Intraband photoconductivity due to light holes and heating of carriers in *p*-type Ge by submillimeter laser excitation

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An investigation was made of infrared μ-photoconductivity of p-type Ge at various rates of excitation with submillimeter laser radiation. A shift of the point of carrier-density-dependent inversion of the sign of the relative photoconductivity of p-type Ge, compared with the case of excitation by infrared radiation, was observed when the dependence on the intensity was linear. The effect represented the dominant contribution of directly photoexcited carriers to the intraband photoconductivity of p-type Ge in the investigated spectral range. At high excitation rates an inversion of the sign of the relative photoconductivity of p-type Ge at $T = 78$ K depended on the radiation intensity. The inversion was due to a reduction in the absorption coefficient representing direct transitions in the valence band of p-type Ge and due to the associated change in the dominant photoconductivity.

Much work has been done recently on the heating and cooling of a hole gas in p-type Ge as a result of intraband absorption of infrared CO_2 laser radiation.[1-4] It has been found that the absorption of such radiation heats the hole gas and gives rise to a photoconductivity. However, the heating is relatively weak because of the rapid transfer of the bulk of the optical energy to the lattice due to the emission of several optical phonons.

The present paper reports an investigation of the heating of the hole gas and the appearance of a photoconductivity as a result of absorption of submillimeter radiation when practically the whole radiation energy was used to heat the hole gas. Experiments were carried out using a pulsed NH_3 laser pumped optically by a CO_2 laser.[5] The wavelength of the submillimeter radiation was 90.55 μ, the pulse duration was 40 nsec, and the radiation intensity was $I \lesssim 4$ kW/cm^2.

1. LOW EXCITATION RATE $I \lesssim 1$ kW/cm^2

An investigation was made of the dependence of the relative photoconductivity of p-type Ge at T = 78 K on the density of holes p in the range of carrier densities from 10^{13} to 10^{16} cm^{-3} when the radiation intensity was $I \lesssim 1$ kW/cm^2 so that the nonlinear effects were unimportant. The experimental results are presented in Fig. 1. Clearly, an increase in the carrier density resulted in inversion of the sign of the photoconductivity at $p \sim 5 \cdot 10^{14}$ cm^{-3}. This result differed from that obtained when the hole gas was heated by CO_2 laser radiation in which case the sign of the photoconductivity changed at a much higher carrier density ($p \sim 5 \cdot 10^{15}$ cm^{-3}) (Ref. 2). This shift of the inversion point on the carrier-density scale in the case of the 90.55 μ radiation could not be explained by the photoconductivity due to the carrier heating. As shown in Ref. 2, the change in the sign of the photocond

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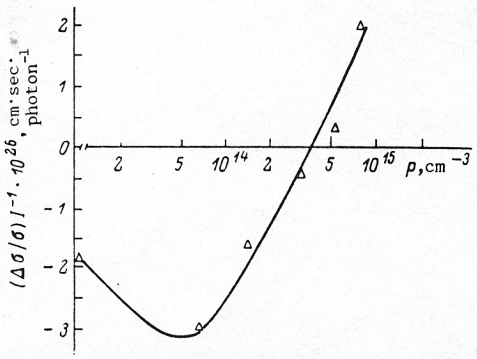

FIG. 1. Dependence of the relative photoconductivity normalized to the radiation intensity $(\Delta\sigma/\sigma)I^{-1}$ on the carrier density p in p-type Ge at T = 78 K when excitation was provided by radiation of the wavelength λ = 90.55 μ and of I $\lesssim$ 1 kW/cm^2 intensity.

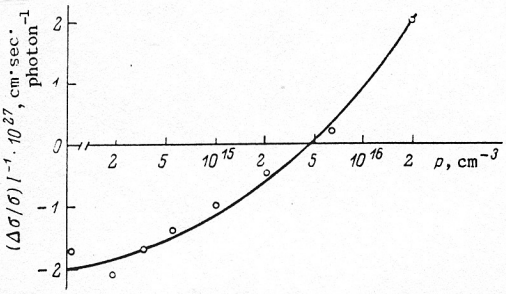

FIG. 2. Dependence of the relative photoconductivity normalized to the radiation intensity $(\Delta\sigma/\sigma)I^{-1}$ on the density p in carriers of p-type Ge at T = 78 K when the sample was excited with λ = 10.6 μ radiation.[2]

tivity in the case of the 10.6 μ radiation is due to a change from the scattering by acoustic phonons to the scattering by ionized impurities when the impurity concentration is increased.[1)] The carrier density at which the relative photoconductivity due to heating showed a change in the sign was governed by the parameters of a given material and its lattice temperature, but was independent of the heating method. Therefore, a shift of the inversion point on the carrier-density scale (in our case by more than one order of magnitude) to lower densities indicated the occurrence of an additional mechanism which gave rise to a positive photoconductivity. We attributed it to the photoconductivity of directly photoexcited carriers participating in direct optical transitions from the heavy-hole subband v_1 to the light-hole subband v_2. As shown in Ref. 6, the absorption cross section of p-type Ge at T = 78 K for λ = 90.55 μ in the case of direct optical transitions was approximately 10 times higher than the corresponding cross section in the case of indirect transitions. The absorption of photons of energy $\hbar\omega$ = 13.7 meV transferred a carrier from a state of energy $\varepsilon_i^{(1)}$ = 2.1 meV in the heavy-hole subband to a state of energy $\varepsilon_f^{(2)}$ = 15.8 meV in the light-hole subband, i.e., to a state of energy considerably less than the optical phonon energy ($\hbar\omega_0$ = 37 meV). Estimates carried out on the basis of Refs. 7 and 8 indicated that the loss of photocarriers to the heavy-hole subband practically throughout the investigated range of carrier densities (up to p = 10^{16} cm^{-3}) was due to the scattering by short-wavelength acoustic phonons in a relaxation time of $5\cdot10^{-12}$ sec. In addition to the photoconductivity due to the heating of the hole gas, there could be a significant contribution of the photoconductivity due to nonequilibrium light holes. The contribution of directly photoexcited carriers to the resultant photoconductivity signal was determined by the change in the mobility $\mu L(\varepsilon_f^{(2)}) - \mu h\,\varepsilon_f^{(2)}]$ on transition of the initial state at $\varepsilon_i^{(1)}$ to the final state at $\varepsilon_f^{(2)}$ [$\mu h(\varepsilon)$ and $\mu L(\varepsilon)$ are the mobilities of heavy and light holes of energy ε].

We shall now consider the dependence of this contribution on the carrier density p. At low values of p when the mobility of carriers of energy $\varepsilon_i^{(1)}$ in the heavy-hole subband and those of energy $\varepsilon_f^{(2)}$ in the light-hold subband is governed by the scattering on acoustic phonons and we have

$$\mu_L(\varepsilon_f^{(2)}) \approx \frac{m_h}{m_i}\left(\frac{\varepsilon_i^{(1)}}{\varepsilon_f^{(2)}}\right)\mu_h(\varepsilon_f^{(1)}).$$

This situation occurs right up to p $\sim 10^{14}$ cm^{-3}, when – as estimated in Refs. 7 and 8 – the relaxation times due to the scattering by acoustic phonons and ionized impurities to a state with $\varepsilon_i^{(1)}$ become comparable. In a state with $\varepsilon_f^{(2)}$ the main scattering mechanism is that involving acoustic phonons. This reduces $\mu h[\varepsilon_i^{(1)}]$ and increases correspondingly the investigated contribution to the photoconductivity as the carrier density increases. Wnhen this density rises to p $\sim 10^{16}$ cm^{-3}, the scattering times for acoustic phonons and ionized impurities become comparable in the state with $\varepsilon_f^{(2)}$. Then, the scattering to the states with $\varepsilon_i^{(1)}$ and $\varepsilon_f^{(2)}$ occurs on ionized impurities and because of a reduction in the absolute value of $\mu t,L(\varepsilon)$, the photoconductivity rises on increase in p.

We shall now consider the dependence of the net photoconductivity on the carrier density (Fig. 1). At low carrier densities p the photoconductivity is governed by the negative component due to the heating of the bulk of the carriers as a result of hole–hole collisions. An increase in p reduces the heating photoconductivity[2] (Fig. 2) and, as shown above, the photoconductivity due to photoholes rises. This alters the sign of the photoconductivity at p $\sim 5\cdot10^{14}$ cm^{-3}. The photoconductivity is then determined directly by photoholes[2)] right up to p $\sim 5\cdot10^{15}$ cm^{-3}, and the main role is played by nonequilibrium light holes.

The absence of this contribution of nonequilibrium light holes to the photoconductivity in the case of excitation with CO_2 laser radiation is due to the fact that in this case an optical transition creates light holes of energies $\varepsilon_f^{(2)} > \hbar\omega_0$. In a time of $\sim 10^{-13}$ sec these holes emit several optical phonons and because of the high density of states they are found in the heavy subband. In the case of excitation with λ = 90.55 μ radiation the energy of carriers in the light-hole subband is less than $\hbar\omega_0$ and in the investigated range of carrier densities the time in which a carrier is transferred to the heavy-hole subband ($\sim 5\cdot10^{-12}$ sec) is more than an order of magnitude longer than the corresponding time in the case of CO_2 laser excitation.

2. HIGH EXCITATION RATE I $\gtrsim$ 4 kW/cm^2

Figure 3 shows the dependences of the relative photoconductivity of p-type Ge at T = 78 K (p = $8\cdot10^{13}$-10^{16} cm^{-3}) on the intensity of the incident radiation. Clearly, in the range of hole densities p = $5\cdot10^{14}$-$5\cdot10^{15}$ cm^{-3} when in the linear case (I $\lesssim$ 1 kW/cm^2) the photoconductivity is due to photoexcited light holes and its sign is opposite to the heating photoconductivity, an increase in the radiation intensity altered the sign of the photoconductivity. Outside this range when p $\gtrsim 5\cdot10^{15}$ cm^{-3}, so that

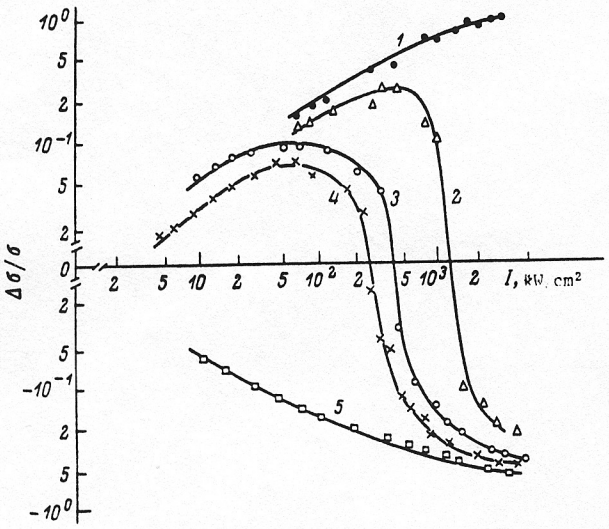

FIG. 3. Dependence of the relative photoconductivity $\Delta\sigma/\sigma$ of p-type Ge at T = 78 K when the sample was excited with λ = 90.55 μ radiation on the intensity I of this radiation. Hole density p (cm^{-3}): 1) 10^{16}; 2) $3\cdot10^{15}$; 3) $1.2\cdot10^{15}$; 4) $6\cdot10^{14}$; 5) $8\cdot10^{13}$.

the signs of the photoconductivity for the first and second mechanisms were identical, or when $p < 5\cdot10^{14}$ cm^{-3}, when the heating photoconductivity predominated, there was an inversion of the sign. The observed inversion of the sign of the photoconductivity could not be explained by a change in the mechanism of the scattering of the bulk of carriers because of strong optical heating, as in the case of n-type Ge (Ref. 9), since the mobility in the absence of optical excitation would have to be determined by ionized impurities. In our case the inversion of the photoconductivity was observed in the samples for which in the case when I = 0 the mobility was due to acoustic phonons and an increase in the temperature of the hole gas could not alter the scattering mechanims.

As shown in Ref. 10, in the case of p-type Ge at T = 78 K when λ = 90.55 μ, the samples were bleached, as manifested by a reduction in the value of the absorption coefficient for direct transitions K_{dir}. This was due to a change in the occupancy of the initial state of energy ε_i[1] as a result of heating of the hole gas. At intensities I $\sim$ 400 kW/cm^2 the value of K_{dir} fell by more than one order of magnitude and under these conditions the absorption due to indirect transitions K_{ind} predominated.

The considerable reduction (by a factor of $\sim$10) of the direct-transition absorption coefficient on increase in I and the corresponding reduction of the contributions to the photoconductivity made by direct transitions resulted in predominance of the contribution of the heating photoconductivity because of the absorption due to indirect transitions.[3] In the range of densities from $5\cdot10^{14}$ to $5\cdot10^{15}$ cm^{-3} the sign of this photoconductivity was opposite to the sign of the resultant photoconductivity at low illumination intensities. Therefore, the fall of the absorption coefficient representing direct transitions observed on increase in the radiation intensity resulted in this case in a change in the sign of the photoconductivity.

We shall conclude by noting that in the experiments described above we were able for the first time to excite the intraband photoconductivity directly due to photoexcited light holes.

[1]The mobility governed by the scattering on acoustic phonons is $\mu_{ac} \propto T_e^{-1/2}$, whereas in the case of scattering by ionized impurities, we have $\mu_{imp} \propto T_e^{3/2}$.

[2]When the carrier density was higher than $5\cdot10^{15}$ cm^{-3}, it was difficult to distinguish different contributions to the photoconductivity, since both mechanisms resulted in a positive photoconductivity.

[3]At low radiation intensities its magnitude was small because $K_{dir} \sim 10K_{ind}$.

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