Nonlinear absorption of light in $p$-type Ge in the infrared part of the spectrum

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A study was made of the behavior of the absorption coefficient of $p$-type Ge as a function of the intensity of the incident light. It was found that at high intensities the absorption coefficient was affected not only by the bleaching effect considered earlier, but also by two-photon intraband absorption.

The action of high-power laser radiation on semiconductors gives rise to nonlinearities in the absorption of light. An increase in the light intensity in the case of intraband absorption of light in semiconductors with the band structure of the type found in $p$-type Ge can reduce the absorption coefficient, which is known as the bleaching effect.1-8 and can increase this coefficient, as a result of multiphoton absorption.9-10 These two effects have been considered earlier independently of one another and the experimental results have thus been treated only from the point of view of one of these two nonlinearities.

Our aim will be to consider the available experimen-


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It is suggested in Refs. 5-6 that the bleaching effect in p-type Ge should be considered as occurring in a system with an inhomogeneous broadening of the absorption of light so that \( l = 1/2 \).

The bleaching effect had been investigated earlier in p-type Ge at temperatures \( T = 78 \) and \( 300 \) K using radiation from a tunable CO\(_2\) laser. The greatest excess of the gain over \( I_g \), which made it possible to determine the nature of the dependence \( \alpha(I) \), was achieved at \( T = 78 \) K in the studies reported in Refs. 2-3 and at \( T = 300 \) K in the investigation described in Ref. 8.

At \( T = 78 \) K the experiments were carried out on samples with a free-carrier density in the range \( 10^{12} < p < 10^{15} \) cm\(^{-3}\). The experimental results obtained in this study are plotted in Fig. 1. This figure includes also curves described by Eq. (1) with \( l = 1 \) and \( l = 1/2 \). The excess of \( I_1 \) above \( I_g \) was a factor of 20. It is clear from Fig. 1 that the experimental values fitted well the dependence of Eq. (1) with \( l = 1 \).

The results of the experimental study at \( T = 300 \) K are plotted in Fig. 2. The dependences obtained were explained in Ref. 8 entirely by the bleaching effect and they were compared with dependences of the type described by Eq. (1) with \( l = 1 \) and \( l = 1/2 \). The excess of \( I_1 \) above \( I_g \) was a factor of \( \sim 10 \). It is clear from Fig. 2 that the dependence (1) with \( l = 1 \) was incapable of describing the results obtained, but \( l = 1/2 \) ensured a satisfactory agreement with the experimental data.

High illumination intensities were used in the experiments described above. Under these conditions the contribution of two-photon transitions could be considerable, but this was ignored in reports of these investigations. We shall allow for this contribution to the overall absorption coefficient. The relationship between the two- and one-photon absorption coefficients, obtained theoretically in the lowest order of perturbation theory using the approximation of spherical constant-energy surfaces in the light- and heavy-hole subbands without allowance for the bleaching effect are of the form

\[
\frac{\alpha_2(I)}{\alpha_1(I)} = \frac{h^2}{I}.
\]

FIG. 1. Dependences of \( \alpha \) on the illumination intensity \( I \) at \( T = 78 \) K (Ref. 3). The points are the experimental values and the curves are plotted on the basis of Eq. (1) for the following values of \( p \) (10\(^{12}\) cm\(^{-3}\)): 1) 2.6; 2) 6.7; 3) 4)

FIG. 2. Dependence of the reciprocal of the transmission \( 1/I_{out} \) on the absorbed intensity \( I_{out} \) (selected from Ref. 8. \( T = 300 \) K, \( p = 4.5 \times 10^{15} \) cm\(^{-3}\)). The points are the experimental results and the curve is theoretical, \( I_a \) (MW/cm\(^2\)): 1) 3.2; 2) 9.3. Exponent \( l \), 1) 0.5; 2) 1.

FIG. 3. Comparison of the experimental results from Ref. 8 with a theoretical dependence of the reciprocal of the transmission \( 1/I_{out} \) on the absorbed intensity \( I_{out} \) (dependence \( \alpha(I) \) of the type given by Eq. (4)). \( T = 300 \) K, \( I_1 = 12.7 \) MW/cm\(^2\). Value of \( b \) (10\(^{15}\) MW/cm\(^2\)): 1) 0.78; 2) 0.28; 3) 0.

FIG. 4. Comparison of the experimental results from Ref. 8 with a theoretical dependence of the reciprocal of the transmission \( 1/I_{out} \) on the absorbed intensity \( I_{out} \) (dependence \( \alpha(I) \) of the type given by Eq. (4)). \( T = 300 \) K, \( I = 0.5, I_2 = 3.2 \) MW/cm\(^2\). Value of \( b \) (10\(^{15}\) MW/cm\(^2\)): 1) 0.78; 2) 0.28; 3) 0.

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where $\omega$ is the frequency of light; $n(\omega)$ is the refractive index of the medium at the frequency $\omega$; $\varepsilon_0 = \hbar \omega m_l / (m_l - m_i)$ is the energy of the initial state participating in the one-photon reactions; $m_l$ and $m_i$ are the effective masses of the heavy and light holes, respectively; $P_c$ is the degree of the circular polarization of the incident light.

A calculation of $\eta^\uparrow$ at the maximum light intensities $I_\text{max}$ attained in the experiments described in Refs. 2, 3, and 8 gave the following values: $I_\text{max} = 200 \text{ MW/cm}^2$ and $\eta^\uparrow = 1.6 \cdot 10^{-1}$ at $T = 300 \text{ K}$; $I_\text{max} = 20 \text{ MW/cm}^2$ and $\eta^\uparrow = 2.4 \cdot 10^{-3}$ at $T = 78 \text{ K}$.

It should be pointed out that an allowance for the observed bleaching increases by an order of magnitude the ratio of the two-photon absorption to the one-photon effect. Therefore, it is clear from these estimates that at liquid nitrogen temperature the absorption coefficient is entirely due to one-photon transitions. At $T = 300 \text{ K}$ we have to allow for both one- and two-photon transitions, and the bleaching effect in the one-photon transitions increases the contribution of the two-photon transitions. The overall dependence of the absorption coefficient is now described by

$$z(t) = z_0 (1 + I_\text{eff}^\uparrow) + z_0 b I_t.$$  \hspace{1cm} (4)

Figures 3 and 4 show the experimental results obtained at $T = 300 \text{ K}$ in Ref. 8 together with the curves calculated using Eq. (4) on the assumption that $l = 1$ (Fig. 3) or $l = 1/2$ (Fig. 4); these calculations were carried out\textsuperscript{1} for different values of the parameter $b$.

It is clear from Fig. 3 that an allowance for the two-photon absorption processes calculated on the basis of Eq. (3) makes it possible to describe satisfactorily the experimental results by Eq. (4) with $l = 1$ without any additional assumptions. The value of the parameter $b$ is then close to the theoretical value of $b^\uparrow$ deduced from Eq. (3). A good agreement for $l = 1/2$ is obtained on the assumption that $b = (1/3)b^\uparrow$ (Fig. 4).

Summarizing the above and using the results of Refs. 2 and 3, obtained at $T = 78 \text{ K}$ up to the light intensities $\sim 20\text{ GW}$, we can draw the conclusion that the behavior of the absorption coefficient of $p$-type Ge at $T = 78 \text{ K}$ is governed entirely by the bleaching effect involving one-photon transitions and it is described by the dependence given in Eq. (1) with $l = 1$. However, at $T = 300 \text{ K}$, although the same bleaching law ($l = 1$) still applies, we need to allow for the two-photon absorption at high illumination intensities.

The value of $l$ in Eq. (1) can be determined only finally in an experiment utilizing circularly polarized light, which alters considerably the contribution of two-photon transitions to the total absorption coefficient [see Eq. (3)].

\textsuperscript{1}The values of $a_1$ and $l_1$ are calculated from the condition of the best agreement between these curves in the range of low illumination intensities, where the contribution of two-photon transitions is small.

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