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The role of optical phonons in heating electrons by IR radiation in Ge

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Abstract. An expression for the coefficient of light absorption by "hot" electrons in many-valley semiconductors for carrier scattering by nonpolar optical phonons in dependence on the carrier temperature and electron concentration in each valley has been obtained. It was shown that taking into account the contribution of such scattering into absorption of a CO_2 laser radiation enables to achieve a quantitative agreement between the calculated and experimental values for the intervalley redistribution of electrons due to heating carriers by the light wave in Ge at 300 and 77 K.

Keywords: many-valley semiconductor, free electron light absorption, carrier heating, intervalley redistribution.

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There exists a number of nonlinear optical phenomena in many-valley semiconductors associated with the light-induced redistribution of free electrons between the equivalent valleys. The intervalley redistribution in the field of strong electromagnetic radiation was considered theoretically in [1]. It was shown that the main cause for this redistribution is the different heating the electrons due to the light absorption in valleys oriented in different directions in regard to the electric field of the light wave.

Experimentally, the existence of such a nonlinear mechanism was proved in our studies of the briefringence [2] and degenerate 4-wave interaction [3] induced by CO_2 laser radiation (λ = 10.6 μm) in Ge with a carrier concentration $N = 5 \cdot 10^{16}$ cm^{-3} at 300 and 77 K. The magnitude of intervalley redistribution of electrons for various IR radiation intensities was determined from the measured variation of the refraction index.

At the same time, the magnitude of the electron redistribution calculated according to the formulae given in [1] turned out to be less than the experimental ones for all the intensities of CO_2 laser radiation used in the experiment. In those calculations, one assumed that the light absorption by free electrons in Ge is only related to intravalley scattering of electrons by acoustic phonons. On the other hand, the experimental studies have revealed that in Ge at $T > 77$ K a considerable contribution to the equilibrium light absorption by free electrons at λ = 10.6 μm is related to the carrier scattering by nonpolar optical phonons (cf for example [4, 5]). Besides, in heavily doped crystals at $T < 300$ K, a noticeable contribution to the light absorption may arise due to the scattering by ionized impurities.

The goal of the present paper is to take into account scattering by optical phonons and impurities in the light absorption of free electrons in order to achieve an agreement of calculated results with experimental data of the electron redistribution among equivalent valleys from [2, 3].

In order to determine the carrier temperatures and electron concentrations in different valleys, one should know the energy that they absorb from a light wave in a unit time via different scattering mechanisms. In the case of acoustical and impurity scattering, the expression for it in dependence on the orientation of the electric field with respect to the valley rotation axis, the electron concentration and the temperature in the valleys was obtained in [6, 7]. As mentioned above, when considering the scattering by optical phonons, the light absorption by free electrons in the many-valley semiconductors was analyzed only in the case of their thermal equilibrium with the crystal lattice [5, 8]. Therefore, at first the expressions obtained in [5, 8] were generalized to the non-equilibrium case of different temperatures of electrons and phonons.

The probability of intraband electron transition between the states with wavevectors $\vec{k}$ and $\vec{k}'$ due to the interaction with a photon possessing the energy $\hbar\omega$ and a phonon with the energy $\hbar\omega_0$ as well as the wavevector $\vec{q}$ is calculated in the second order of the perturbation theory

$$W^{\text{abs,emis}} = \sum_i \sum_f \frac{2\pi}{\hbar} \left| \sum_m \frac{H^{\omega} H_{\pm}^{\text{ph}}}{\widetilde{E}_m - \widetilde{E}_i} \right|^2 \times \times f_{\vec{k}} \cdot \left(1 - f_{\vec{k}'}\right) \cdot \delta\left(\widetilde{E}_f - \widetilde{E}_i\right), \quad (1)$$

where $W^{\text{abs,emis}}$ are the probabilities of transitions with an absorption and emission of a photon; $\widetilde{E}_i$, $\widetilde{E}_m$, and $\widetilde{E}_f$ are the total energies of the system "electron + photon + phonon" in the initial, intermediate, and final states, respectively; H^{ω} is the matrix element for the interaction of an electron with the light, $H_{\pm}^{\text{ph}}$ is the matrix element for the interaction of an electron with a phonon ("±" corresponds to emission and absorption of phonons, respectively).

For the photon absorption, $\widetilde{E}_f - \widetilde{E}_i = E_{\vec{k}\pm\vec{q}} - E_{\vec{k}} - -\hbar\omega \mp \hbar\omega_0$, and for the photon emission, $\widetilde{E}_f - \widetilde{E}_i = E_{\vec{k}\pm\vec{q}} - E_{\vec{k}} + \hbar\omega \mp \hbar\omega_0$. Summation over m in Eq. (1) takes into account the fact that an electron can initially interact with a photon, which result in an intermediate state m, and then interact with a phonon or in the reverse order.

The coefficient of optical absorption is expressed by the transition probabilities according to the following relation

$$\alpha = \frac{n}{c}\left(W^{\text{abs}} - W^{\text{emis}}\right), \quad (2)$$

where n is the refraction index of the medium.

If one assumes the function of electron distribution in the laser field in each valley to be the Maxwellian function with some effective temperature T_e^j, then the expression (1) may be integrated over the angles by a standard procedure. The integration over the energy may be carried out completely with a result in the form of the Hankel function, while for numerical calculations it is more convenient to use the following formulae

$$\alpha_j^{\text{abs}} = = B_j \int_0^{\infty} \left\{ \begin{array}{l} N_0\left[x^{3/2}\left(X+S+Z\right)^{1/2} + x^{1/2}\left(X+S+Z\right)^{3/2}\right] + \\ \left(N_0+1\right)\left[x^{3/2}\left(X+S-Z\right)^{1/2} \right. \\ \left. + x^{1/2}\left(X+S-Z\right)^{3/2}\right] \end{array} \right\} \times \times e^{-\gamma_j X} dX, \quad (3)$$

$$B_j = \frac{2\sqrt{2}}{3\pi^{1/2}} \frac{e^2 k^{3/2} D^2 \sqrt{m_l}}{\rho\hbar^4 n^2 \omega_0} \times \times \frac{T^3}{\omega^3}\left(\sin^2\theta_j + \frac{m_t}{m_l}\cos^2\theta_j\right) N_j,$$

where N_j is the electron concentration in j-valley, θ_j is the angle between the vectors of the light polarization and the rotation axis of the mass ellipsoid of the j-th valley, D is the constant of interaction with phonons, m_l and m_t are the longitudinal and the transverse effective masses of the electron, T is the lattice temperature, ρ is the crystal density, N_0 is the quantum phonons, and number of $\gamma_j = T/T_e^j$, $S = \hbar\omega/kT$, $Z = \hbar\omega_0/kT$.

For the processes with photon emission, the absorption coefficient α_j^{emis} may be obtained from (3) by replacing $+S$ by $-S$ and multiplying by the factor $\exp\left(S\gamma_j\right)$.

With expressions for the absorption coefficient taking into account different kinds of phonons and impurities, one may calculate the average electron energies and concentrations in the valleys under light absorption using the Maxwellian function to describe the electron distribution as above[1]. To attain these ends, the electron temperature should be determined from the balance of powers that were imparted into the electron subsystem under light absorption and transferred to the lattice due to interaction with phonons.

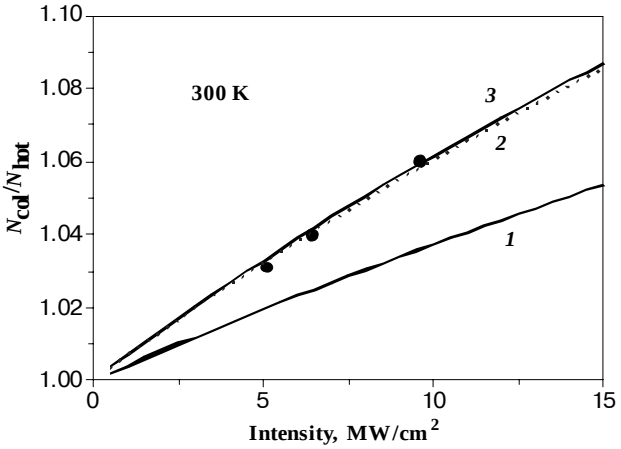
The product of the coefficient for the absorption by electrons in one valley (the sum of absorption coefficients related to scattering by the acoustic phonons and impurities [6, 7] as well as optical phonons) times the energy flux of the electromagnetic field incident upon the semiconductor gives the power which was derived by electrons from the light wave.

In many works, presented are the formulae for the average energy loss rate by electrons in the course of scattering by acoustic and optical phonons. We have used the formulae from [9]. The constants characterizing the electron scattering, the anisotropy parameter of scattering by the acoustic phonons, the frequencies of optical phonons, and the parameters of Ge conduction bands were taken as in [10]. The impurity scattering was calculated by the formulae for anisotropic scattering [11].

Although the intervalley scattering with transitions of electrons between valleys in Ge is small, generally the electrons in separate valleys do not obey an independent balance since collisions of electrons of different valleys tend to equalize average electron energies. Therefore, the term of electron-electron interaction in the form presented in [11] was taken into account in the energy balance equation.

The electron concentrations in the valleys were calculated from the equation of particle balance in each valley. It was assumed that the redistribution of "hot" electrons among the valleys occurs in consequence of scattering by intervalley phonons. In this case, the

[1] In general, the distribution function should be determined from the Boltzmann equation from the very beginning and used further to calculate the absorption coefficient and redistribution of electrons. However, at higher electron concentrations and not too strong heating, this function may be used in the Maxwell form.



Electron concentration ratio in the "cold" and "hot" vallies of *n*-Ge vs CO_2 laser radiation intensity. Calculations taking into account the light absorption under scattering by acoustic phonons (1), acoustic and optical phonons (2), phonons and impurities (3); experimental data – circles; $N = 5 \cdot 10^{16}$ cm^{-3} , $T = 300$ K.

equation of particle balance is as follows [9]

$$\frac{N_i}{N_j} = \frac{\gamma_j^{1/2} \cdot e^{\gamma_j S_M/2}\left\{-H_1\left(i\gamma_j S_M/2\right)\right\}\cdot\left[e^{(1-\gamma_j)S_M}+1\right]}{\gamma_i^{1/2} \cdot e^{\gamma_i S_M/2}\left\{-H_1\left(i\gamma_i S_M/2\right)\right\}\cdot\left[e^{(1-\gamma_i)S_M}+1\right]}, \quad (5)$$

where H_1 is the modified Hankel function, $S_M = \hbar\omega_M / kT$ (ω_M is the intervalley phonon frequency).

The figure shows some results of the calculation of the electron concentration ratio in the "cold" and "hot" valleys $N^{\text{cold}} / N^{\text{hot}}$ at the lattice temperature $T = 300$ K and the total electron concentration $N = 5 \cdot 10^{16}$ cm^{-3} under irradiation by the CO_2 laser with the polarization direction coinciding with the [111] crystal axis. In the figure, experimental data from [2] are shown too. For such a field orientation, the electrons in the valley with its rotation axis coinciding with the [111] direction are heated weaker, while the electrons in the other three valleys being equivalent in regard to the field direction are heated stronger. As a consequence, the electrons from the "hot" valleys are transferred to the "cold" one.

As seen from the figure, if being based on the only acoustic scattering, the calculated electron concentration ratios of the "cold" and "hot" valleys $N^{\text{cold}} / N^{\text{hot}}$ are almost twice as small as the experimental values for all the IR light intensities.

The calculated and experimental results are in a good agreement if, in addition to the acoustic scattering, one takes into account also the scattering by the optical phonons. The influence of the impurity scattering turned out to be weak. It can be seen from the comparison of the curves 2 and 3 in the figure presenting the ratio $N^{\text{cold}} / N^{\text{hot}}$ obtained with and without the electron scattering by the impurities on light absorption. The absorption coefficient related to the carrier scattering by impurities is only $\alpha_{\text{imp}} = 0.03$ cm^{-1} at low light intensities, while the total measured absorption coefficient is $\alpha = 2.0$ cm^{-1}. It decreases with increasing the light intensity, which is caused by a decrease of the electron scattering by impurities due to heating the carriers by the light. At the same time, the coefficients of linear light absorption by electrons when scattering from the acoustic and optical phonons are $\alpha_{\text{ac}} = 1.10$ cm^{-1} and $\alpha_{\text{opt}} = 0.87$ cm^{-1}, respectively. These increase by about 10 % with increasing the light intensity up to 20 MW/cm^2.

At 77 K, a good agreement between experimental and calculated results of the intervalley electron redistribution is also achieved, if one includes the contribution of scattering by optical phonons into the absorption processes.

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