7th Int. Symp. "Nanostructures: Physics and Technology"
St Petersburg, Russia, June 14–18, 1999

Combined magnetopolaron in magnetooptical effects in quantum wells

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Abstract. Combined polaron states in a rectangular quantum well (QW) in a strong magnetic field directed perpendicular to the QW plane have been considered. At low temperatures these states are due to interaction of two electron energy levels (with different Landau quantum numbers (n and n_1) and different size-quantization quantum numbers (m and m_1)) with confined LO phonons under condition when the energy difference of the electron levels is close to the confined LO phonon energy. The resonant magnetic field $H_{\rm res}$, at which a combined polaron forms, depends on the energy difference of the size-quantization levels and consequently depends on QW's parameters. The separation between the branches of the combined polaron energy spectrum $\Delta E_{\rm res}$ and $H_{\rm res}$ as functions of the QW's width d have been calculated. It is shown that $H_{\rm res}$ may be reduced significantly in comparison to $H_{\rm res}$ for the case $m = m_1$.

In a strong magnetic field the polaron shift due to weak electron-LO phonon interaction is determined by the perturbation theory. However under condition

$$\omega_{\rm L1} = j\Omega_{\rm e}, \quad j = 1, 2, 3, \dots . \tag{1}$$

($\omega_{\rm L1}$ is the LO phonon frequency, $\Omega_{\rm e}$ is the electron cyclotron frequency) there appeares resonant coupling between Landau levels: an electron on the upper Landau level n emits LO phonon in a real transition and transits to the lower Landau level $n - j = n_1$. Being on the level $n - j$ the electron can absorb the earlier emitted phonon and transit on the initial level, emit a LO phonon again and so on. All these processes contribute essentially into the polaron state forming under condition (1) and they have to be taken into account.

The energy spectrum of the unperturbed electron-phonon system consists of two energy levels (one electron on the Landau level n and one electron on the Landau level $n - j = n_1$ plus one LO phonon), which intercross in the point $\Omega_{\rm e} = \omega_{\rm L1}/j$ as functions of frequency $\Omega_{\rm e}$. The transition from the unperturbed electron-phonon system to the polaron state under condition (1) means a summing up the terms of the perturbation theory sequence (on the electron-phonon coupling constant) corresponding to multiple emitting and absorption processes.

This summing results in lifting of degeneracy in the point $\Omega_{\rm e} = \omega_{\rm L1}/j$ and the polaron energy spectrum is represented by two noncrossing branches the separation between of which at the point $\Omega_{\rm e} = \omega_{\rm L1}/j$ is determined by the electron-phonon coupling constant. For the first time such polaron state was discovered in interband magnetoabsorption of bulk InSb [1].

The polaron states formation in strong magnetic fields takes place in quasi-two dimensional (2D) systems as well as in three-dimensional (3D) ones. In both 3D and 2D semiconductor structures the polaron states are very important in the frequency dependence formation of magnetooptical effects such as interband light absorption. The main difference between these systems is in the electron (hole) energy spectra: these are the one-dimensional

Landau bands in 3D case and the discrete energy levels in 2D case. This distinction results in different polaron energy spectrum splitting in the crossing point $\Omega_{\mathrm{e}} = \omega_{\mathrm{L1}}/j$ growing with the system dimensionality reduction: the energy splitting is proportional to $\sim \alpha^{2/3}$ [2] in 3D case and to $\sim \alpha^{1/2}$ [3, 4] in 2D case, where $\alpha \ll 1$ is the Frölich non-dimensional electron-phonon coupling constant.

The discribed above polaron state in a QW was called a double magnetopolaron (on the number of the intercrossing energy levels of the unperturbed electron-phonon system). More complicate polaron states are possible: triple magnetopolaron, quaternate and so on [4–6]. All these states relate to the same size-quantization energy level with the quantum number m. Therefore the resonant condition (1) does not depend on the position of the size-quantization energy level and, consequently, on the QW's width d.

However the electron (hole) energy levels in QW depend on two discrete quantum numbers: the Landau quantum number n and the size-quantization quantum number m. Therefore alongside the condition (1) it is possible performing of the other type resonant condition, when electron phonon interaction links two electron (holes) energy levels with different m and n. In this case the QW width d (and consequently the difference of the size-quantization level energies) determines the resonant magnetic field value. The role of such combined polaron states in frequency dependence formation of magnetooptical effects has been investigated.

In a QW of type I with the energy gap E_{g}, barriers ΔE_{e} and ΔE_{h} for electrons and holes respectively in a magnetic field $\mathbf{H}$ directed perpendicular to the QW plane the electron and hole energy spectra are discrete and have the form

$$E^{\mathrm{e}}_{m,n} = \varepsilon^{e}_{m} + (n+1/2)\,\hbar\Omega_{\mathrm{e}}, \quad E^{\mathrm{h}}_{m,n} = E_g + \varepsilon^{h}_{m} + (n+1/2)\,\hbar\Omega_{\mathrm{h}}, \quad \Omega_{\mathrm{e(h)}} = \frac{|e|H}{m_{c(v)}c}, \tag{2}$$

where e is the electron charge, c is the velocity of light in vacuum, $m_{c(v)}$ is the electron (hole) effective mass, $\varepsilon^{\mathrm{e(h)}}_{m} = \hbar\omega^{\mathrm{e(h)}}_{m}$ is the electron (hole) size-quantized energy in the QW.

The resonant condition for a combined magnetopolaron is satisfied if

$$E^{\mathrm{e}}_{m,n} = E^{\mathrm{e}}_{m_1,n_1} + \hbar\omega_{\mathrm{L1}}. \tag{3}$$

The resonant interaction takes place for an electron because the resonant condition does not hold for a hole due to the difference of electron and hole effective masses .

Substitution of the $E^{\mathrm{e}}_{m,n}$ from Eq. (2) into Eq. (3) results into the expression for the resonant cyclotron frequency of the combined magnetopolaron

$$\Omega^{\mathrm{res}}_{\mathrm{e}} = \frac{\omega_{\mathrm{L1}} - (\omega^{\mathrm{e}}_{m} - \omega^{\mathrm{e}}_{m_1})}{n - n_1}. \tag{4}$$

As it follows from the definition (4) there are three possible interrelations between m, m_1 and n, n_1. First, $m > m_1$ and $n > n_1$; second, $m > m_1$ and $n < n_1$; third, $m < m_1$ and $n > n_1$. The variant $m < m_1$ and $n < n_1$ leads to the negative $\Omega^{\mathrm{res}}_{\mathrm{e}}$ and must be neglected.

The first variant demands the condition

$$\hbar\omega_{\mathrm{L1}} \geq \varepsilon^{\mathrm{e}}_{m}(d) - \varepsilon^{\mathrm{e}}_{m_1}(d). \tag{5}$$

to be satisfied. Let us suppose that the equality in Eq. (5) is performed if $d = d_{\mathrm{min}}(m) > d'_{\mathrm{min}}(m)$, where

$$d'_{\mathrm{min}}(m) = (m-1)\pi\sqrt{\hbar^2/2m_c\Delta E_{\mathrm{e}}} \tag{6}$$

is the value of d at which the upper level m gets out of the QW. Because the value $\varepsilon^{\mathrm{e}}_{m}(d) - \varepsilon^{\mathrm{e}}_{m_1}(d)$ diminishes smoothly with growing the QW width d from the value $\Delta E_{\mathrm{e}} - \varepsilon^{\mathrm{e}}_{m_1}(d'_{\min}(m))$ to zero, the inequality (5) is satisfied in the interval

$$\infty > d > d_{\min}(m). \tag{7}$$

If it happenes that $\hbar\omega_{\mathrm{L1}} > \Delta E_{\mathrm{e}} - \varepsilon^{\mathrm{e}}_{m_1}(d'_{\min}(m))$ (a shallow QW), the condition (5) is satisfied at $d < d_{\min}(m)$, i.e. for any d when upper energy level exists in a QW.

In the second variant the condition

$$\hbar\omega_{\mathrm{L1}} \leq \varepsilon^{\mathrm{e}}_{m}(d) - \varepsilon^{\mathrm{e}}_{m_1}(d), \tag{8}$$

is to be satisfied in the interval

$$d'_{\min}(m) < d < d_{\min}(m), \tag{9}$$

because for $d > d_{\min}(m)$ the variant 2 polaron disappeares and for $d < d'_{\min}(m)$ the energy level m gets out of the QW. Let us note that both variants 1 and 2 cannot be unified because they correspond to the different intersecting energy levels of the electron-phonon system.

The terms of Eq. (3) and Eq. (4) distinguish radically from Eq. (1) for the double polaron for which the resonant magnetic field value does not depend on the QW parameters. For a combined magnetopolaron the value $\Omega^{\mathrm{res}}_{\mathrm{e}}$ depends on both the QW width and depth, in other words every concrete QW has its own resonant magnetic field H_{res}.

There are intersections of the electron-phonon energy levels with equal numbers N of phonons. These polaron states are analogous to the weak polarons introduced in [6] when the difference of the phonon numbers, regarding to the two energy levels of the electron-phonon system, $\Delta N \neq 1$. In such a case the interlevel transitions with one LO phonon emitting are impossible. One has to take into account here the transitions through the virtual states. Then the degeneration in the crossing point is lifted, however the splitting value will be higher order on α, than $\alpha^{1/2}$.

There is also a resonant binding between the energy levels of the electron-phonon system existing at any magnetic field value. It realizes under condition

$$\hbar\omega_{\mathrm{L1}} = \varepsilon^{\mathrm{e}}_{m} - \varepsilon^{\mathrm{e}}_{m_1}. \tag{10}$$

This is the case of the resonant binding between the two size-quantization energy levels with coinciding Landau quantum numbers, i.e. $n = n_1$. Eq. (4) is performed in a wide interval of QWs parameters because magnetic field compensates a divergence of an energy levels difference from the value $\hbar\omega_{\mathrm{L1}}$.

The energy difference of two combined magnetopolaron branches is $(2 \cdot 10^{-3}$–$4 \cdot 10^{-3})$ eV, what is less than the appropriate value for the double magnetopolaron [6] $(3 \cdot 10^{-3}$–$6 \cdot 10^{-3})$ eV, nevertheless it is quite observable. But in the case of a combined magnetopolaron the resonant magnetic field H_{res} is less than H_{res} for the double polaron. H_{res} diminishes with increasing of value $j = n - n_1$ (Eq. (1)) for the double magnetopolaron but in the case of a combined magnetopolaron (Eq. (4)) $\hbar\Omega_{\mathrm{e}}$ diminishes, first, with growing j and, second, due to decreasing $\hbar\omega_{\mathrm{L1}} - (\varepsilon^{\mathrm{e}}_{m} - \varepsilon^{\mathrm{e}}_{m_1})$. This is so for the variant 1 of Eq. (4).

The double polaron appropriating to the lowest size-quantized energy level $m = 1$ can exist at any QW width. So long as a combined magnetopolaron is due to two size-quantized energy levels it cannot exist in the width region $d < d'(m)$, where $d'(m)$ is the QW width at which the upper energy level gets out from the QW. $d'(m)$ increases with increasing of quantum number m. It means that the lower limit for the existance of the 1 variant combined polaron increases with $d'(m)$ increasing.

The damping of the branches of the combined polaron energy spectrum due to LO phonon inharmonicity as well as interband absorption and reflection of light by QW at an arbitrary interrelation between radiative and "phonon" lifetimes of combined polarons have been investigated.

This work has been partially supported by the Russian Foundation for Basic Research and by the Program "Solid State Nanostructures Physics" (97-1049).

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