"SELF-TRANSPARENCY EFFECT" IN SEMICONDUCTORS

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The effect of "stimulated" transparency of a medium consisting of two-level molecules in the ground state by the passage of a powerful ultrashort pulse of coherent light, was theoretically predicted and experimentally observed in [1, 2]. This transparency is not connected with the usual saturation effect and occurs when the light pulse duration is $\tau \ll T_2$, where T_2 is the relaxation time of the polarization of the medium, and also

$$\frac{\mu}{\hbar}\int_{-\infty}^{\infty} F\,dt > \pi,$$

where F is the amplitude of the field of the light pulse and μ is the dipole matrix element of the transition. Physically the effect consists in the fact that the light pulse looses energy on the leading front as it excites the molecules coherently; this energy is then returned to the pulse on the trailing edge as a result of the secondary radiation of the molecules. It is of great interest to investigate whether a similar effect is feasible in principle in interband absorption in semiconductors, which produces electron-hole pairs as a result. We shall consider optical transitions usually occurring in semiconductors, with conservation of the electron quasimomentum $\vec{k}$ (direct transitions). The formal description of such transitions is similar to the description of transitions in two-level systems with an asymmetric inhomogeneously-broadened line [1].

If, just as in [1], we seek the solution of the equations for the field in the form of a stationary pulse, i.e., it is assumed that the dependence on z and on t reduces to a single variable $t - (z/v)$, where v is the velocity of the steady-state pulse ($v < c$), then Maxwell's equations and the equations for the matrix elements of the density operator of the medium admit of a unique solution, and the expression for the velocity takes the form

$$v = \frac{c}{n}\left(1 + \frac{4\pi\mu^2\tau^2}{n^2\hbar^2} I_2\right)^{1/2}\left(1 + \frac{2\pi\mu^2\tau^2\omega}{n^2\hbar^2} I_1\right)^{-1}, \qquad (1)$$

where

$$I_1 = \sum_k \frac{n_k^0}{1 + (\Delta\omega_k \tau)^2}, \quad I_2 = \sum_k \frac{n_k^0 \, \Delta\omega_k}{1 + (\Delta\omega_k \tau)^2},$$

n is the lattice part of the refractive index, ω is the frequency of the light pulse,

$$\Delta\omega_k = \frac{1}{\hbar}(\varepsilon_k^c - \varepsilon_k^v) - \omega$$

ε_k^c and ε_k^v are the electron energies in the conduction and valence bands, respectively, and n_k^0 is the difference between the initial populations of the level k in the bands.

This solution differs from the case of a two-level system with an inhomogeneously-broadened line in the presence of an additional factor under the radical in the expression for the velocity v. In the case of greatest interest, when the density of the states in the bands is proportional to $(\hbar\omega - \Delta)^{1/2}$, with $\hbar\omega - \Delta \ll \Delta_v$ and $\hbar\omega - \Delta \gg \hbar/\tau$ (Δ - width of forbidden band, Δ_v - width of valence band), the corresponding expressions for I_1 and I_2 become much simpler, and if we take the values $\Delta \approx 1$ eV, $\mu \approx e\hbar(m^*\Delta)^{-1/2} \approx 3 \times 10^{-17}$ cgs esu, $\tau = 5 \times 10^{-12}$ sec, $\hbar\omega - \Delta \approx 0.1$ eV, and $m^* \approx 10^{-28}$ g, then $I_1 \approx 1.5 \times 10^{-17}$ cm^{-3} and $I_2 \approx 3 \times 10^{29}$ cm^{-3} sec^{-1}.

Estimates of the quantities $I_{1,2}$ with other model state densities (e.g., a uniform density over the band) yield numerical values of $I_{1,2}$ of the same order of magnitude.

Substituting further the values of I_1 and I_2 in the expression for the velocity v, we get $v \approx 10^{-1}$ c/n [cm/sec], i.e., the "stationary" pulse moves with a velocity smaller by one order of magnitude than the velocity of light in the given material. The foregoing analysis is valid only if the condition $v\tau > \lambda$ is satisfied, as it evidently is in our case when $\tau \approx 10^{-12}$ sec and $\lambda < 10^{-4}$ cm.

We note that for semiconductors the relaxation time T_2 depends on the kinetic energy ε of the produced electrons; thus, for example, if $\varepsilon > h\omega_0$ (ω_0 - frequency of the optical phonon), then a strong interaction with the optical phonon leads to a decrease of T_2, so that light-pulse duration required to observe "self-transparency" at a sufficiently large distance from the edge of the band is $\tau < 10^{-12}$ sec (when $\varepsilon < \hbar\omega_0$ and at low temperatures, $T_2 > 10^{-12}$ sec).

We assume now that a constant electric field E is applied along the layer of an electron-hole plasma produced by a "stationary" pulse. Then, according to [3], the spatial separation of the generated electron-hole pairs should cause the "self transparency" effect to vanish in fields satisfying the relation

$$\frac{1}{\hbar}\left[\frac{e^2E^2\hbar^2}{m^*}\right]^{1/3} \gtrsim \frac{1}{\tau},$$

which makes it possible in principle to determine the mass m* far from the edge of the band. The fields E required for this purpose are not large (E $\approx$ 300 V/cm at $m^* \approx 10^{-28}$ g and $\tau \approx 10^{-12}$ sec). At the same time, knowing m*, measurement of the pulse velocity v makes it possible to determine the matrix element of the dipole moment μ_k.

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[3] L. V. Keldysh, Zh. Eksp. Teor. Fiz. 34, 1138 (1958) [Sov. Phys.-JETP 7, 788 (1958)].