Inverse distributions of electrons in semiconductors in a monochromatic radiation field

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It is shown that if the frequency of the field ω is slightly greater than the value $n\omega_0$ (ω_0 is the frequency of the optical phonon, $n = 1, 2, 3,...$), then under certain conditions an electronic distribution over energies ϵ with a narrow peak situated in the region $0 < \epsilon < h\omega_0$ is formed. The position of the peak in this interval depends on the light intensity.

We shall examine the behavior of an electron at low temperatures in the field formed by monochromatic light with quantum energy $\hbar\omega = n\hbar\omega_0 + \Delta$, where $0 < \Delta \ll \hbar\omega_0$, and n is an integer. An electron with energy $\epsilon < \hbar\omega_0$ (in the passive region) can absorb a light quantum with the simultaneous emission of an optical phonon. The electron is then transferred to the active region and its energy assumes the value $\epsilon + \hbar(\omega - \omega_0) = \epsilon + (n - 1)\hbar\omega_0 + \Delta$. After rapid emission of several optical phonons, it again returns to the passive region with energy $\epsilon + \Delta$. We can therefore say that the act of absorption of a light quantum transfers the electron from the state with energy ϵ to the state with energy $\epsilon + \Delta$ (Fig. 1). As a result, the energy of all electrons in the passive region gradually increases. After reaching an energy $h\omega_0$ and shedding an optical phonon, the electrons end up at the bottom of the passive region and again begin to move upwards in energy (Fig. 2).

We have so far ignored the scattering by acoustic phonons. Acoustic scattering leads to energy losses and slows down the movement of electrons upwards in energy. The rate of this deceleration increases with increasing energy of the electron. The rate of ascent also increases, but more slowly. (The case $n = 1$, in the presence of strain-

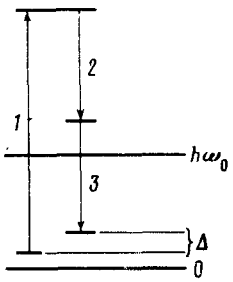

FIG. 1. Increase in the energy of an electron accompanying absorption of light quantum (with the participation of an optical phonon) and subsequent emission of optical phonons. In the transition 1 the energy increases by $\hbar(\omega - \omega_0)$. Each subsequent rapid transition 2,3 decreases the energy by $h\omega_0$. It is assumed that $\hbar\omega = 2\hbar\omega_0 + \Delta$.

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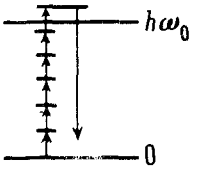

FIG. 2. Motion of electrons with respect to energy in a monochromatic light field ($\hbar\omega = n\hbar\omega_0 + \Delta$). The slow ascent with a "step" Δ and rapid descent from the $h\omega_0$ level to the bottom of the passive region.

induced interaction with optical phonons, is an exception; see below.) The light intensity can be selected in such a way that the rate of ascent in energy under the action of continuous absorption would be equal to the rate of loss with acoustic scattering at some point ϵ_0 in the passive region. Indirect absorption, which strives to increase the energy of the electron, will then dominate at $\epsilon < \epsilon_0$ and acoustic scattering, which strives to decrease the energy, will dominate at $\epsilon > \epsilon_0$. As a result, a peak forms in the electron energy distribution near $\epsilon = \epsilon_0$ (Fig. 3). We assume that the energy acquired by the electron in the field during the period of oscillation of the field can be ignored - a situation opposite to the one discussed in Ref. 1.

To determine the position and width of the peak, we shall write out an expression for the electron flux in energy space

$$J = -Bf - D\frac{\partial f}{\partial \epsilon}\ , \tag{1}$$

where B is the "coefficient of dynamic friction in energy space." D is the coefficient of energy diffusion, and f is the distribution function. If the peak is narrow, then it may be assumed that f is small at the boundary of the active region and that $J = 0$. (The flux J appears because the electrons whose energy is close to $h\omega_0$ diffuse into the active region.) From Eq. (1) we then find

$$f = C\exp\left(-\int \frac{B}{D}d\epsilon\right). \tag{2}$$

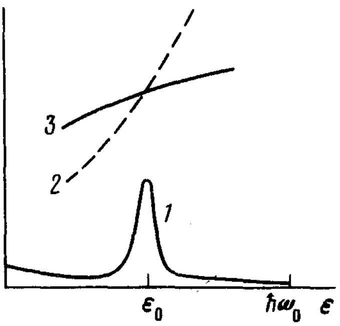

FIG. 3. Schematic representation of the peak in the electron energy distribution and the behavior of the coefficients of dynamic friction. 1 $-f(\epsilon)$, 2 $- B_{AC}(\epsilon)$, 3 $- B_L(\epsilon)$.

In accordance with what was said above, the coefficient B is the sum of two terms with opposite signs $B = -B_L + B_{AC}$ where B_L is linked with the absorption of light, and B_{AC} is linked with acoustic scattering. The coefficient B vanishes at the point ϵ_0 and near this point $B \sim (\epsilon - \epsilon_0)$. Taking D in (1) outside the integral at the point $\epsilon = \epsilon_0$, we obtain an expression describing the peak

$$f = C \exp [-(\epsilon - \epsilon_0)^2 / \alpha^2], \tag{3}$$

where α determines the width of the peak

$$\alpha^2 = 2D(\epsilon_0) / \left(\frac{dB}{d\epsilon} \right)_{\epsilon = \epsilon_0} .$$

A simple calculation shows that $B_L = I(\Delta / \tau_0^*) \rho(\epsilon)$, where $I = (e^2 E^2)/(m\omega^2 \hbar\omega)$ is the dimensionless intensity of light, E is the amplitude of the electric field intensity of the light wave, m is the effective mass of the electron, $\rho(\epsilon)$ is the state density, and τ_0 is the time on the order of the emission time of an optical phonon. In the case of strain-induced scattering we would have

$$\frac{1}{\tau_0^*} = \frac{\sqrt{2}}{\tau_0 \, 3\hbar\omega \sqrt{\hbar\omega_0}} (2\epsilon + \hbar\omega - \hbar\omega_0) \sqrt{\epsilon + \hbar\omega - \hbar\omega_0} .$$

In the case of polar scattering we would have

$$\frac{1}{\tau_0^*} = \frac{1}{\tau_0 \hbar\omega} \sqrt{(\epsilon + \hbar\omega - \hbar\omega_0)\hbar\omega_0} .$$

Here τ_0 is the emission time of an optical phonon with $\epsilon = 3\hbar\omega_0$. On the other hand, $B_{AC} = (\epsilon / \tau_\epsilon) \rho(\epsilon)$, where τ_ϵ is the time for energy relaxation into acoustic phonons. From the condition $B_L = B_{AC}$ we find the condition for the point ϵ_0: $\epsilon_0 = (\tau_\epsilon / \tau_0^*) I\Delta$. If we assume, for a ballpark estimate, that $\tau_0^* = 10^{-12}$–10^{-13}s, $\tau_\epsilon = 10^{-9}$–10^{-10}s, $\Delta = 0.1\ \hbar\omega_0$, we find that $I \sim 10^{-3}$ in order for the peak to be located at the center of the passive region. This corresponds to an irradiation intensity on the order of MW/cm^2, if $n = 2$ and the effective mass is the mass of a free electron. The required intensity is much lower in materials with a low effective mass of electrons.

We shall now estimate the width of the peak. We will ignore the energy dependence of B_L. Taking into account the fact that $B_{AC} \sim \epsilon^2$ and $D(\epsilon_0) = B_{AC}(\epsilon_0)kT + (\Delta / 2)B_L(\epsilon_0) = B_{AC}(\epsilon_0)(kT + \Delta / 2)$, we then obtain an estimate for the width of the peak: $\alpha = \sqrt{\epsilon_0 (kT + \Delta / 2)}$.

We shall now discuss the role of impurity scattering and electron-electron collisions. In the process of photon absorption, together with simultaneous scattering by an impurity, an electron with energy ϵ is transferred to the active region and acquires an energy $n\hbar\omega_0 + \Delta$; after emitting n optical photons it again appears in the passive region with energy $\epsilon + \Delta$. Thus indirect absorption with the participation of impurities acts just like absorption with the participation of an optical phonon and their effects simply add. Impurities increase B and decrease the light intensity required for the formation of the peak. Electron-electron scattering smears the peak, so that the peak can only be observed at low electron densities, when the rate of energy relaxation to acoustic phonons exceeds the electron-electron collision rate.

It should be noted that some peculiarities arising near the frequencies $\omega = n\omega_0$, were pointed out by Vas'ko and Gribnikov,[2] but they did not observe the formation of the peak in the electron energy distribution.

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[1]V. L. Gurevich and D. A. Parshin, Solid State Commun. **37**, 515 (1981); see also Invertirovannye raspredeleniya goryachikh elektrononv v poluprovodnikakh (Inverted Distributions of Hot Electrons in Semiconductors), edited by A. A. Andronov and Yu. K. Pozhela, Institute of the Physics of Semiconductors, Academy of Sciences of the USSR, Gorky, 1983.
[2]F. T. Vas'ko and Z. S. Gribnikov, Pis'ma Zh. Eksp. Teor. Fiz. **21**, 629 (1975) [JETP Lett. **21**, 297 (1975)].

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