θ is the angle between the direction of the magnetic field and the c axis of the sample (i.e., on the reciprocal of the component of the magnetic field perpendicular to the layers), is shown in Fig. 3 (with the monotonic part compensated). The fact that the quantization depended only on this component of the magnetic field was an indication of two-dimensional p-type conduction in InSe at low temperatures (the angular dependence of the oscillation frequency corresponded to a cylindrical Fermi surface; see Fig. 3b). The carrier density was $\approx 2\cdot 10^{11}$ cm^{-3}. The temperature and field dependences of the oscillation amplitudes were used to calculate also the cyclotron mass of carriers $m^* = (0.14 \pm 0.02)m_0$ (m_0 is the mass of a free electron) and the Dingle temperature $T_D = 1 \pm 0.1$ K. The value of the mass agreed with the cyclotron resonance data.[4] The oscillation amplitude decreased on increase in the angle θ. Figure 3a shows the dependence of the relative change in the amplitude of the oscillatory peak observed in a field B = 1.26 T on the angle θ. The reduction in the amplitude of the Shubnikov–de Haas oscillations was most likely associated with the specific energy spectrum of carriers, i.e., with the fact that the Fermi surface was cylindrical. This effect was calculated for a two-dimensional system in Ref 5.

The existence of monochromatic oscillations made it possible to observe the spin splitting of the levels in strong magnetic fields (Fig. 3). The fact that the spin splitting did occur was confirmed by measurements in a magnetic field inclined at various angles θ relative to the c axis. The experimental results indicated that the ratio γ of the spin to the orbital splitting was ≈ 0.32. Since $\gamma = gm^*/2m_0$, the value of the g factor for two-dimensional electrons in InSe was $g \approx 4.6$. The same values of the g factor were typical also of other two-dimensional systems, such as GaAs–GaAlAs (Ref. 6), characterized by g = 5. An increase in the g factor in a two-dimensional electron gas present in GaAs–GaAlAs structures was attributed to enhancement of the exchange interaction of electrons which in all probability could be exhibited also by two-dimensional electrons in InSe.

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Translated by A. Tybulewicz

Nonlinear absorption of submillimeter radiation in germanium due to optical heating of charge carriers

E. V. Beregulin, S. D. Ganichev, K. Yu. Glukh, and I. D. Yaroshetskiĭ

A. F. Ioffe Physicotechnical Institute, Academy of Sciences of the USSR, Leningrad

(Submitted September 3, 1986; accepted for publication October 25, 1986)

Fiz. Tekh. Poluprovodn. 21, 1005–1010 (June 1987)

An investigation was made of the bleaching due to direct intraband transitions in *p*-type Ge under the influence of submillimeter laser radiation. The observed nonlinearity of the absorption coefficient was attributed to the heating of the hole gas by the optical wave field. The bleaching threshold, observed at a low hole density ($\sim 10^{14}$ cm^{-3}) when the temperature was $T = 78$ K, amounted to ~ 10 kW/cm^2 and it increased on increase in the hole density and temperature. A calculation was made of the dependence of the absorption coefficient on the electron temperature of *p*-type Ge ($T = 78$ K, $\lambda = 90\,\mu$). The results of the calculation were in good agreement with the experimental data.

Several new photoelectric and optical phenomena due to interaction of submillimeter laser radiation with semiconductors had been observed and investigated recently.[1-4]

The present paper reports an investigation of nonlinear and linear absorption in n- and p-type germanium excited by pulses from an optically pumped NH_3 laser ($\lambda = 90.55$ μ).[3,4] The dependence of the absorption coefficient on the illumination intensity was determined for n- and p-type Ge ($3\cdot 10^{14} <$ n, p $< 10^{16}$ cm^{-3}) at temperatures T = 78 and 300 K in the illumination intensity range from 10 to 1500 kW/cm^2. Measurements were made of the reciprocal of the transmission $\Lambda^{-1} = I_{in}/I_{out}$, where I_{in} and I_{out} are the intensities of light entering and leaving the crystal, respectively. In the case of p-type Ge at T = 78 K it was found that initially the reciprocal of the transmission depended strongly on the intensity of light and it decreased by more than an order of magnitude when the intensity was increased, i.e., a strong bleaching of the sample was observed. At higher illumination intensities (I_{in}) this dependence became weaker and I_{in} had practically no influence on the transmission. In the case of p-type Ge at T = 300 K and n-type Ge at T = 300 and 78 K there was no significant change in the transmission throughout the investigated range of intensities.

An analysis of the observed dependences requires the knowledge of the absorption coefficients at low intensities, when the nonlinear effects are inactive. With this in mind we carried out suitable

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TABLE I. Absorption Cross Sections and Lattice Absorption Coefficient of p- and n-Type Germanium Obtained for Low Intensities of Illumination with λ = 90.55 μ Radiation

Type of conduct	T, K	K_p, cm^{-1}	$\sigma_d \cdot 10^{16}$, cm^2	$\sigma_i \cdot 10^{16}$, cm^2
n	78	0.3	—	3.5
p	78	0.3	32	3.2
n	300	1.8	—	13.5
p	300	1.8	2.1	11.5

measurements of the transmission of germanium at temperatures of 78 and 300 K.

The absorption coefficient was found to be described well by the following dependence on the free-carrier density p (or n):

$$K = \sigma p(n) + K_p.$$

The values of K_p for n- and p-type samples were the same at a given temperature (Table I) and K_p obtained by us at T = 300 K agreed with the value deduced from the spectral measurements for pure p-type Ge ($p < 7 \cdot 10^{13}$ cm^{-3}) reported in Ref. 5, where it was shown that this value represents the lattice absorption.

The quantity σ is determined by indirect absorption in the case of n-type Ge and by both direct and indirect intraband transitions in the case of p-type Ge. Using the experimental results and allowing for the temperature dependence of the absorption coefficient due to direct transitions, obtained theoretically in Ref. 6, we can separate the contributions made to the absorption cross section by the direct σ_d and indirect σ_i transitions. These cross sections are given in Table I.

We shall now analyze the observed dependences of the reciprocal transmission on the illumination intensity. Only in the case of p-type Ge at T = 78 K did the value of Λ^{-1} depend on I_{in}, in which case the main absorption mechanism involved direct intraband transitions (Table I). In the remaining cases the absorption was mainly due to indirect intraband transitions (in the case of p-type Ge at T = 300 K the inequality $\sigma_d \ll \sigma_0$ was obeyed). Therefore, the experimentally observed dependence of the absorption coefficient on the illumination intensity was due to the bleaching as a result of direct intraband transitions.

Two bleaching mechanisms are known in the case of direct intraband transitions in semiconductors with the valence band structure of the type found in p-type Ge. The first mechanism was discovered experimentally and investigated in Refs. 7-9, and it is due to the "burning" of a dip in the energy distribution function near the energy of the initial state ε_0, which occurs because the rate of loss of holes due to the absorption of light exceeds the rate of energy relaxation in the hole system. The second mechanism was considered theoretically in Ref. 10: it is related to the dipole moment of the system and it becomes significant when the probability of the absorption of a photon is comparable with the probability of the absorption of a photon is comparable with the probability of the loss of the phase of the dipole moment.

These mechanisms give rise to different dependences of the absorption coefficient K on the illumination intensity I and the net effect is the dependence

$$K = K_0 / \left(\sqrt{1 + I/I_{s_2}} + I/I_{s_1}\right),$$

where K_0 is the absorption coefficient in the case of direct intraband transitions at a low intensity; $I_{s_1} = 1/\sigma_d \tau$ is the saturation parameter associated with the "burning" of a hole in the energy distribution function; τ is the energy relaxation time; I_{s_2} is the saturation parameter associated with the dipole moment.

It is estimated that at low carrier densities ($p \sim 3 \cdot 10^{14}$ cm^{-3}) the bleaching should be dominated by the mechanism associated with the dipole moment.[1)] As shown in Ref. 10, the application of a weak electric field has a strong influence on this mechanism, so that already in fields $E \lesssim 1.0$ V/cm the bleaching parameter I_{s_2} increases strongly and thus bleaching associated with the dipole moment activity disappears. This dependence of I_{s_2} on the electric field and its absence in the case of the mechanism associated with the "burning" of a hole in the energy distribution function allow us to determine experimentally whether the dipole moment mechanism is responsible for the observed bleaching.

Figure 1 shows the results obtained in the presence and absence of an electric field. Clearly, an electric field had no effect. Hence, we concluded that the observed nonlinearity is not associated with the bleaching due to the dipole moment.

We shall now analyze the experimental data from the point of view of the bleaching due to the "burning" of a dip in the distribution function.[7-9] Figures 1 and 2 give the experimental data and the calculated dependences $\Lambda^{-1}(I)$ obtained from the differential Bouguer law. The experimental and calculated results agree well if we assume that the absorption coefficient is described by

$$K = \frac{K_0}{1 + I/I_s} + K_p. \tag{1}$$

This dependence would seem to correspond to the mechanism under investigation. The values of I_s obtained for samples with different carrier densities by ensuring the best agreement between the experimental and theoretical dependences are plotted in Fig. 3. We can see that I_s is practially independent up to carrier densities of the order of $3 \cdot 10^{15}$ cm^{-3}, whereas at higher densities the value of I_s rises on increase in p. A similar dependence had already been observed in a study of bleaching at the wavelength of 10.6 μ reported in Ref. 9, where energy relaxation below the optical phonon energy $\hbar\omega_0$ was attributed to two parallel processes: relaxation due to the interaction with acoustic phonons and relaxation due to hole–hole collisions. In this case the bleaching parameter is determined by the fastest relaxation process. As shown in Ref. 9, the plateau of the dependence $I_s = f(p)$ is associated with acoustic phonons and the linear rise is due to hole–hole collisions. In our case (Fig. 3), the observed behavior of I_s cannot be explained in this way. If the plateau had been associated with acoustic phonons, the bleaching parameter would have been two orders of magnitude less than the observed value and hole–hole collisions alone cannot explain the part of the curve independent of the carriers density. Moreover, the parameter representing bleaching due to hole–hole collisions should be considerably greater than the observed value of I_s.

It therefore follows that none of the investigated mechanisms can account for the experimental data.

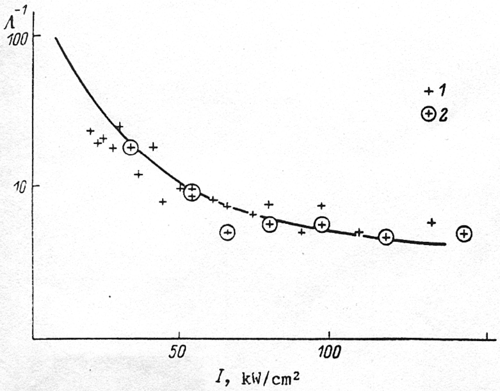

FIG. 1. Dependence of the reciprocal of the transmission Λ^{-1} on the intensity of illumination I_{in} of p-type Ge ($p = 3\cdot10^{14}$ cm^{-3}, T = 78 K, d = 4 cm). The points are the experimental values and the curve is calculated using Eq. (1); I_S = 8 kW/cm²; E (V/cm): 1) 0; 2) 2.

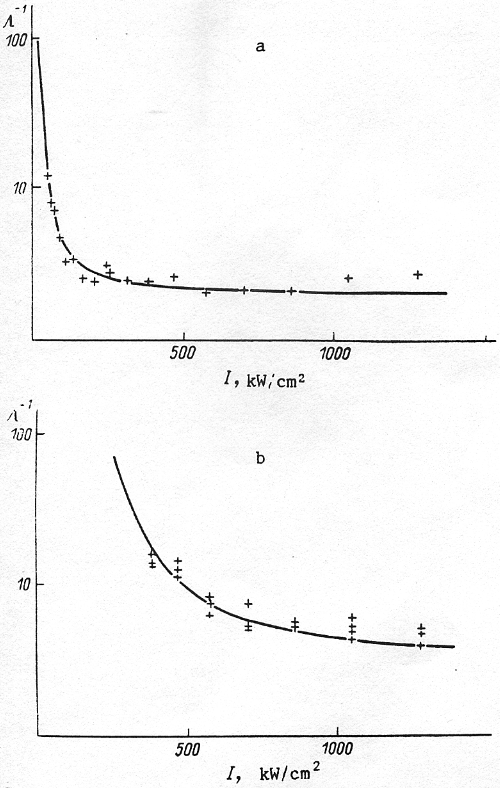

FIG. 2. Dependence of the reciprocal of the transmission Λ^{-1} on the intensity I_{in} of illumination of p-type Ge at T = 78 K for samples with different hole densities p (10^{16} cm^{-3}): a) ~~36.5~~;0,36 b) 1.27. The thickness of the sample d (cm): a) 0.47; b) 0.22. The curves are calculated on the basis of Eq. (1). I_S (kW/cm²): a) 8.5; b) 25.

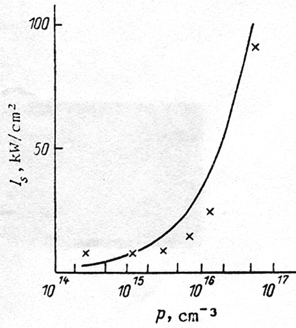

FIG. 3. Dependence of the bleaching parameter I_S on the carrier density p. The points are the experimental values and the curve is calculated on the basis of Eqs. (3) and (4).

We shall assume that the observed effect is associated with the reduction in the absorption coefficient in the case of direct transitions when the hole gas is heated optically by the incident radiation. We shall now consider this mechanism in greater detail. The absorp tion due to direct intraband transitions occurs from an initial state of energy ε_0 governed by the laws of conservation of energy and momentum. The hole heating due to the transfer of the energy of photocarriers to the bulk of the carriers alters the distribution function and, consequently, the population of the initial state. If ε_0 lies in the rising part of the occupancy function $dp/d\varepsilon$, which is true in our case ($\varepsilon_0 \sim 2$ meV), the heating of holes reduces the absorption coefficient.

We shall now estimate the change in the absorption coefficient due to the heating of holes. In the case of the Maxwellian distribution function it can be represented as follows:

$$K_a(I)=\frac{f_1(T_e,\varepsilon_0)[1-f_2(T_e,\varepsilon_0+\hbar\omega)]}{f_1(T_0,\varepsilon_0)[1-f_2(T_0,\varepsilon_0+\hbar\omega)]}K_a^0=A(T_e)K_a^0, \tag{2}$$

where $f_{1,2}(T_e, \varepsilon)$ are the Maxwellian hole energy distribution functions with an effective temperature T_e for the heavy- and light-hole energy bands.

The effective temperature of holes can be estimated from the equation describing the balance between the energy deposition in hole plasma and the losses due to the emission of acoustic and optical phonons

$$P_{\hbar\omega}=P_{opt}+P_{ac}, \tag{3}$$

where $P_{\hbar\omega}$ represents the energy gained as a result of the absorption of light of photon energy $\hbar\omega$ given by

$$P_{\hbar\omega}=[\sigma_i+\sigma_d(T_e)]\,Ip\hbar\omega=[\sigma_i+\sigma_i A(T_e)]\,Ip\hbar\omega, \tag{4}$$

and P_{opt} and P_{ac} are the losses due to the interaction with optical and acoustic phonons[11] described by

$$P_{opt}=\frac{4}{\sqrt{\pi}}\hbar\omega_0 p\nu_{ee}(T_e)\,\Phi(0)\left[\exp\left(-\frac{\hbar\omega_0}{T_e}\right)-\exp\left(-\frac{\hbar\omega_0}{T_0}\right)\right], \tag{5}$$

$$P_{ac}=\frac{S\sqrt{2}}{\pi^{3/2}}\frac{E_1^2 m_1^{5/2}}{\hbar^4\rho}T_e^{3/2}\left(1-\frac{T_0}{T_e}\right). \tag{6}$$

Here, $\Phi(0)$ is the function used in Refs. 12 and 13 governed by the relationship between the hole–hole collision frequency $\nu_{ee}(T_e)$ (Ref. 14) and the optical phonon emission frequency; E_1 is the deformation potential constant; ρ is the density of the investigated material; m_1 is the effective mass of heavy holes.

The dependences $T_e(I)$ and $K_a(I)$ obtained from the balance equation and from Eq. (2) demonstrate that in the range of carrier densities of interest to us (10^{14}–10^{16} cm^{-3}) the absorption coefficient $K_a(I)$ is described well by Eq. (1). As pointed out already, this expression is in agreement with the experimental dependences.

The calculated dependence of I_S on the carrier density is shown in Fig. 3. We can see that the values of I_S are close to those found experimentally. It should be pointed out that the calculations do not allow for the dependence of the cross section for indirect transitions on the effective temperature of the hole plasma.

The absence of a dependence of the transmission on the intensity of illumination of n-type Ge at T = 78 and 300 K and of p-type Ge at T = 300 K is due to the considerable contribution made to the total absorption by the lattice vibrations and by indirect intraband transitions, the intensity of which varies little with the hole temperature.

The authors are grateful to V. I. Perel', I. N. Yassievich, D. A. Parshin, and A. R. Shabaev for discussions.

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Translated by A. Tybulewicz

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

S. D. Ganichev, S. A. Emel'yanov, and I. D. Yaroshetskiĭ

A. F. Ioffe Physicotechnical Institute, Academy of Sciences of the USSR, Leningrad

(Submitted September 3, 1986; accepted for publication October 25, 1986)
Fiz. Tekh. Poluprovodn. **21**, 1011–1015 (June 1987)

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/cm².

1. LOW EXCITATION RATE $I \lesssim 1$ kW/cm²

An investigation was made of the dependen of the relative photoconductivity of p-type Ge a $T = 78$ K on the density of holes p in the range carrier densities from 10^{13} to 10^{16} cm⁻³ when th radiation intensity was $I \lesssim 1$ kW/cm² so that the linear effects were unimportant. The experimen results are presented in Fig. 1. Clearly, an increase in the carrier density resulted in inversi of the sign of the photoconductivity at $p \sim 5 \cdot 10^{14}$ cm⁻³. This result differed from that obtai when the hole gas was heated by CO_2 laser radi 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 inversio point on the carrier-density scale in the case of 90.55 μ radiation could not be explained by the conductivity due to the carrier heating. As sho in Ref. 2, the change in the sign of the photoco

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