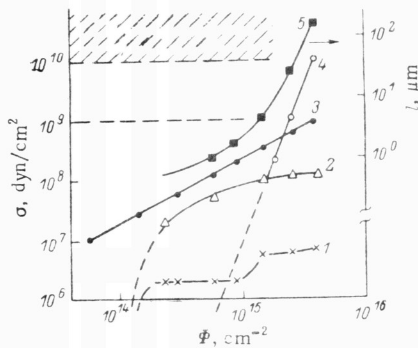

FIG. 3. Dependences of the elastic stresses in surface layers of epitaxial silicon films on the Ar^+ ion dose, showing the contributions made to the stresses by stacking faults (1), dislocations (2), difference between the atomic radii of the implanted impurity and substrate atoms (3), and grain boundaries (4). Curve 5 is the dose dependence of the size of the region adjoining a gettering region and free of shallow etch pits. The shaded area shows the mechanical strength of Si and the dashed line at 10^9 dyn/cm² corresponds to the critical shear stress at T ~ 1100°C.

as demonstrated by the disappearance of shallow etch pits within and close to the implanted region (Figs. 1c and 2). Nonequilibrium point defects flow to dislocation loops during the film cooling at time (~ 15 min). When the argon ion dose reaches $\sim 3 \cdot 10^{15}$ cm^{-2}, there is a strong increase in the density of defects in the gettering region, indicating that the critical dose for the amorphization of the surface has been reached. However, there is no significant increase in the planar gettering length at this stage. Only when the dose is increased to $\gtrsim 5 \cdot 10^{15}$ cm^{-2} (region III in Fig. 2) does the polycrystalline phase appear and there is a strong increase in the gettering length, i.e., there is an increase in the length of the region free of point-defect (of type B) clusters (Figs. 1d and 3).

Estimates of the diffusion coefficients of intrinsic point defects (condensing to form clusters) obtained using the cooling time and the gettering length give ~ 10^{-7} cm²/sec, indicating a considerable contribution of the surface diffusion of point defects to the gettering processes in the course of epitaxial growth of a film. A strong increase in the planar gettering length at doses of $> 5 \cdot 10^{15}$ cm^{-2} is due to the appearance of grain boundaries[8] when the implantation dose reaches a value corresponding to the solubility limit of argon in silicon at the epitaxial growth temperature. Calculations indicate (Fig. 3) that it is then that the elastic stresses in the planar structure become maximal. Hence, this mechanism is the dominant one in the planar (edge) gettering by a structural getter.

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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 nonlinearity mechanisms.

Our aim will be to consider the available experimental data on the absorption of light in the case of intraband transitions in p-type Ge allowing for both nonlinearity mechanisms.

The bleaching effect gives rise to the following dependence of the absorption coefficient α on the illumination intensity I:

$$\alpha(I) = \alpha_0 (1 + I I_s^{-1})^l, \tag{1}$$

where α_0 is the absorption coefficient at low intensities and I_s is the bleaching parameter; according to the microscopic theory of energy relaxation of photoexcited holes, in the case of homogeneous broadening of the spectral transition[4] the power exponent should be $l = 4$.

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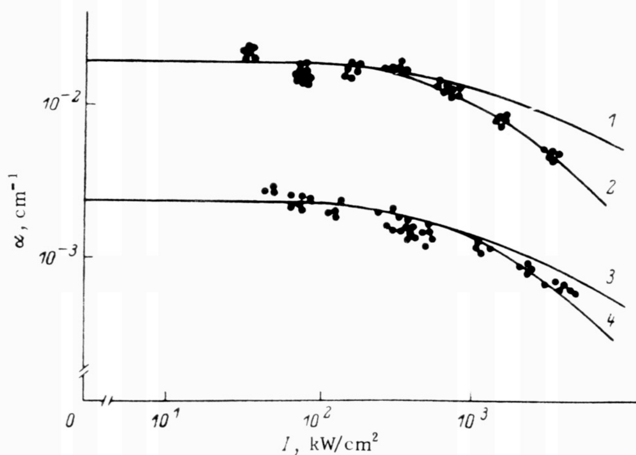

FIG. 1. Dependences of α on the illumination intensity I at T = 78 K (Ref. 3). The points are the experimental values and the curves are plotted on the basis of Eq. (1) for the following values of p (10^{13} cm^{-3}): 1), 2) 6.7; 3), 4) 0.66. Power exponent l; 1), 3) 0.5; 2), 4) 1. I_s (kW/cm^2): 1) 650; 2) 700; 3) 370; 4) 600.

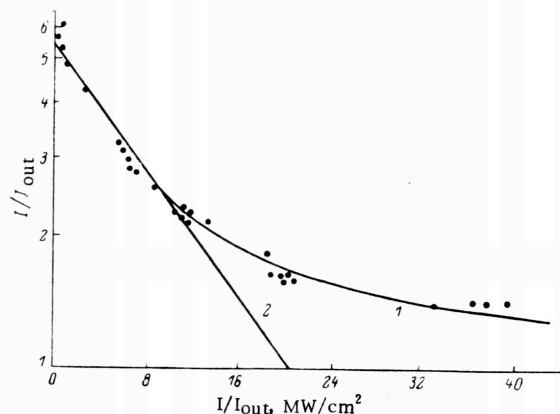

FIG. 3. Comparison of the experimental results from Ref. 8 with a theoretical dependence of the reciprocal of the transmission I/I_{out} on the absorbed intensity $I - I_{out}$ [dependence α(I) of the type given by Eq. (4)]. T = 300 K, l = 1, I_s = 12.7 MW/cm^2. Value of b (cm^2/MW): 1) $0.78 \cdot 10^{-3}$;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

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 I over I_S, which made it possible to determine the nature of the dependence α(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 above I_S 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 above I_S was a factor of ~ 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[9]

$$\eta_0^t = \frac{\alpha_0^{(2)}(\omega)}{\alpha_0^{(1)}(\omega)} = b_0^t I, \qquad (2)$$

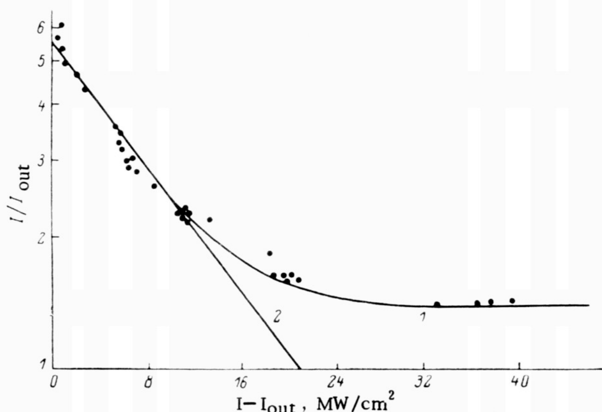

FIG. 2. Dependence of the reciprocal of the transmission I/I_{out} on the absorbed intensity $I - I_{out}$ taken from Ref. 8. T = 300 K, p = $4.5 \cdot 10^{15}$ cm^{-3}. The points are the experimental results and the curve is theoretical. I_s (MW/cm^2): 1) 3.2; 2) 9.3. Exponent l. 1) 0.5; 2) 1.

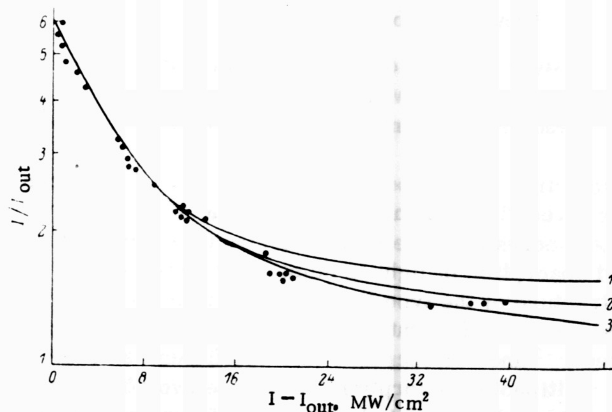

FIG. 4. Comparison of the experimental results from Ref. 8 with a theoretical dependence of the reciprocal of the transmission I/I_{out} on the absorbed intensity $I - I_{out}$ [dependence α(I) of the type given by Eq. (4)]. T = 300 K, l = 0.5, I_s = 3.2 MW/cm^2. Value of b (10^3 cm^2/MW): 1) 0.78; 2) 0.26; 3) 0.

$$b_0^t = \frac{4\sqrt{2}\,\pi e^2}{\hbar\omega^3 c n(\omega) m_l} e^{-\varepsilon_0/kT}\left(1 + e^{-\hbar\omega/kT}\right)\left(1 + \frac{P_c}{2}\right), \tag{3}$$

where ω is the frequency of light; $n(\omega)$ is the refractive index of the medium at the frequency ω; $\varepsilon_0 = \hbar\omega m_l/(m_h - m_l)$ is the energy of the initial state participating in the one-photon transitions; m_h and m_l 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 η^t at the maximum light intensities I_{max} attained in the experiments described in Refs. 2, 3, and 8 gave the following values: $I^{max} = 200$ MW/cm^2 and $\eta^t = 1.6 \cdot 10^{-1}$ at T = 300 K; $I^{max} = 20$ MW/cm^2 and $\eta^t = 2.4 \cdot 10^{-3}$ at T = 78 K.

It should be pointed out that an allowance for the observed bleaching increases practically 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 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

$$\alpha(I) = \alpha_0 (1 + I I_s^{-1})^l + \alpha_0 b I. \tag{4}$$

Figures 3 and 4 show the experimental results obtained at T = 300 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[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^t deduced from Eq. (3). A good agreement for $l = 1/2$ is obtained on the assumption that $b = (1/3)b^t$ (Fig. 4).

Summarizing the above and using the results of Refs. 2 and 3, obtained at T = 78 K up to the light intensities $\sim 20 I_s$, we can draw the conclusion that the behavior of the absorption coefficient of p-type Ge at T = 78 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 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)].

[1)]The values of α_0 and I_s are calculated from the condition of the best agreement between these curves in the range of low illumination intensities, where the contribution of two-phonon transitions is small.

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