and $I(t)$ for $\sigma(t)$ and $V(t)$.

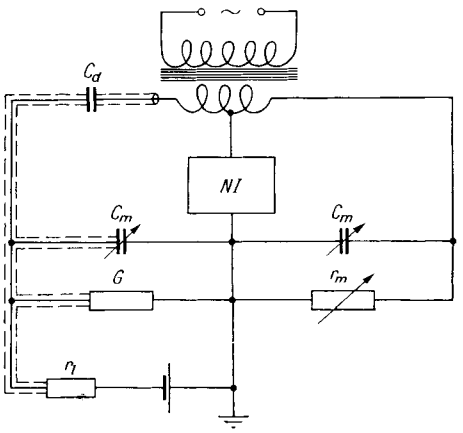

Fig. 1. Circuit for sample impedance measurements. G is the sample, r_l the load resistance, C_m the measuring capacity; r_m the measuring resistance, C_d the dividing capacitor, NI is the null indicator (resonance amplifier and oscillograph)

400 kHz were used. The results did not depend on the signal frequency and on the sign of the d.c. voltage. The load resistance r_l was in all cases more than 20 times higher than that of the sample. The r.f. voltage applied to the sample was not greater than 0.1 mV.

Samples of dimensions $10 \times 1 \times 1$ mm^3 were placed after soldering indium contacts, into a helium cryostat inside a small copper cylinder fitted at the end of the coaxial lead-in. In analyzing the results the dependence of the impedance of the coaxial cable on the load at its end was taken into account.

In addition to g and Y the d.c. i-V characteristic and the Hall coefficient were measured by the known methods in the temperature range from 1.77 °K to 4.2 °K.

3. Experimental Results

We studied four n-type InSb samples with an excess electron concentration of $n = (3 \text{ to } 5) \times 10^{13}$ cm^{-3} and a mobility $\mu \approx (2 \text{ to } 5) \times 10^4$ cm^2/Vs at 4.2 °K in a weak electrical field. The results obtained for different samples proved to be identical. It should be noted that fairly good reproducibility can be obtained with samples having fresh-ground surfaces. Repeated measurements (within the interval of 2 to 3 weeks) at helium temperature revealed a continuous increase of the electrical conductivity at low voltages which was 2 to 4 times higher than the initial one in the long run. At the same time a decrease of non-linear effects took place. The initial properties of the samples were restored after grinding their surface. All results given below refer to a single sample (№ 33—1). Fig. 2 represents the dependence of the electrical conductivity of the sample on the square of the electrical field at various lattice temperatures T_0. The curves of the initial region correspond to the square relationship between σ and E. At higher fields the electrical conductivity increases faster than E^2. The rate of increase becomes higher for lower T_0. At the lowest temperatures ($T_0 \leqq 2.5$ °K) the i-V characteristics and the curve $\sigma \sim \sigma(E^2)$ are of the S-type.

The same figure shows the curves $\beta = \beta(E^2)$ (for different T_0) obtained by the above procedure. It is seen that the curves $\beta(E^2)$ correlate with the curves $\sigma(E^2)$. For E values corresponding to the S-type region of the i-V characteristic the curves $\beta(E^2)$ break and pass into the region of negative values (not shown in the figure).

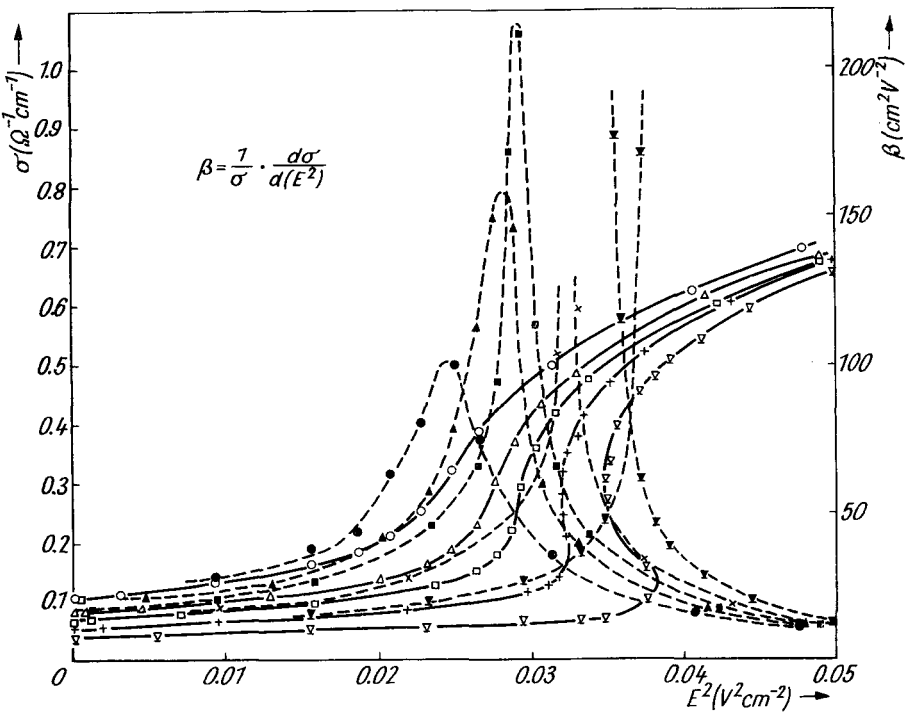

Fig. 2. Dependence of σ (solid lines) and β (dotted lines) on E^2. The symbols corresponding to different temperatures T_0 are in this and the other figures:
○, ● 4.2 °K; △, ▲ 3.5 °K; □, ■ 3.2 °K; +, × 2.5 °K; ▽, ▼ 1.87 °K

Fig. 3 shows the dependence of τ_E and τ_p on the power dissipated in the sample for different temperatures T_0. Attention is drawn to the sharp difference in the shapes of the curves τ_p and τ_E and in their numerical values and the significantly greater influence of T_0 on τ_E. At $T_0 \lesssim 2.5$ °K and for P values close to the points where σ_{diff} turns into infinity, τ_E abruptly increases. This reflects the unstable character of the regime of constant voltage in the S-type region where small deviations of σ_t from the stationary value should not decrease (see equation (1)), but increase.

The part of the τ_p curve corresponding to the S-type region could not be measured with high accuracy in our circuit which contained an a.c. generator $\varepsilon_G(t)$ since in this case arbitrary small signals ε_{G_0} bring considerably great variations of σ (see footnote[1]). Therefore this part is shown by a dash-and-dot line.

From (5) it is seen that such a noticeable difference in the behaviour of τ_E and τ_p is explained by the fact that for the fields used the non-linearity of the i-V characteristic was great and $\beta E^2 \gg 1$.

4. Discussion

In the general case the concentration of free charge carriers and their mobility may vary with electric field in a semiconductor. In order to find out whether the electron concentration in the conduction band remains constant we have

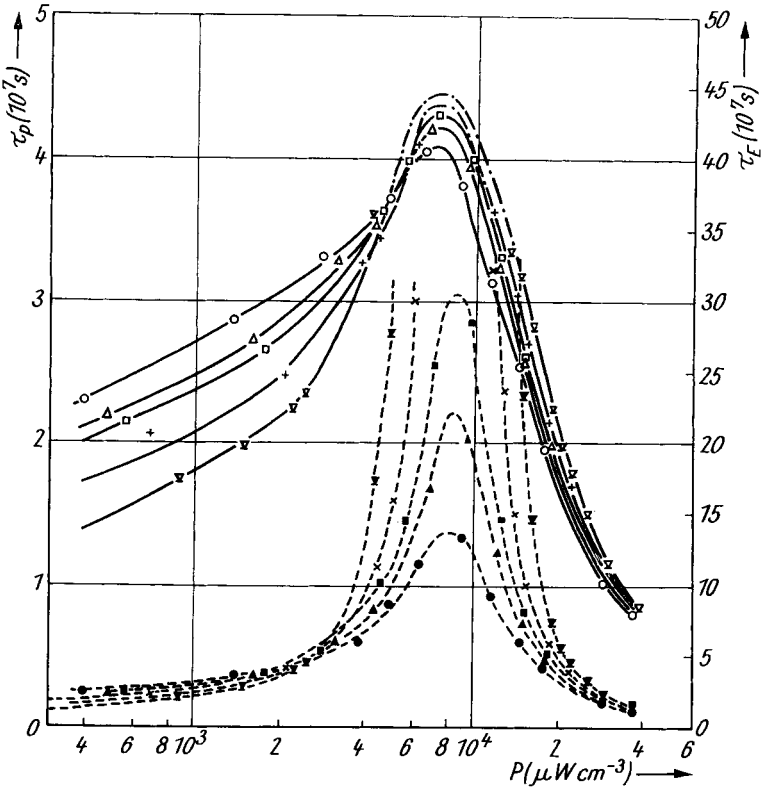

Fig. 3. Dependence of τ_E (solid lines) and τ_p (dotted lines) on the power dissipated in one unit volume of the sample

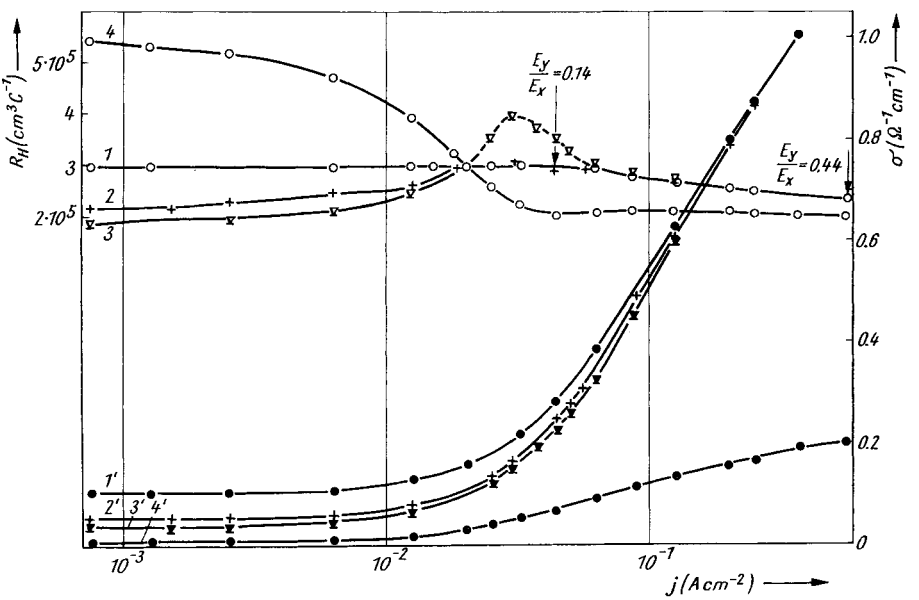

Fig. 4. Dependence of R_H (1 to 4) and σ (1′ to 4′) on current density. H = 170 Oe for curves 1 to 3 and 1′ to 3′ and H = 6300 Oe for curves 4, 4′

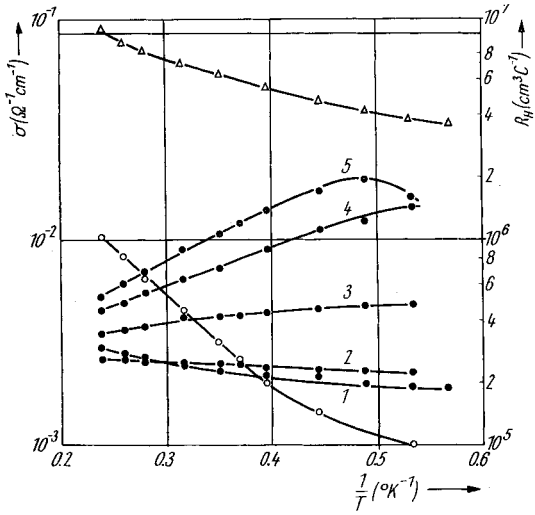

Fig. 5. Dependence of R_H and σ on lattice temperature — ● — R_H; 1 — 170 Oe; 2 — 1000 Oe; 3 — 3000 Oe; 4 — 5000 Oe; 5 — 6300 Oe; △ — σ for $H = 0$; ○ — σ for $H = 6300$ Oe. All curves were plotted for a current density $j = 1 \times 10^{-3}$ A/cm²

studied the dependence of the Hall coefficient R_H in a weak magnetic field H on E (or the current density) at different T_0 and, also the temperature dependence of R_H for different H. The results are represented in Fig. 4 and 5. The dependence of R_H and σ on current and temperature T_0 in a strong magnetic field $H = 6300$ Oe, points out, as it should be expected [5, 7], the presence of "freeze out" of electrons in this magnetic feld. A field of $H = 170$ Oe (which is equal for all curves of Fig. 4, except for 4 and 4') did not affect the conductivity, and the dependence of $\sigma(E^2)$ remained the same as for $H = 0$. The part of the curve $R_H(j)$ for $T_E = 1.87$ °K (dotted line) corresponds to the field region in which the current is not a single-valued function of the field. For such values of T_0 oscillations of several hundred kHz were observed (see arrows on the x-axis bounding this region). The measurements of R_H in this part of the curve are not accurate because it was not certain whether the current distribution in the sample cross-section remained uniform [8]. Except for this part, R_H varied along the i–V characteristic no more than 1.5 times (at the lowest crystal temperatures).

It shall be noted that one and the same value of σ in the curves of Fig. 4 and 5 corresponds to equal values of R_H measured in a weak magnetic field and at a corresponding T_0. In other words, an identical relation between σ and R_H is found for the i–V characteristic and the temperature dependence, i.e. if $\sigma(j_1, T_{01}) = \sigma(j_2, T_{02})$ then $R_H(j_1, T_{01}) = R_H(j_2, T_{02})$. From this follows that in both cases these quantities are functions of one parameter, viz., of the electron temperature T. In one case it is equal to the lattice temperature T_0, in another case it is the temperature of the electron gas heated by the field.[2])

In the analysis of the temperature and field dependence of R_H in the case of weak magnetic fields one should take into account that the mobility ratio μ_H/μ_d differs from unity and that it depends on T (due to the screening of the scattering potential of the charged impurity centres [9]) as well as on the Hall angle.

[2]) As to the applicability of the concept of electron temperature to the non-equilibrium electron gas in n-type InSb at helium temperatures see, for instance, [2 to 4, 12].

The variations of μ_H/μ_d should be of the order of the observable variations of R_H and are of the same sign. With regard to this the results presented in Fig. 4 and 5 lead us to the conclusion that for $H = 0$ (or in a weak magnetic field) no considerable variations of the electron concentration in the conduction band take place and, consequently, the whole variation of σ should be attributed to the mobility variation with T. It follows then that the electrical conductivity relaxation time measured by us is the relaxation time of the electron temperature or of the average electron gas energy in the sample.

To determine the electron temperature of a semiconductor with non-zero current one can apply the equation of the electron gas energy balance which directly leads to the expression for the average energy relaxation time τ and the non-linearity coefficient β [4]

$$\tau_E = \frac{n\,c}{\frac{dP}{dT} - E^2 \frac{d\sigma}{dT}}, \qquad \tilde{\beta} = \frac{\frac{d\sigma}{dT} E^2}{\frac{dP}{dT} - E^2 \frac{d\sigma}{dT}} = \beta E^2, \quad (r_0 \gg r_1),$$

$$\tau_p = \frac{n\,c}{\frac{dP}{dT}}, \qquad \tilde{\beta} = \frac{\frac{d\sigma}{dT}}{\frac{dP}{dT}} E^2 = \frac{1}{\sigma} \frac{d\sigma}{dP} P, \qquad (r_0 = r_1). \tag{6}$$

Here n is the electron concentration, $c = \frac{d\varepsilon}{dT}$ the thermal heat capacity per electron of the electron gas, $P(T, T_0)$ the power transfered by the electron gas of temperature T to the crystal lattice of temperature T_0 in a unit volume[3]) (here and further the temperature is measured in energy units).

The non-monotonous dependence of β on E was observed previously [3]. It was qualitatively explained by the fact that the energy loss through the piezoelectric potential of acoustic phonons is replaced at higher electron temperatures by the energy loss through the deformation potential. We shall make an attempt to analyze in more detail the mechanism of excess energy transfer from electrons to the lattice in n-type InSb by using the field dependence of the energy relaxation time. This can be done by comparing the experimental curve $\tau_p(T, T_0)$ with formula (6). Determination of T corresponding to the dissipated power $P = j E$ in the sample and the derivation of $\tau_p(T)$ from the experimentally obtained relationship $\tau_p(P)$ was carried out taking into account the dependence of σ on T_0 measured in a weak electrical field.

For the power dissipated by piezoelectric and deformation potentials of acoustic phonons we have used the known expressions [2]

$$P_{\text{piez}}(T, T_0) = (T - T_0)\, T^{-1/2}\, \frac{32\sqrt{2\pi}\, n e^2 m^{3/2} a e_{14}^2}{\hbar^2 \varkappa^2}, \tag{7}$$

$$P_{\text{def}}(T, T_0) = (T - T_0)\, T^{1/2}\, \frac{8\sqrt{2}\, n\, m^{5/2} \mathcal{E}_c^2}{\pi^{3/2} \hbar^4 \varrho}, \tag{8}$$

[3]) From (6) it can be seen, that the constancy of n means the constancy of the expression $1/c \cdot \tau_E/\beta \cdot d\sigma/dT$ (for a non-degenerate gas). Actually, for small fields (in the left hand side of the maxima of the curves in Fig. 2 and 3) $1/c \cdot \tau_E/\beta \cdot d\sigma/dT$ varies only slightly and further remains constant. It is equal to 3.25×10^{13} cm^{-3} which is very close to the result obtained from measurements of R_H (3.13×10^{13} cm^{-3}).

where $m = 0.013\, m_0$, $\varrho = 5.8$ g/cm^3, $a = 0.4$; the dielectric permeability is $\varkappa = 17$, $\mathcal{E}_c$ is the deformation potential constant, and e_{14} the piezoelectric modulus.

Different authors give two values of $\mathcal{E}_c$ for InSb: 7.2 eV [10] and 30 eV [11]. According to the approximate experimental [1] and theoretical [12] estimates the piezoelectric constant is equal to $e_{14} \approx (2.6 \text{ to } 3) \times 10^4$ dyn$^{1/2}$ cm^{-1}. Since, in fact, accurate values of the constants are unknown we have determined them by comparing the experimental and theoretical relationships $\tau_p(T)$ at $T_0 = 4.2$ °K.

Fig. 6 shows the experimentally obtained relationships $\tau_p(T)$ for five lattice temperatures T_0. The characteristic feature of these curves is, besides of the non-monotonous dependence, the coincidence of their right-hand branches behind the maxima. The same figure presents the theoretical curves $\tau_p(T)$ plotted according to formula (6) where $P = P_{\text{piez}} + P_{\text{def}}$ and the following values of the constants are used: $e_{14} = 2.6 \times 10^4$ dyn$^{1/2}$ cm^{-1}; $\mathcal{E}_c = 5.8$ eV. These values fit best theory and experiment at 4.2 °K in the region on the left hand side of the maxima. It is important to note that for these values of the constants a satisfactory coincidence of the theory with experimental data at

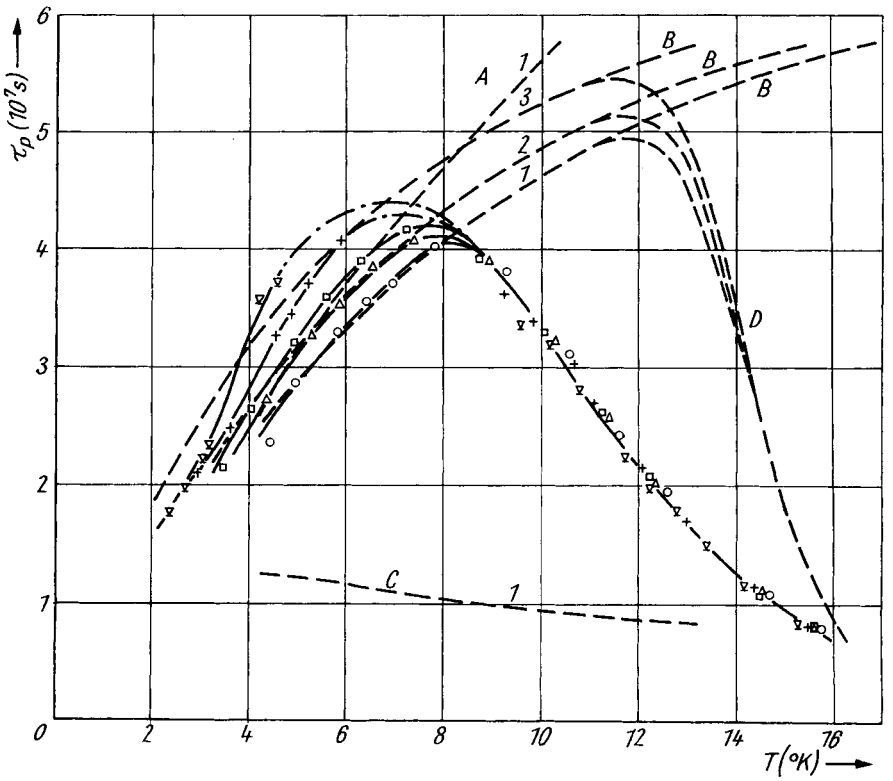

Fig. 6. Dependence of τ_p on the electron gas temperature. Solid lines — experiment, dotted lines — theory. A — $P = P_{\text{piez}}$, B — $P = P_{\text{piez}} + P_{\text{def}}$, D — $P = P_{\text{piez}} + P_{\text{def}} + P_{\text{opt}}$, $e_{14} = 2.6 \times 10^4$ dyn$^{1/2}$ cm^{-1}, $\mathcal{E}_c = 5.8$ eV, $e^*/e = 0.16$; C — $P = P_{\text{piez}} + P_{\text{def}}$, $e_{14} = 2.6 \times 10^4$ dyn$^{1/2}$ cm^{-1}, $\mathcal{E}_c = 30$ eV. 1 — 4.2 °K; 2 — 3.2 °K; 3 — 1.85 °K

$T_0 = 3$ to 4 °K takes place for other samples too [18]. At lower crystal temperatures the coincidence of the theory with the experimental data is somewhat worse. This may be attributed to the fact that for lower T_0 the influence of impurities (neglected in theory) on the energy spectrum of the conduction electrons and on their interaction with phonons becomes greater. Moreover, at the lowest temperatures the condition of applicability of the Boltzmann kinetic equation $\left(\frac{\hbar}{\tau_i} \ll T,\ \tau_i - \text{is the momentum relaxation time}\right)$ and the condition for the idealness of the electron gas $\left(\frac{e^2 n^{1/3}}{T} \ll 1\right)$ are not fulfilled. However, in spite of this it must be said that the theory quite satisfactorily describes the dependence of the curves $\tau(T)$ in the region up to the maximum at all lattice temperatures which were investigated. In this region the energy dissipation by the piezoelectric potential predominates which is evident from the comparison of the experimental curves in Fig. 6 with the theoretical ones plotted for dissipation by piezoelectric and deformation potentials (Curve B1), and only by piezoelectric potential (Curve A1). This is indicated also by the S-type shape of the i–V characteristic in Fig. 2 (See [2]). In the S-shape region we should have $\frac{d \ln \sigma}{dT} = \frac{d \ln P}{dT}$ for $\sigma_{diff} = \infty$. This, together with formula (6), makes it possible to estimate n from the experimental values of P, τ, σ, and $d\sigma/dT$. The quantity $n = 2.7 \times 10^{13}$ cm^{-3} thus obtained is close to the one measured directly. As to the constants e_{14} and $\mathscr{E}_c$ we can only say that the accuracy of their determination is restricted by the accuracy with which the theory used here is applicable to our conditions. Within the boundaries of this theory even insignificant deviations of the constants $\mathscr{E}_c$ and, particularly e_{14}, from the above mentioned values lead to a marked difference of theoretical and experimental curves.

At higher electron temperatures the experimental and theoretical curves (B) sharply differ, and there is no qualitative correspondence between their dependence. It is necessary to note that no agreement between theory and experiment could be reached in the whole investigated temperatures range for any values of the constants e_{14} and $\mathscr{E}_c$ if energy dissipation is assumed to occur only by acoustic phonons. In effect, from (7) and (8) it follows that at sufficiently high electron temperatures $\tau_p \sim \frac{1}{\mathscr{E}_c^2 T^{1/2}}$ and it seems that with higher values of $\mathscr{E}_c$ better agreement can be obtained with experiment. However, this is not so. For example, Fig. 6 presents a calculated curve plotted for the values of $\mathscr{E}_c = 30$ eV and $e_{14} = 2.6 \times 10^4$ dyn$^{1/2}$ cm^{-1}. This shows that even no qualitative correspondence exists with experimental results. The conclusion that the value $\mathscr{E}_c = 30$ eV is apparently too high was also made by other authors [17]. It is essential that if one takes into consideration energy dissipation only by acoustic phonons the decrease of τ_p with T is much slower than experimentally observed. Besides, theoretical curves for different T_0 show only a feeble tendency to coincide with increasing T whereas the corresponding experimental curves, as it was mentioned above, combine into one curve after the maximum. All said above leads to the conclusion that the idea of electron energy dissipation by piezoelectric and deformation potentials of acoustic phonons is in sufficiently good agreement with the experimental data only for relatively insignificant heating of the electron gas ($T < 8$ °K).

At high electron temperatures the rate of the electron energy transfer to the lattice is considerably higher than can be provided by interaction with acoustic phonons and, consequently, another energy dissipation mechanism exists which becomes predominant in this range of electron temperatures.

First of all the contribution of optical phonons should be estimated . Though the number of electrons possessing an energy sufficient for generation of optical phonons is small, a high energy is released during each scattering act.

Consider, for qualitative estimation, that within an electron energy range of the order of $\hbar\omega_0$ (ω_0 is the maximum frequency of the longitudinal optical phonons) the distribution remains also Maxwellian. Then the power $P_{\text{opt}}(T, T_0)$ transmitted to the optical phonons from the electrons is expressed by the formula [13]:

$$P_{\text{opt}}(T, T_0) = n \frac{2^{3/2}\pi (e^* e)^2 m^{1/2}}{\sqrt{k\theta_0}\, M a^3} \left(e^{-\frac{k\theta_0}{T}} - e^{-\frac{k\theta_0}{T_0}} \right), \tag{9}$$

where for InSb $e^* = 0.16\, e$ is the effective ion charge [14], $k\theta_0$ is the longitudinal optical phonon energy, $\theta_0 = 283$ °K [15], $M = 9.85 \times 10^{-23}$ g is the reduced mass of atoms in a cell, $a = 2.8 \times 10^{-8}$ cm is the distance between the atoms In and Sb. The curves D1, 2, 3 in Fig. 6 are plotted according to formula (6) with regard to energy loss by acoustic and optical phonons ($P(T, T_0) = P_{\text{piez}} + P_{\text{def}} + P_{\text{opt}}$). The dependence of these curves qualitatively corresponds to the experimental curves. The optical phonons contribute to energy dissipation in the temperature range behind the maximum of the curves $\tau_p(T)$ and do not influence the dependence of their left-hand branches where the dissipation by acoustic phonons describes properly the experimental results. On the contrary, on the right hand side of the maximum, the abrupt onset of optical phonon dissipation results in a rapid decrease of τ with T and in a coincidence of curves for various T_0 as found in the experiment. A quantitative coincidence could not be expected since we used the rough assumption on the Maxwellian electron distribution function in the high-energy region. In fact, owing to the effect of hot electron runaway [12, 16] the number of electrons in the region of energies ε (where $\varepsilon/T \gg 1$) is greater than follows from the Maxwellian distribution. From this follows that the onset of optical phonons dissipation should be shifted to lower electron temperatures.

5. Conclusion

It is shown that the average electron energy relaxation time in InSb at helium temperatures depends on the power supplied to the sample. This dependence is not monotonous due to the change of mechanisms of energy transfer to the lattice from the electron gas during increase of its temperature. If the crystal lattice has helium temperatures at not very high electron temperatures ($T < 8$ °K) the predominant mechanism of energy loss is the loss by the piezoelectric potential of acoustic phonons. This mechanism determines the increase of τ with T and also the S-type shape of the d.c. i-V characteristic at low lattice temperatures. The deformation potential of acoustic phonons contributes relatively little to the energy loss. The experimental results of the dependence $\tau(T)$ at low heating which are theoretically well described, lead to a piezoelectric modulus in InSb of $e_{14} = 2.6 \times 10^4$ dyn$^{1/2}$ cm^{-1} and indicate that the deformation potential constant $\mathcal{E}_c < 10$ eV.

At $T \geqq 10$ °K the predominant energy loss mechanism is the generation of optical phonons. To take into account this dissipation correctly it is necessary to calculate a special electron energy distribution function in the electrical field.

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