Impact ionization in semiconductors under the influence of the electric field of an optical wave

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The electron-hole pair generation was observed in a semiconductor by light of photon energy much (tens of times) less than the band gap of the semiconductor. Luminescence of n-type InSb was observed experimentally in the fundamental absorption region as a result of excitation with light of the wavelength $\lambda = 90.55\,\mu$. Generation of electron-hole pairs was due to impact ionization caused by electrons (or holes) in the field of a high-power optical wave. A study was made of the field, frequency, and carrier-density dependences of the number of nonequilibrium carriers. Theoretical calculations were made and the results of these calculations agreed well with the experimental data.

INTRODUCTION

We shall report experimental observation of generation of electron-hole (EH) pairs by light incident on a semiconductor when the photon energy $\hbar\omega$ is much (tens of times) less than the band gap of the semiconductor ε_g (preliminary results were given in Ref. 1). Our radiation source was a high-power pulsed tunable laser utilizing NH_3 and D_2O, pumped optically by a CO_2 laser. The emission wavelengths used in our experiments were 90.55, 140, and 385 μ and the pulse duration was $(40\text{–}100)\times 10^{-9}$ sec. The intensity of the radiation reaching a semiconductor sample was 2 MW/cm^2. The investigation was carried out on n- and p-type InSb samples at $T = 78$ K. Luminescence of InSb was observed in the fundamental absorption region and a study was made of the dependence of the photoconductivity associated with the appearance of nonequilibrium excess carriers on the frequency and intensity of the incident radiation. It was found that the generation of EH pairs under the influence of light of $\hbar\omega \ll \varepsilon_g$ energy was due to impact ionization by electrons (holes) heated in the field of the high-power optical wave. The results of theoretical calculations were found to be in good agreement with the experimental data.

Up to now the process of generation of EH pairs as a result of excitation with high-intensity laser radiation of photon energy less than the band gap of a semiconductor has been observed only in the case of two- and three-photon interband transitions.[2,3] It has been reported[4,5] that the excitation of EH pairs in germanium at $T = 300$ K is possible under the action of CO_2 laser radiation of the $10.6\,\mu$ wavelength ($\hbar\omega \approx \varepsilon_g/8$). Impact ionization is mentioned in Ref. 4 as one of the possible mechanisms of this effect. However, according to the authors of Ref. 4, the experimental results and particularly the weak dependence of the density of nonequilibrium carriers on the intensity of the exciting radiation I (which is nearly linear) cannot be explained by the model of impact ionization. The problem of the mechanism of pair generation in these experiments has not yet been solved.

Impact ionization has been studied extensively in semiconductors subjected to static electric fields (see, for example, Ref. 6). In the case of InSb it has been studied also in the microwave range[7] in the case when the criterion $\omega\tau_p \ll 1$ is satisfied by a large margin; here, ω is the frequency of oscillations of the electric field of the optical wave and τ_p is the momentum relaxation time of the carriers. At these frequencies the carrier heating mechanism is essentially the same as in a static electric field: the number of carriers with high energies capable of causing impact ionization increases on increase in their mean free path, i.e., on increase in τ_p. Under our experimental conditions the electric field of the optical wave had a sufficiently high frequency for the opposite inequality $\omega\tau_p \gg 1$ to be satisfied. It should be pointed out that under these conditions carriers acquire high energies entirely because of collisions in the presence of a high-frequency electric field, but an increase in τ_p reduces the heating effect.

1. EXPERIMENTAL RESULTS ON n-TYPE InSb AND DISCUSSION

1.1. Generation of electron-hole pairs in n-type InSb under the action of high-power radiation of 90.55 μ wavelength

The main experiments on the generation of EH pairs in n-type InSb were carried out using a high-power pulsed NH_3 laser (emitting at the wavelength of $\lambda = 90.55\,\mu$) pumped optically by a CO_2 laser. The duration of the laser pulses τ_l was 40 nsec. The maximum intensity of the laser radiation reaching the sample was $I = 2$ MW/cm^2. A study was made of the photoconductivity of n-type InSb samples with carrier densities from $n_0 = 9.3\times 10^{12}$ to 2.3×10^{15} cm^{-3} at $T = 78$ K.

Figure 1 shows a typical oscillogram of the photoconductivity signal recorded for a sample of n-type InSb at sufficiently high radiation intensities. We can see that in addition to a short-lived component of the photoconductivity, which duplicated exactly the profile of the initial laser pulse and was clearly due to a change in the mobility of free carriers (μ photoconductivity),[8] there was an additional component of the photoconductivity in the form of a decay process with

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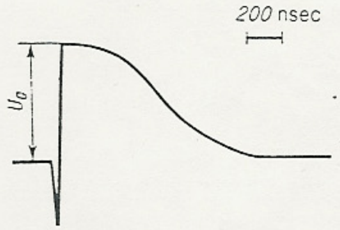

FIG. 1. Typical oscillogram of the photoconductivity signal observed for InSb samples at $T = 78$ K illuminated with light of sufficiently high intensity.

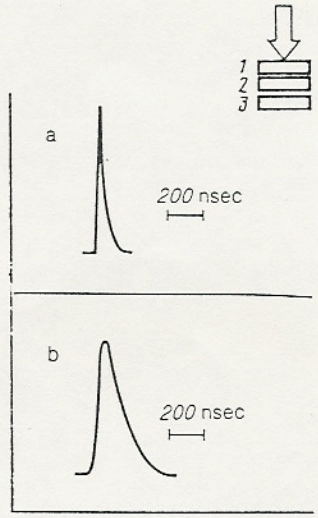

FIG. 2. Experimental arrangement used in the observation of the luminescence of n-type InSb at $T = 78$ K for a sample with a carrier density $n_0 = 2.3\times10^{15}$ cm^{-3} created by laser radiation of the $\lambda = 90.55\,\mu$ wavelength: 1) sample; 2) mica filter; 3) Ge:Au detector. Oscillograms: a) exciting pulses; b) luminescence pulse ($\lambda \approx 5\,\mu$).

much slower kinetics. The order of magnitude of decay of the signal and the nature of its dependence on the density of dark carriers were similar to the corresponding dependences applicable to the lifetime of nonequilibrium carriers in n-type InSb at $T = 78$ K (see, for example, Ref. 9). This led us to the hypothesis that EH pair generation occurred in our samples. This hypothesis was checked in an experiment in which luminescence of n-type InSb was recorded in the fundamental absorption region ($\lambda \approx 5\,\mu$, $\varepsilon_g = 224$ meV) when samples were excited with high-power laser radiation of the $\lambda = 90.55\,\mu$ wavelength ($\hbar\omega = 13.7$ meV). Use was made of the experimental arrangement shown in Fig. 2. A Ge:Au extrinsic photodetector with an impurity level at 160 meV was employed and this photodetector was in principle insensitive to the radiation with $\hbar\omega = 13.7$ meV. Nevertheless, a weak photoresponse was observed at sufficiently high radiation intensities. Therefore, mica filters were placed in front of the detector and these attenuated the long-wavelength radiation, but they were practically completely transparent in the $\lambda \approx 5\,\mu$ range. These filters ensured that in the absence of the sample there was no signal from the photodetector even at the highest intensity of the incident light (2 MW/cm^2). In the case of n-type InSb samples with a carrier density $n_0 \lesssim 10^{13}$ cm^{-3} there was no photodetector signal at $T = 78$ K. Consequently, the stray effects, such as those associated with the appearance of a laser spark on the semiconductor surface, were unimportant. The luminescence was recorded for a sample of n-type InSb with $n_0 = 2.3\times10^{15}$ cm^{-3}. Typical oscillograms were of the form shown in Fig. 2. As expected, the kinetics of the luminescence signal was governed by the nonequilibrium carrier lifetime in n-type InSb at $T = 78$ K when $n_0 = 2.3\times10^{15}$ cm^{-3}. Therefore, the experimental results confirmed that EH pairs were generated in our samples

1.2. Experimental studies of the mechanism of generation of electron-hole pairs

Figure 3 shows the experimental dependences of the nonequilibrium carrier density Δn in n-type InSb at $T = 78$ K on the intensity of the incident radiation of the $\lambda = 90.55\,\mu$ wavelength, obtained for three values of the carrier density in darkness. The excess density was deduced directly from the maximum of the photoconductivity signal U_0 associated with the generation of nonequilibrium carriers (Fig. 1), because the duration of the light pulses in our experiments was much less than the lifetime of nonequilibrium carriers and, consequently, the process of recombination could be ignored. Under these conditions the experimentally determined relative photoconductivity $\Delta\sigma/\sigma_0$ of n-type InSb represented effectively $\Delta n/n_0$, since the electron mobility μ_n was much higher than the hole mobility μ_p. The results (Fig. 3) show that the curves were strongly nonlinear and exhibited a quasithreshold dependence on the exciting radiation intensity. A dependence of this type could be associated with just two mechanisms of creation of nonequilibrium electrons: many-photon interband absorption (known as dielectric breakdown) or impact ionization in the field of an optical wave.

Many-photon interband absorption of light has been in-

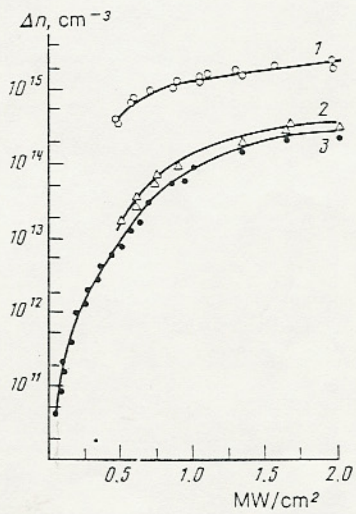

FIG. 3. Dependences of the density of excess carriers Δn on the intensity of the incident light I at the $\lambda = 90.55\,\mu$ wavelength: 1) $n_0 = 2.3\times10^{15}$ cm^{-3}; 2) 3.4×10^{14} cm^{-3}; 3) 3.7×10^{13} cm^{-3}.

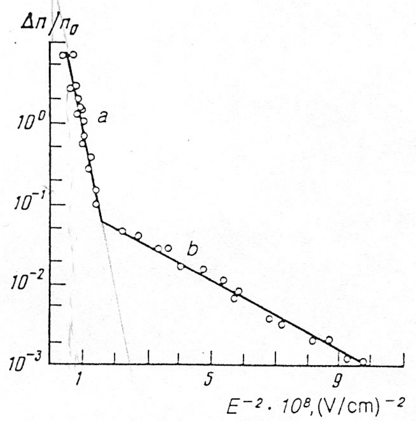

FIG. 4. Dependence of $\Delta n/n_0$ on the reciprocal of the square of the electric field E^{-2} of a light wave incident on n-type InSb at $T = 78$ K for $\lambda = 90.55\ \mu$. The points are the experimental values for $n_0 = 3.7\times10^{13}$ cm^{-3} and the continuous curve is a plot of $\Delta n/n_0 = A\exp[-(E/E_0)^2]$: a) $E_{01} = 1.7\times10^4$ V/cm; b) $E_{02} = 0.7\times10^4$ V/cm.

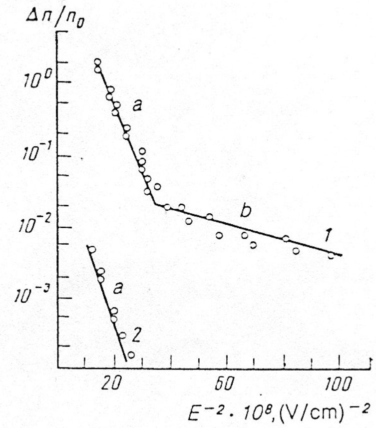

FIG. 5. Dependences of $\Delta n/n_0$ on the reciprocal of the square of the electric field E^{-2} of a light wave incident on n-type InSb: 1) $\lambda = 385\ \mu$; 2) 140 μ. The points are the experimental values corresponding to $n_0 = 3.7\times10^{13}$ cm^{-3} and the continuous curve is a plot of $\Delta n/n_0 = A\exp[-(E/E_0)^2]$: 1$a$) $E_{01} = 0.45\times10^4$ V/cm; 1b) $E_{02} = 0.18\times10^4$ V/cm; 2a) $E_{02} = 0.5\times10^4$ V/cm.

vestigated in detail from the theoretical point of view.[10,11] Here, we shall simply mention that an increase in the frequency of light increases the rate of generation of EH pairs as a result of many-photon interband absorption and, naturally, this rate is independent of the dark density of carriers in a sample. However, the rate of generation as a result of impact ionization by free carriers heated in the field of an optical wave increases on increase in the dark density of carriers and, as shown in the next section, it falls exponentially on increase in the radiation frequency. In the impact ionization case we can expect the following depenence of the density of excess carriers on the intensity of the electric field E of an optical wave:

$$\Delta n/n_0 = A\exp(-E_0^2/E^2), \tag{1}$$

where A is a factor dependent weakly on the field and E_0 is the characteristic field intensity proportional to the frequency of the exciting radiation.

In general, the carrier-density dependence of the absolute number of nonequilibrium electrons (Fig. 3) supports the second mechanism. However, in order to ensure reliable identification of the pair generation mechanism, we carried out additional experiments at two wavelengths of a D_2O laser: $\lambda_2 = 140\ \mu$ and $\lambda_3 = 385\ \mu$. These experiments showed that an increase in the radiation wavelength reduced strongly the threshold of generation of excess carriers. This unambiguously indicated that the generation of EH pairs was in our case due to impact ionization caused by the heating of free carriers in the field of an optical wave.

Figures 4 and 5 give the experimental dependences of $\Delta n/n_0$ on the reciprocal of the square of the amplitude of the electric field E^{-2} of optical waves of three different wavelengths incident on a sample of n-type InSb with $n_0 = 3.67\times10^{13}$ cm^{-3} at $T = 78$ K. The dependences are indeed described well by Eq. (1). It is worth noting the existence of two rectilinear regions with different values of the parameter E_0, governed by the slope of these regions relative to the selected axes. The absolute values of E_{01} and E_{02} differ approximately twofold and depend linearly on the frequency of the incident radiation. The existence of these two regions can be attributed to interband impact ionization corresponding to the slope E_{01} and characterized by a threshold energy $\varepsilon_i \approx \varepsilon_g$ and to impact ionization of an impurity (structure defect) level located in the case of InSb approximately in the middle of the band gap ($\varepsilon_i \approx \varepsilon_g/2$) and characterized by a defect concentration of $\sim 10^{14}$ cm^{-3} (Refs. 9 and 12); this is represented by the section E_{02}.

Figure 6 gives the dependences of the density of excess carriers on the reciprocal of the square of the field in the interband impact ionization region obtained for a number of samples with carrier densities from 10^{13} to 2×10^{15} cm^{-3}. We can see that the changes in the dark density of carriers have practically no effect on the characteristic field E_{01}, but the absolute value of the excess density at a fixed radiation intensity is considerably greater for samples with a high dark carrier density.

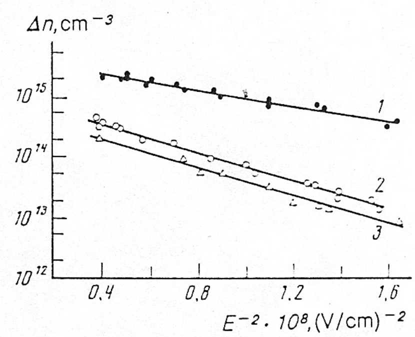

FIG. 6. Dependences of $\Delta n/n_0$ on the reciprocal of the square of the electric field E^{-2} of a light wave incident on n-type InSb at $T = 78$ K for $\lambda = 90.55\ \mu$: ●) $n_0 = 2.3\times10^{15}$ cm^{-3}; ○) 3.4×10^{14} cm^{-3}; △) 3.7×10^{13} cm^{-3}. The continuous lines are plots of $\Delta n/n_0 = A\exp[-(E/E_0)^2]$.

2. THEORY

2.1. Impact ionization by electrons in an optical wave field

Heating of free carriers as a result of intraband absorption of infrared radiation has been studied frequently from the quantum[13] and classical (see, for example, Ref. 14) points of view. It has been shown that the quantum approach is essential in the case of relatively weak heating when the average energy ε of hot carriers is comparable with the photon energy $\hbar\omega$. The case of strong heating ($\varepsilon \gg \hbar\omega$) corresponds to the classical limit, so that the distribution function of hot carriers $f(\mathbf{p})$ obeys the classical Boltzmann equation. The actual form of $f(\mathbf{p})$ depends strongly on the relationship between the radiation frequency ω and the momentum and relaxation time τ_p and τ_ε, respectively. We shall be interested in the case when the inequality $\omega\tau_p \gg 1$ is obeyed. In this case the distribution of carriers in the momentum space is slightly asymmetric and the symmetric part of the distribution function $f_0(\varepsilon)$ averaged over one period of oscillations of the wave field obeys the Fokker-Planck equation[15]:

$$\frac{1}{g(\varepsilon)}\frac{d}{d\varepsilon}[g(\varepsilon)J(\varepsilon)]=0, \tag{2}$$

where $g(\varepsilon)$ is the density of states in an allowed band and $J(\varepsilon)$ is the flux of electrons in the energy space given by

$$J(\varepsilon)=-D(\varepsilon)\,df_0(\varepsilon)/d\varepsilon-R(\varepsilon)f_0(\varepsilon). \tag{3}$$

The first term in the above equation describes the diffusion of particle energy in the field of a wave, characterized by a diffusion coefficient $D(\varepsilon)$ proportional to the square of the energy acquired by an electron during one oscillation period T_0 and also proportional to the momentum relaxation frequency, i.e., $D(\varepsilon)\propto(eEvT_0)^2\nu_p$ (v is the electron velocity). The second term represents dynamic friction which is due to the inelasticity of the interaction of electrons with the lattice, so that $R(\varepsilon)$ is equal to the rate of loss of energy by an electron due to the emission of optical phonons.

We shall continue this analysis in the specific case of InSb. We shall first consider an n-type semiconductor. The main mechanism of relaxation of high-energy ($\varepsilon \lesssim \varepsilon_g$, where ε_g is the band gap) electrons in respect of their momentum and energy in indium antimonide is the polar interaction with longitudinal optical phonons. When the temperature is sufficiently low ($\hbar\omega_0 \gg kT$, where ω_0 is the frequency of longitudinal optical vibrations) and only the spontaneous emission of phonons need be allowed for, the reciprocal of the phonon emission time in the range $\varepsilon \gg \hbar\omega_0$ is

$$\tau_{pol}^{-1}\equiv\nu^{pol}(\varepsilon)$$

$$=\frac{e^2\hbar\omega_0(m^*/2)^{1/2}}{\hbar^2}\,\frac{\chi_0-\chi_\infty}{\chi_0\chi_\infty}\,\frac{2\varepsilon+\varepsilon_g}{[\varepsilon\varepsilon_g(\varepsilon+\varepsilon_g)]^{1/2}}\ln\frac{4\varepsilon(\varepsilon+\varepsilon_g)}{\hbar\omega_0(2\varepsilon+\varepsilon_g)}, \tag{4}$$

where m^* is the effective mass of an electron at the bottom of the conduction band; χ_0 and χ_∞ are the static and high-frequency permittivities, respectively. The above formula is derived allowing for the Kane nature of the electron spectrum in InSb (Ref. 16):

$$\varepsilon(p)=\left(\frac{\varepsilon_g^2}{4}+\frac{p^2\varepsilon_g}{2m^*}\right)^{1/2}-\frac{\varepsilon_g}{2}. \tag{5}$$

The frequency of momentum relaxation as a result of the interaction with longitudinal optical phonons is given by

$$\tau_p^{-1}(\varepsilon)\equiv\nu_p(\varepsilon)=\nu^{pol}(\varepsilon)\left[\ln\frac{4\varepsilon(\varepsilon+\varepsilon_g)}{\hbar\omega_0(2\varepsilon+\varepsilon_g)}\right]^{-1}. \tag{6}$$

If we use Eq. (4) and assume standard values of the parameters $m^*=0.013m_0$, where m_0 is the mass of a free electron, $\hbar\omega_0=24$ meV, $\varepsilon_g=224$ meV, $\chi_\infty=16.0$, and $\chi_0=18.7$, we find that the frequency $\nu^{\rm pol}$ varies from 1.5×10^{12} to 2.2×10^{12} sec^{-1} between $2\hbar\omega_0$ and ε_g. It should be pointed out that the published values of χ_∞ suffer from a large scatter. Our value is that accepted currently by the majority of authors (see, for example, Ref. 17).

The contribution of the acoustic scattering is analyzed in Ref. 18. The corresponding frequency $\nu^{\rm ac}$ increases on increase in the energy proportionally to $\varepsilon^{1/2}$ and at $\varepsilon\approx\varepsilon_g$ it amounts to $\approx2\times10^{11}$ sec^{-1}. The frequency of scattering by charged impurities falls on increase in the energy in accordance with the law $\varepsilon^{-3/2}$ and at impurity concentrations of the order of 10^{15} cm^{-3} it becomes $\approx10^{10}$ sec^{-1} for $\varepsilon=\varepsilon_g$. It is therefore clear that in considering the kinetics of hot electrons in InSb we can indeed confine our analysis to just the polar interaction with optical phonons. However, it should be pointed out that this can be done only in the case of a sufficiently high electric field (light intensity), when the criterion $eE\lambda^{\rm pol}>\hbar\omega_0(\omega\tau_{\rm pol})$ is obeyed (here, $\lambda^{\rm pol}=\tau_{\rm pol}\partial\varepsilon/\partial p$ and E is the amplitude of the wave field).[1)]

The diffusion coefficient $D(\varepsilon)$ and the dynamic friction coefficient $R(\varepsilon)$ occurring in Eq. (3) for an electron flux are described by

$$D(\varepsilon)=\frac{e^2E^2}{6}\left(\frac{\partial\varepsilon}{\partial p}\right)^2\frac{\nu_p(\varepsilon)}{\omega^2},\qquad R(\varepsilon)=\nu^{pol}(\varepsilon)\hbar\omega_0. \tag{7}$$

Assuming now that the electron flux J vanishes in the energy space and using Eqs. (4)–(7), we can obtain the solution of Eq. (2) for the distribution function $f_0(\varepsilon)$ in the form

$$f_0(\varepsilon)=A\exp\left\{-\frac{3\hbar\omega_0\omega^2m^*}{e^2E^2}\int_{\hbar\omega_0}^{\varepsilon}\frac{(2\varepsilon'+\varepsilon_g)^2}{\varepsilon'(\varepsilon'+\varepsilon_g)}\right.$$

$$\left.\times\ln\left[\frac{4\varepsilon'(\varepsilon'+\varepsilon_g)}{\hbar\omega_0(2\varepsilon'+\varepsilon_g)}\right]\frac{d\varepsilon'}{\varepsilon_g}\right\}, \tag{8}$$

where the constant A should be found from the normalization condition

$$\int_0^\infty f_0(\varepsilon)g(\varepsilon)\,d\varepsilon=n_0.$$

The rate of generation of EH pairs created by the process of impact ionization by electrons heated in the field of an optical wave, is given by

$$W(E)=\frac{1}{n_0}\int_{\varepsilon_i} w_i(\varepsilon-\varepsilon_i)f_0(\varepsilon)g(\varepsilon)\,d\varepsilon, \tag{9}$$

where ε_i is the threshold energy for impact ionization in InSb, which is slightly higher than ε_g (for details see Ref. 19).

The probability of an elementary event of interband impact ionization $w_i(\varepsilon-\varepsilon_i)$ in InSb was investigated experimentally earlier.[20] It was found that the function $w_i(\varepsilon-\varepsilon_i)$

quite rapidly (in the range $\varepsilon - \varepsilon_i \gtrsim \hbar\omega_0$) reached saturation and its value was then $W_{is} = 10^{10}$ sec^{-1}, considerably less than the frequency of collisions with optical phonons. It follows that impact ionization does not affect the distribution function and Eq. (8) can be also used in the range $\varepsilon > \varepsilon_i$. Under the conditions assumed in our calculations, which correspond also to the experimental situation, the scale of the fall of the distribution function is considerably greater than $\hbar\omega_0$. Therefore, it follows from Eq. (9) for $W(E)$ that

$$W(E) \approx W_{is} \Delta n_i / n_0,$$

where Δn_i is the number of electrons of energy $\varepsilon > \varepsilon_i \simeq \varepsilon_g$. Since the fall of the distribution function is exponential, we can estimate it using the formula

$$W(E) = W_{is} \gamma \exp(-E_0^2/E^2), \tag{10}$$

$$E_0^2 = \frac{3\hbar\omega_0\omega^2 m^*}{e^2} \int_{\hbar\omega_0}^{\varepsilon_p} \frac{(2\varepsilon'+\varepsilon_g)^2}{\varepsilon'(\varepsilon'+\varepsilon_g)} \ln \frac{4\varepsilon'(\varepsilon'+\varepsilon_g)}{\hbar\omega_0(2\varepsilon'+\varepsilon_g)} \frac{d\varepsilon'}{\varepsilon_g}.$$

The exact value of the pre-exponential factor $\gamma(E)$ can be found generally only by numerical calculation. Its order of magnitude is the same as of the ratio $g(\varepsilon_i)/g(\varepsilon)$, which gives rise to a power-law dependence of γ on the field. We shall assume that $\gamma = \text{const}$. Ionization of impurity levels is also described by Eq. (10) if instead of W_{is} and ε_i we use the corresponding values for an impurity level.

2.2. Impact ionization by holes in *p*-type InSb in an optical wave field

We shall first discuss the role of various scattering mechanisms in the valence band of InSb. It should be pointed out that, as in the case of the conduction band electrons, the scattering of high-energy holes due to their interaction with acoustic phonons can be ignored. The scattering of light holes due to the polar interaction with longitudinal optical phonons may occur within the light-hole subband (we shall denote the corresponding frequency by $\nu_{ll}^{\rm pol}$) or it may be accompanied by transfer to the heavy-hole subband (frequency $\nu_{lh}^{\rm pol}$). The frequency $\nu_{ll}^{\rm pol}$ is governed by Eq. (4), because $m_l \simeq m^*$ (m_l is the effective mass of the light holes). The intersubband polar scattering is strongly suppressed, since it is accompanied by a large transfer of momentum $q \sim p(m_h/m_l)^{1/2}$ (p is the momentum of a light hole) and the matrix element of the interaction with phonons is inversely proportional to q.

In addition to these scattering mechanisms in the valence band, it is found that—in contrast to the conduction band—an important role is played by the scattering due to the deformation interaction with optical vibrations. We analyzed indetail the role of such scattering in InSb using the method of Ref. 21. Our analysis showed that in the heavy-hole subband the scattering frequencies due to the polar and deformation interactions are comparable at high energies, whereas the contribution of the deformation interaction within the light-hole subband is small. The transitions of holes from the light to the heavy subband are governed mainly by the deformation interaction. However, the frequency of such scattering $\nu_{lh}^{\rm def}$ at energies $\varepsilon \lesssim \varepsilon_g$ is still less than $\nu_{ll}^{\rm pol}$.

We can now summarize the results as follows: in the case of the light and heavy holes the dominant scattering mechanism is the intraband process with frequencies $\nu_{ll}^{\rm pol}$ for the light holes and $\nu_{hh}^{\rm pol} + \nu_{hh}^{\rm def}$ for the heavy holes.[2)] The intersubband scattering $\nu_{lh}^{\rm def}$ and $\nu_{hl}^{\rm def} \ll \nu_{lh}^{\rm def}$ ensures a weak coupling between the light and heavy holes. Under these conditions the heating in each of the subbands is of the diffusion type and the common (for both subbands) asymptote of the distribution function is dominated by the light-hole subband, because the heating in this subband is stronger.

It therefore follows that the distribution functions of holes in both subbands are described by expressions of the (8) type with the normalization constants A_l and A_h and with the replacement m^* with m_l (we recall that $m_l \simeq m^*$). The main contribution to the impact ionization is made by the light holes, because the threshold energy is $\varepsilon_{il} \simeq \varepsilon_g$, whereas in the case of the heavy holes we have $\varepsilon_{ih} \simeq 2\varepsilon_g$. Since the number of the light holes is approximately $(m_h/m_l)^{3/2}$ times less (with amounts $\simeq 10^2$ in the case of InSb) than the total number of holes, it follows that (other conditions being equal) the rate of ionization in *p*-type InSb is 10^2 times less than in *n*-type InSb.

3. QUANTITATIVE COMPARISON OF THE THEORY AND EXPERIMENTS FOR *n*-TYPE InSb

It is shown in Sec. 1.2 that the EH-pair generation observed by us in *n*-type InSb is due to impact ionization by electrons heated in the field of an optical wave. We shall compare the experimental results with the theoretical calculations given in Sec. 2.1. It is clear from Figs. 4 and 5 that the density of excess carriers Δn is described well by Eq. (1) with two characteristic values of E_0. Table I lists the experimental and theoretical values of E_0 at three wavelengths. The theoretical values E^t_{01} and E^t_{02} correspond to the interband ionization and to the ionization of an impurity level of energy $\varepsilon_g/2$. It is clear from Table I that $E^e_{01}/E^e_{02} = E^t_{01}/E^t_{02}$ and that $E_{01,2}$ and $E_{01,2} \propto \omega$ (the absolute values of $E^e_{01,2}$ and $E^t_{01,2}$ differ by a factor of 2.5–3).

This difference is clearly due to the following circumstance. In an analysis of the experimental data the intensity $I \propto E^2$ is the quantity averaged over the laser beam cross section, i.e., the mode structure of the laser radiation is ignored. However, the rate of impact ionization depends exponentially on the intensity of light, so that the recorded photoconductivity signal is dominated by the generation of pairs in the regions where the local intensity exceeds the average value. An allowance for this circumstance would increase the experimental value of E_0. For example, in the simplest case when the intensity distribution over the cross section of a laser beam is described by the linear function $I(r) = I_{\max}(1 - r/r_0)$, where r_0 is the beam radius, the average value $I_{\rm av}$ is three times less than the maximum value $I_{\max}$. If in an analysis of the experimental results we use not $I_{\rm av}$ but $I_{\max}$, then the value of E_0 is overestimated by the factor $\sqrt{3}$.

Another point should also be made. In calculating the value of the field acting on electrons in a crystal we used the Fresnel formulas valid for a continuous medium. However, the field amplitude in a crystal is strongly modulated over

TABLE I. Experimental and theoretical values of E_0 for n-type InSb ($T = 78$ K, $n_0 = 3.7\times10^{13}$ cm^{-3}).

λ, μ	E_{01}, V/cm		E_{02}, V/cm	
	theory	experiment	theory	experiment
90.55	$6.2\cdot10^4$	$1.7\cdot10^4$	$3.7\cdot10^4$	$0.7\cdot10^4$
140	$4\cdot10^4$	–	$2.4\cdot10^4$	$0.5\cdot10^4$
385	$1.46\cdot10^4$	$0.45\cdot10^4$	$0.87\cdot10^4$	$0.18\cdot10^4$

distances of the order of the lattice constant so that at energies $\simeq\varepsilon_g$ there may be an increase in the effective field acting on electrons.[23]

It should be stressed that these two circumstances increase the experimental values of $E^e_{01,2}$, which improves the agreement with the theoretical calculations. As pointed out already in Sec. 2.1, in view of the difficulties encountered in the determination of the preexponential factor, it is difficult to determine the theoretical absolute value of the excess density. We can only estimate its order of magnitude.

The rise of the number of excess electrons as a result of impact ionization is described by the equation

$$dn/dt = W(E(t))n,$$

where $E(t)$ is the time-dependent field amplitude in a pulse. Hence, we find that the number of electrons created during a pulse is

$$\Delta n = n_0\left(\exp\int_{-\infty}^{+\infty} W(E(t))\,dt - 1\right).$$

If $\Delta n < n_0$, which is almost always true in experiments, the exponential function can be expanded as a series and only the first term of the expansion need be retained. We then obtain

$$\Delta n/n_0 = \int_{-\infty}^{+\infty} W(E(t))\,dt. \tag{11}$$

If the dependence $E^2(t)$ is approximated by a triangle with a half-width τ_l, then integration in Eq. (11) subject to Eq. (10) for $W(E)$ gives

$$\Delta n/n_0 \approx 2\gamma\tau_l W_{is}(E^2_{max}/E_0^2)\exp(-E_0^2/E^2_{max}), \tag{12}$$

where $E_{\max}$ is the maximum field in a pulse. An estimate obtained from Eq. (12) using the experimental values of $E_0^2/E^2_{\max}$ as well as the parameters $W_{is} = 10^{10}$ sec^{-1} (Ref. 20), $\tau_l = 40\times10^{-9}$ sec, and $\gamma = 2$ gives a value of $\Delta n/n_0$ which is approximately twenty times as large as that found experimentally.

In the analysis of the experimental results we assumed that the laser pulse duration ($\tau_l \simeq 40$ nsec) is much less than the nonequilibrium carrier lifetime. We shall now consider this point in greater detail.

In fact, the lifetime of excess carriers under interband ionization conditions in InSb exceeds considerably 40 nsec in the range of densities from 10^{12} to 10^{15} cm^{-3}. However, in the ionization of an impurity level of a structure defect the lifetime of excess carriers should at first sight become considerably shorter because of the rapid capture by the ionized level. However, we can see from the experimental dependences (Fig. 4) that the process of impurity impact ionization ionizes not more than 10^{12} cm^{-3} of the centers. Such a small number of the ionized centers clearly does not affect significantly the lifetime of excess carriers. These qualitative considerations are supported by the directly observed kinetics of the photoconductivity signal in the impurity ionization region, the characteristic time of which is usually consider-

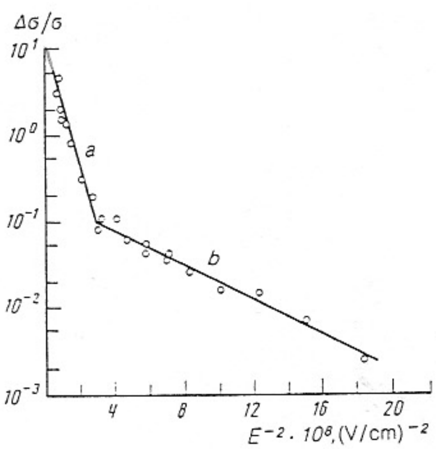

FIG. 7. Dependence of $\Delta\sigma/\sigma$ on the reciprocal of the square of the electric field E^{-2} of a light wave incident on p-type InSb at $T = 78$ K for $\lambda = 90.55$ μ. The points are the experimental values for $p_0 = 1.5\times10^{13}$ cm^{-3} and the continuous curve is a plot of $\Delta\sigma/\sigma = A\exp[-(E/E_0)^2]$: a) $E_{01} = 1.3\times10^4$ V/cm; b) $E_{02} = 0.5\times10^4$ V/cm.

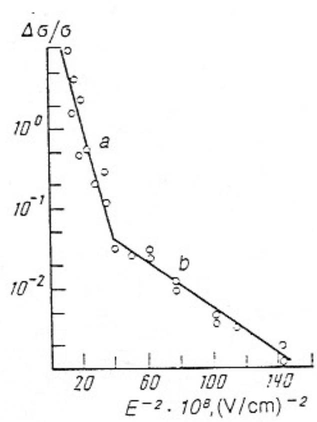

FIG. 8. Dependence of $\Delta\sigma/\sigma$ on the reciprocal of the square of the electric field E^{-2} of a light wave incident on p-type InSb at $T = 78$ K for $\lambda = 385$ μ. The points are the experimental values for $p_0 = 1.5\times10^{13}$ cm^{-3} and the continuous curve is a plot of $\Delta\sigma/\sigma = A\exp[-(E/E_0)^2]$: a) $E_{01} = 0.35\times10^4$ V/cm; b) $E_{02} = 0.15\times10^4$ V/cm.

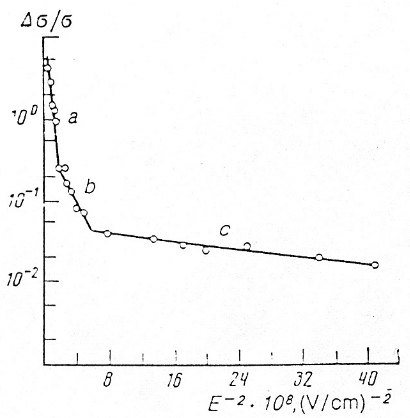

FIG. 9. Dependence of $\Delta\sigma/\sigma$ on the reciprocal of the square of the electric field E^{-2} of a light wave incident on p-type InSb at $T = 78$ K for $\lambda = 90.55$ μ. The points are the experimental values for $p_0 = 1.36\times 10^{15}$ cm^{-3} and the continuous curve is a plot of $\Delta\sigma/\sigma = A \exp[-(E/E_0)^2]$: a) $E_{01} = 1.4\times 10^4$ V/cm; b) $E_{02} = 0.7\times 10^4$ V/cm; c) $E_{03} = 0.3\times 10^4$ V/cm.

ably greater than the duration of laser pulses.

4. GENERATION OF ELECTRON-HOLE PAIRS IN p-TYPE InSb. EXPERIMENTS AND DISCUSSION OF RESULTS

The phenomenon of creation of EH pairs by photons of energy $\hbar\omega \ll \varepsilon_g$ has been observed also in p-type InSb at $T = 78$ K for samples with different dark carrier densities p_0. As in the case of n-type InSb, in addition to a short component of the photoconductivity signal, there is also an extended slow decay component.

Figures 7 and 8 give the experimental dependences of the relative photoconductivity $\Delta\sigma/\sigma_0$ of p-type InSb on the reciprocal of the square of the field. The dependences were obtained at two wavelengths: 90.55 and 385 μ. It is clear from these figures that the situation was analogous to n-type InSb and the behavior $\Delta\sigma/\sigma_0$ was described well by Eq. (1). The values of E_{0i} depended linearly on the frequency of the incident radiation. The nature of the field, frequency, and carrier-density dependences of $\Delta\sigma/\sigma_0$ indicated that, as in the case of n-type InSb, the process of generation of pairs was again due to impact ionization. As in n-type InSb, there was an interband ionization region (with the parameter E_{01}) and a region of ionization of an impurity level (with the parameter E_{02}). In the case of a sample with $p_0 = 1.36\times 10^{15}$ cm^{-3}, i.e., when the Fermi level at $T = 78$ K was located quite close to the top of the valence band, once again there was a region of impact ionization of an impurity level located about 60 meV above the top of the valence band (see, for example, Refs. 9 and 12) with a corresponding characteristic field E_0 (Fig. 9). It should be pointed out that in the case of ionization of an impurity level we have $\Delta\sigma/\sigma_0 = \Delta p/p_0$. However, in the case of interband ionization, since an electron and a hole are created simultaneously, we obtain

$$\frac{\Delta\sigma}{\sigma_0} = \frac{\Delta n\mu_n + \Delta p\mu_p}{p_0\mu_p} \approx \frac{\Delta n\mu_n}{p_0\mu_p},$$

since $\mu_n \gg \mu_p$ ($\mu_n/\mu_p \approx 10^2$).

This is naturally valid if the lifetime of nonequilibrium electrons is much longer than the pulse duration, which follows directly from the experimentally observed photoconductivity signal kinetics ($\tau \gg \tau_l$). In the impurity ionization region the observed kinetics agrees with the known relaxation times of excess holes in p-type InSb at $T = 78$ K. However, in the interband ionization region where the photoconductivity is due to the generation of excess electrons, such slow kinetics is unusual because of the rapid capture of electrons by the impurity levels of a structure defect located at 60 and 120 meV above the top of the valence band (mentioned above), which at the relevant radiation intensities are only partly ionized by the light holes (Figs. 7 and 8). An explanation of this observation will require a special investigation which is outside the scope of the present work.

We shall now consider in greater detail the interband ionization case. It is clear from Figs. 7 and 8 that the characteristic field E_{01} of p-type InSb is practically the same as that of n-type InSb, whereas the absolute number of excess carriers is, other conditions being equal, approximately two orders of magnitude less in p-type InSb than in the n-type material. In our opinion, this is due to the fact that the impact ionization in p-type InSb is performed by the light holes, the mass of which is close to the mass of electrons, and the density of these holes is approximately two orders of magnitude less than the total density of holes p_0 in darkness (see Sec. 2.2).

We shall now consider the range of intensities corresponding to the impurity ionization region. If we assume that the process of ionization is due to the light holes in p-type InSb, the characteristic field E_{02} should be equal to the field E_{02} of n-type InSb, because the level being ionized is located in the middle of the band gap (Sec. 2). It is clear from a comparison of the relevant experimental dependences (in Figs. 7 and 8 and Figs. 4 and 5) that the fields E_{02} are indeed equal for n-type InSb and p-type InSb.

It should be pointed out that in the impurity ionization region the number of excess carriers in p-type InSb is equal to the corresponding number in n-type InSb for the same intensities and we have $p_0 \approx n_0$. Since in the case of ionization by holes the process involves only a small fraction of holes (light holes), this circumstance shows that the probability of impact ionization of an impurity level of a structure defect (with an energy $\varepsilon_i \approx \varepsilon_g/2$) to the valence band is approximately 10^2 times higher than to the conduction band.

We shall conclude by noting that our experiments revealed for the first time the interband impact ionization of holes under conditions when an avalanche is not formed because $\Delta p \ll p_0$. In our opinion, this answers the widely discussed question[24–26,7] as to which carriers can initiate an avalanche in p-type InSb. In one of the recent investigations of this question[7] it was shown experimentally that near the avalanche formation threshold in the absence of injection the breakdown process is initiated by the minority carriers (electrons). This is indeed true but an avalanche is formed by the newly created electrons whose density is already of the order of the dark density of the light holes. The true initiators of the breakdown are not these electrons because their number in the equilibrium state is very small ($n_0 \approx 2\times 10^6$ cm^{-3} when $p_0 = 5\times 10^{13}$ cm^{-3} at $T = 78$ K), but the light holes, as demonstrated directly by the experiments described above. The light holes heated by an electric field create electrons and when the density of electrons becomes of the order of the density of the light holes, their role in the ionization process becomes dominant. Therefore, the electrons created by the light holes are responsible for the avalanche-like multiplication of carriers.

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[1)] In the opposite case the scale of the fall of the distribution function is less than the optical phonon energy $\hbar\omega_0$ and the Boltzmann kinetic equation can no longer be reduced to the Fokker-Planck equation (1). The energy $(eE\partial\varepsilon/\partial p)/\omega$ acquired by an electron from the field of a wave in one period becomes less than the phonon energy lost as a result of a collision, so that in the absence of elastic scattering the heating effect is altogether impossible. The question of the distribution function obtained in such a situation will be discussed in a separate paper.

[2)] It should be pointed out that, for example, in the case of GaAs the situation is quite different and the inequality $\nu_{lh}^{\mathrm{def}} \gg \nu_{ll}^{\mathrm{pol}}$ is obeyed.[22]

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