Absorption of picosecond light pulses in semiconductors

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The absorption is calculated for the case in which thermodynamic equilibrium can be reached in the system of free charge carriers during the pulse, but recombination and electron-phonon interactions cannot occur. The analysis is based on Galitskiĭ-Goreslavskiĭ-Elesin quasiparticles.

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A brightening of semiconductor plates subjected to intense picosecond light pulses with a photon energy $\hbar\omega$ slightly greater than the gap width E_g has been observed in several studies.[1–3] Direct-gap solid solutions Cd(SSe), In(AsP), Ga(InAs), and Te(HgCd) have been used. This brightening occurs after a threshold is reached, and Bryukner *et al.*[1] have suggested that a self-induced transparency is being observed. A necessary condition for self-induced transparency[4] is that the pulse length τ_0 be shorter than the charge-carrier relaxation time. Kumekov and Perel'[5] have shown that this condition cannot be met by shortening the pulse, since the concentration of photoexcited electrons increases with decreasing τ_0.

In this letter we wish to examine the opposite limiting case, in which τ_0 is considerably longer than the scale time between electron-electron collisions (but far shorter than the scale time for relaxation of electrons with phonons and far shorter than the recombination time). We will show that in this case it is possible to construct a simple picture of the absorption of light pulses by working from the quasiparticle model developed by Galitskiĭ *et al.*[6] We will compare our results with the experimental data of Ref. 1.

According to Galitskiĭ *et al.*,[6] quasiparticles can be introduced in the monochromatic field of an electromagnetic wave in such a manner that the interaction with the wave field does not figure explicitly in the Hamiltonian of the system, simply affecting the renormalized quasiparticle spectrum. The interaction of quasiparticles with each other results in a thermodynamic equilibrium, at which the quasiparticles have a Fermi momentum distribution and are characterized exclusively by the temperature T_e and by the position of the Fermi level, E_F (a saturation state). Figure 1 is a schematic band diagram of the quasiparticles α (solid curve) and β (dashed curve) before the field is applied. The particles α are electrons in the conduction band at $p > p_0$ or in the valence band at $p < p_0$, where p is the magnitude of the quasimomentum, $p_0 = \sqrt{2\mu(\hbar\omega - E_g)}$, and μ is the reduced mass of the electron and hole. The particles β are holes in the valence band at $p > p_0$ or in the conduction band at $p < p_0$. We assume that there are no electrons or holes before the field is applied. This assumption means that the quasiparticles α and β have occupied all the states at $p < p_0$, while at $p > p_0$ all the states are empty. Without a field the probability for quasiparticle transitions in collisions between quasiparticles from the states $p < p_0$ to states $p > p_0$ is zero.

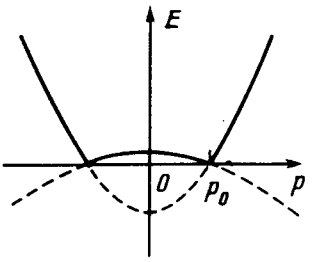

FIG. 1.

In a field, these transitions become possible, and a saturation state is eventually reached (even in a weak field), in which the quasiparticles have a Fermi distribution. It is during this process that the field energy is absorbed; no absorption occurs in the saturation state.[6] With a further slow increase and removal of the field, the saturation state is preserved; after the field is removed, the quasiparticle bands again assume the shape in Fig. 1, but the quasiparticles have a Fermi distribution. The temperature T_e and the Fermi level of this distribution can be found from two conditions: the neutrality and the conservation of the total energy of the quasiparticles. The latter condition is based on the circumstance that energy is conserved in collisions of quasiparticles with each other, while the interaction with the lattice can be ignored during the pulse. These conditions are

$$\int f_\alpha d^3p = \int f_\beta d^3p, \tag{1}$$

$$\int E_\alpha f_\alpha d^3p + \int E_\beta f_\beta d^3p = \int\limits_{p<p_0} E_\alpha d^3p + \int\limits_{p<p_0} E_\beta d^3p, \tag{2}$$

where

$$f_\alpha = \left[\exp\left(\frac{E_\alpha - E_F}{kT_e}\right) + 1\right]^{-1}, \quad f_\beta = \left[\exp\left(\frac{E_\beta + E_F}{kT_e}\right) + 1\right]^{-1}$$

are the quasiparticle distribution functions, and $E_\alpha = |p^2 - p_0^2|/2m_\alpha$, $E_\beta = |p^2 - p_0^2|/2m_\beta$ are the quasiparticle energies. At $p<p_0$ we have $m_\alpha = m_v$ and $m_\beta = m_c$; at $p>p_0$, we have the opposite.

Conditions (1) and (2) constitute a system of two equations for two unknowns, $kT_e/(\hbar\omega - E_g)$ and $E_F/(\hbar\omega - E_g)$, with a single parameter, m_v/m_c. The results of a numerical solution of these equations are shown in Fig. 2.

The total energy absorbed during the pulse can be calculated in a straightforward manner, since we know the concentration (n_1) of the photoexcited electrons after the field is removed. The results of this calculation are shown in Fig. 3. We see that n_1 depends only slightly on the mass ratio and is about 1.3 times as large as the concentration required for occupying all states with $p<p_0$, i.e., 1.3 times larger than the energy required for the absorption to disappear by virtue of the Moss-Burshtein effect involving nonequilibrium, completely degenerate carriers.

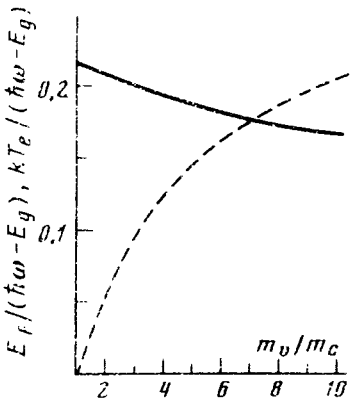

FIG. 2. The temperature T_e (solid curve) and the Fermi energy E_F (dashed curve) of the quasiparticles vs the parameter m_v/m_c.

Let us consider a numerical example corresponding to the experimental conditions of Ref. 1. We adopt $\hbar\omega = 2.3$ eV, $\hbar\omega - E_g = 5$ meV, and $\mu = 0.2m_0$. The electron concentration required to occupy all states with $p < p_0$ is then $n_0 = 7\times 10^{16}$ cm^{-3}. According to Fig. 3, the electron concentration is $n_1 = 10^{17}$ cm^{-3} after the saturating pulse. The energy absorbed by a unit volume is $U_S = \hbar\omega n_1 \approx 3\times 10^{-2}$ J/cm^3. For a pulse length $\tau_0 = 5$ ns and a crystal length $l = 4$ mm, the saturation power $P_S = n_1 l\hbar\omega/\tau_0$ is 2.5×10^9 V/cm^2.

It should be noted that under the condition $\hbar\omega - E_g \ll E_g$ the estimate of the saturation energy $U_S = n_1\hbar\omega$ does not change substantially even if the pulse is longer than the scale time for the energy relaxation of the electrons with the phonons (but, of course, shorter than the recombination scale time). The additional energy absorption by the lattice is far smaller than U_S.

We note in conclusion that Eqs. (1) and (2) are the same as the equations derived by Glazman[7] in an analysis of the absorption of a pulse in a weak field, with the

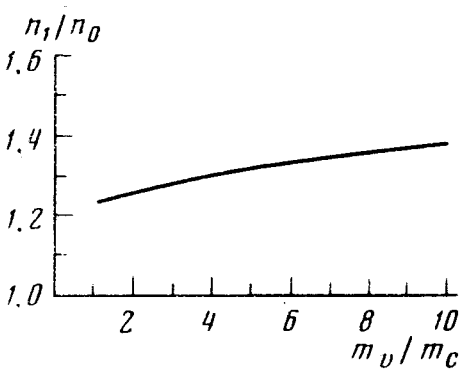

FIG. 3. The concentration of photoexcited electrons, n_1, vs the parameter m_v/m_c. Here n_0 is the electron concentration required to occupy all states with $p < p_0$.

frequency of the field-induced transitions much smaller than the frequency of electron-electron collisions. Glazman[7] showed that under these conditions Eqs. (1) and (2) describe the saturation state during the pulse. In a strong field, the saturation is not described by Eqs. (1) and (2) during the pulse, but, as was shown above, these equations do describe the state of the free carriers after the saturating pulse.

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