THEORY OF THE POLARON EFFECT IN INTERBAND MAGNETOOPTIC ABSORPTION

L. I. Korovin and S. T. Pavlov
Institute of Semiconductors, USSR Academy of Sciences
Submitted 29 April 1967
ZhETF Pis'ma 6, No. 2, 525-528 (15 July 1967)

In a recent investigation of interband magnetooptic absorption in InSb, Johnson and Larsen [1] observed a doublet structure in the absorption-coefficient peak corresponding to interband electron transitions between Landau bands with quantum number n = 1. They attributed this effect to interaction between longitudinal optical (polarized) phonons and electrons thrown into the conduction band by the light. The energy of the electron state with n = 1 intersects the energy of the state with n = 0 plus one phonon. The interaction with the phonons leads to a rearrangement of the terms, two branches of the electron-phonon system spectrum being separated by an energy gap. This is why an additional absorption peak appears in the region $\Omega_c \approx \omega_o$ (Ω_c = cyclotron frequency of the electrons in the conduction band, ω_o = frequency of optical phonon).

We present here the main results of the theory of the Johnson-Larsen effect. We consider an intrinsic semiconductor with simplest band structure (nondegenerate parabolic bands with extrema located in the center of the Brillouin zone). We take into account electron interactions with optical phonons only, the interactions being regarded as small ($\alpha_o \ll 1$, α_o = dimensionless constant of the coupling between the electrons and the longitudinal optical phonons after Frohlich). The temperature is T = 0.

The light-absorption coefficient $K(\omega)$ is expressed in terms of the single-particle retarded Green's function of the electrons $G_r(k_z, \omega - \omega_g)$ in the conduction band

$$K(\omega) \sim \mathrm{Re}\, i \int_{-\infty}^{\infty} dk_z\, G_r(k_z, \omega - \omega_g), \tag{1}$$

k_z is the projection of the wave vector of the electron on the direction of the constant magnetic field H, ω is the frequency of light, and $\hbar\omega_g$ is the width of the forbidden band. G_r was calculated by the standard Feynman diagram technique, the mass operator was calculated in the lowest-order approximation in the interaction, and the contribution of the disregarded terms was small relative to the parameter $\alpha_o^{1/3}$. In this approximation we have for $|\lambda| < 1$

$$G_r(k, \gamma) = \left[\gamma - k^2 + \frac{i\eta}{(\gamma+\lambda)^{1/2}}\right]^{-1}, \tag{2}$$

where $\gamma = \dfrac{\epsilon - \frac{3}{2}\Omega_c}{\Omega_c}$, $\lambda = \dfrac{\Omega_c - \omega_o}{\Omega_c}$, $\eta = \dfrac{\alpha_o}{2}\left(\dfrac{\omega_o}{\Omega_c}\right)^{3/2}$, $k = \dfrac{1}{\sqrt{2}} k_z \ell_H$,

$\ell_H = (c\hbar/eH)^{1/2}$, e is the electron charge, c the speed of light in vacuum, and ϵ the electron energy in the conduction band with allowance for the electron-phonon interaction. In calculating (2) we assumed that $m_c/m_v \ll 1$, as is usually the case in semiconductors (m_c and m_v are the effective masses of the electrons in the conduction and valence bands). The electron spectrum was obtained by determining the poles G_r (2).

In the simplest case of resonance ($\lambda = 0$) and for k = 0 the energies of the upper and lower branches of the spectrum are

$$\epsilon_1 = \frac{3}{2}\,\Omega_c - \eta^{2/3}\Omega_c\,, \tag{3}$$

$$\epsilon_2 = \frac{3}{2}\,\Omega_c + \eta^{2/3}\Omega_c\, e^{-\frac{i\pi}{3}}\,, \tag{4}$$

and the distance between the branches of the spectrum at this point* is

$$\Delta = \epsilon_2 - \epsilon_1 = \frac{3}{2}\,\eta^{2/3}\,\Omega_c\,. \tag{5}$$

An analysis of the poles of G_r in the general case when $\lambda \neq 0$ shows that the upper branch of the spectrum terminates at the point

$$\gamma = 3\left(\frac{\eta}{2}\right)^{2/3}\,. \tag{6}$$

corresponding to a magnetic field value lower than for $\lambda = 0$. An expression for $K(\omega)$ was obtained at $|\lambda| < 1$. At resonance ($\lambda = 0$) the absorption coefficient $K(\Gamma)$ has the simplest form

$$K(\Gamma) = K_0 \begin{cases} 0, & \Gamma < -\eta^{2/3} \quad (7a) \\ [f_1(\Gamma)(\Gamma + \eta^{2/3})]^{-1/2} & -\eta^{2/3} \leqslant \Gamma \leqslant 0 \quad (7b) \\ f_2(\Gamma)[(\Gamma - \frac{1}{2}\eta^{2/3})^2 + \frac{3}{4}\eta^{4/3}]^{-1/2} & 3\left(\frac{\eta^{2/3}}{2}\right) > \Gamma \geqslant 0. \quad (7c) \end{cases}$$

Here

$$\Gamma = \frac{\omega - \omega_g - \frac{3}{2}\Omega_c}{\Omega_c}\,, \quad K_0 = \frac{e^2\,|P|^2 m_c}{\sqrt{2}\,c\,n_0\,\hbar^2\,\omega_g\,m_0^2\,\ell_H}\,, \tag{8}$$

$$f_1 = \frac{\Gamma^2 - \Gamma\eta^{2/3} + \eta^{4/3}}{\Gamma^2 + \eta\sqrt{|\Gamma|}}\,, \quad f_2 = \frac{\Gamma^{1/4}[(\Gamma^3 + \eta^2)^{1/2} + \Gamma^{3/2}]^{1/2}}{\sqrt{2}\,(\Gamma + \eta^{2/3})^{1/2}}\,,$$

n_0 is the refractive index, m_0 the mass of the free electrons, and P the interband momentum matrix element.

We see from (7a-c) that $K(\Gamma)$ has two peaks, one of which corresponds to higher frequencies ω, is located near $\Gamma = \eta^{2/3}/2$, and has a width

$$\delta \simeq \frac{\sqrt{3}}{2}\,\eta^{2/3}\,\hbar\,\Omega_c \tag{9}$$

An analysis of the expression for $K(\omega)$ when $\lambda \neq 0$ shows that this peak broadens when H decreases in the $\Omega_c < \omega_0$ side and becomes narrower when H increases in the $\Omega_c\ \omega_0$ side (when $\lambda^3 >> \eta^2$ the width of this peak is of the order of $\eta/\sqrt{\lambda}\hbar\Omega_c$).

The second maximum of $K(\Gamma)$ is located at lower frequencies. It follows from (7b) that $K(\Gamma)$ becomes infinite when $\Gamma = -\eta^{2/3}$. Infinite $K(\omega)$ are obtained for $\lambda \neq 0$ also at frequencies corresponding to electron transfer from the lower branch of the spectrum. The divergence is connected with the absence of damping in the lower branch of the spectrum: when T = 0 and no optical vibrations are excited in the spectrum, an electron in a state corresponding to the lower branch of the spectrum cannot leave this state, interacting only with the optical phonons. To obtain finite values of $K(\omega)$ corresponding to the second peak, it is necessary to

take into account the scattering of the electrons by the impurities or the deviation of T from zero, and when T = 0 the scattering accompanied by absorption of optical phonons, which has a probability $\sim \exp(-\hbar\omega_0/k_BT)$ (k_B = Boltzmann's constant), can be less significant than scattering by acoustic phonons. By allowing for the deviation of T from zero or for the interaction of the electrons with additional scatterers, we find that $K(\omega)$ has a finite value in the second maximum, and that when H increases in the $\Omega_c > \omega_o$ side the second peak broadens and then disappears. The form of the peak is determined by the magnitude of the interaction with the additional scatterers and by the temperature.

Using for InSb typical values of the parameters used in the theory ($\hbar\omega_o$ = 0.02 eV, α_o = 0.02) we obtain the following: 1) the distance between the absorption-coefficient peaks at resonance (at $\lambda = 0$), $\hbar\Delta \approx 1.5 \times 10^{-3}$ eV [from (5)]; 2) the width of the first peak (at $\lambda = 0$), $\delta \approx 0.8 \times 10^{-3}$ eV [from (9)]; 3) the point where the first peak vanishes at $\Omega_c \approx 0.9\omega_0$ [from (6)]. These results agree well with the experimental data.

The authors are sincerely grateful to Yu. A. Firsov for a discussion of the results.

[1] E. J. Johnson, D. M. Larsen, Phys. Rev. Lett. 16, 655 (1966); J. Phys. Soc. Japan 21 (Suppl.), 443 (1966).

[2] R. M. White, C. S. Koonce, Phys. Rev. Lett. 17, 436 (1966).

*The influence of the electron-phonon interaction on the spectrum of an electron in a magnetic field was considered in [2], where it was found that $\Delta \sim \alpha_o^{1/2}$. The reason for the disparity between this result and (5) is, in our opinion, the omission of a factor from formula (3) of [2].

E R R A T A

Article by L. I. Korovin et al., V. 6, No. 2, p. 52, add the following sentence to the footnote:

This factor takes into account the dependence of the electron energy at the level n = 0 on the projection q_z of the wave vector on the direction of the magnetic field H.