Intraband light absorption by holes in InGaAsP/InP quantum wells

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Abstract. A microscopic analysis of the mechanism of intraband radiation absorption by holes with their transition to a spin-split band for quantum wells based on InGaAsP/InP solid solutions is performed within the framework of the four-band Kane model. The calculation is made for two polarizations of the incident radiation: along the crystal growth axis and in the plane of the quantum well. It is shown that this process can be the main mechanism of internal radiation losses for quantum well lasers. It is also shown that the dependence of the absorption coefficient on the width of the quantum well has a maximum at a well width from 40 to 60 Å.

1. Introduction
At present, semiconductor lasers with quantum wells (QWs) based on InGaAsP/InP compounds with a generation wavelength of 1.3 and 1.55 μm have been widely used in optical communication lines [1-3]. However, these structures are characterized by strong intraband absorption of radiation, which leads to a disruption of generation [4,5]. The intraband absorption increases with decreasing thickness of the active region, and the absorption coefficient can reach several tens of reciprocal centimeters.

The mechanisms of intraband absorption of radiation in QW lasers have been studied both theoretically and experimentally for many years [6]. Experimental results [7,8] show that the coefficient of intraband absorption of laser radiation is substantially higher than that predicted by the theory [9]. One of the candidates for explaining these results is the process of intraband radiation absorption by holes with the transition to the spin-split (so) zone. In this paper, we use a modification of the four-band Kane model [10] proposed by Polkovnikov and Zegrya [11,12], which is based on the use of the 8×8 \( kP \) Hamiltonian. It allows us to obtain explicit analytical expressions for energy spectra and wave functions of charge carriers, as well as matrix elements of transitions. The authors proposed a modification of this method, allowing to take into account the elastic stresses arising in mismatched heterostructures.

The aim of this work is to calculate the coefficient of intraband radiation absorption by holes with their transition to the so-zone for QWs based on \( A_3B_5 \) semiconductors, and also to study the dependence of the results obtained on the electromagnetic wave polarization, temperature, hole concentration, and QW width. The calculations are made for the InGaAsP/InP heterostructure, which is widely used in fabricating semiconductor lasers with a radiation wavelength of 1.55 μm. The structure parameters are taken from [13].

2. Basic Equations
We used the 8×8 \( kP \) Hamiltonian [11] that takes into account the interaction with higher bands and the terms arising from elastic stresses up to quadratic terms by the wave vector but neglects the relativistic linear terms and the term with the heavy-electron mass.

For our calculations, we choose the following representation of basis wave functions:

\[
\left| s \uparrow \right>, \left| s \downarrow \right>, \left| x \uparrow \right>, \left| x \downarrow \right>, \left| y \uparrow \right>, \left| y \downarrow \right>, \left| z \uparrow \right>, \left| z \downarrow \right>,
\]

where the spinors \( s \) and \( x, y, z \) are \( s \)-type and \( p \)-type Bloch functions with an angular momentum of 0 and 1, respectively. The \( s \)-functions describe the conduction band states and the \( p \)-functions describe
the valence band states at the Γ-point. The arrows indicate the spin direction. The carrier wave function 𝜓 can be represented in the form:

\[ \psi = \Psi |u\rangle = \Psi |s\rangle + \Psi_p |p\rangle, \]

where \( \Psi, \Psi_p \) are spinors.

The Kane equations in the spherical approximation near the Γ-point are given by the following expressions:

\[ (E_C - E)\Psi_s - i\hbar \gamma \nabla \Psi_p = 0, \]

\[ (E_V - \delta - E)\Psi_p - i\hbar \gamma \nabla \Psi_s + \frac{\hbar^2}{2m_0}(\gamma_1 + 4\gamma_2)\nabla (\nabla \Psi_p) - \frac{\hbar^2}{2m_0}(\gamma_1 - 2\gamma_2)[\nabla \times [\nabla \times \Psi_p]] + i\delta [\sigma \times \Psi_p] = 0. \] (1)

Here \( E_C \) and \( E_V \) are the energies of the conduction and valence band edges, \( \gamma \) is the Kane matrix element with a dimension of velocity, \( \delta = \Delta_{so}/3 \) is the spin-orbit splitting constant, \( m_0 \) is the free electron mass, \( \gamma_1 \) and \( \gamma_2 = \gamma_1 \) are the generalized Luttinger parameters, \( \sigma \) is the Pauli matrices, \( k \) is the wave vector, and \( E \) is the energy.

The absorption coefficient per one QW in the framework of the Kane model can be calculated from the formula:

\[ \alpha_p^p = \frac{2\gamma^2 e^2}{\hbar c} \frac{1}{n\alpha a} \sum_k \sum_{a(0)} m^0 \sigma^p f(E_h) \] (2)

for the transitions into the discrete spectrum of so-holes and

\[ \alpha_p^c = \frac{\gamma^2 e^2}{2\pi \hbar c n\alpha a} \sum_k \int_{k_h}^{k_m} \frac{\partial E(k^2)}{\partial k^2} dE_h \] (3)

for the transitions into the continuous spectrum of so-holes.

Here, the index \( p \) denotes the polarization of light and takes on a value \( per \) for a wave polarized along the crystal growth axis (i.e., when the amplitude of the vector potential \( A_0 \) is parallel to the \( x \) axis) and the value \( par \) for a wave polarized in the QW plane, \( n \) is the refractive index, \( \alpha \) is the optical transition frequency, \( a \) is the QW width, \( k \) and \( k_h \) are the wave vector \( x \) components of so- and heavy holes, respectively, \( E \) and \( E_h \) are the energies of so- and heavy holes, respectively, \( f(E) \) is the Fermi-Dirac distribution function, \( m_h = \frac{m_0}{\gamma_1 - 2\gamma_2} \) is the heavy hole effective mass, and \( m_r = \frac{m_0 m_{so}}{m_h - m_{so}} \), \( m_{so} \) is the so-hole effective mass. The value of \( \sigma \) is determined by the overlap integrals of the wave functions:

\[ \sigma_{per} = 2\pi |I_{1,x}^p|^2, \]

\[ \sigma_{par} = \pi \left(|I_{1,x}^p|^2 + |I_{1,z}^p|^2\right), \] (4)

where \( I_{1} = \int_{-a/2}^{a/2} \Psi_{h,d}^* \Psi_{s} dx \).
3. Results

Figures 1(a) and 1(b) show the frequency dependences of $\alpha_{\text{per}}^d$ and $\alpha_{\text{par}}^d$ at different temperatures in the InGaAsP/InP heterostructure at $a = 80$ Å and a hole concentration $p = 10^{12}$ cm$^{-2}$. It can be seen that more sharp peaks with a larger amplitude are observed at $T = 150$ K than at $T = 300$ K. It is also clear that the transition energy corresponding to the absorption peaks increases with temperature. It is also noticeable that the radiation polarized in the plane of QW is absorbed more efficiently than the radiation of the transverse polarization.

Figure 1(a). Dependence of the absorption coefficient $\alpha_{\text{par}}^c$ for the discrete levels of so-holes on the incident radiation frequency for different temperatures in the InGaAsP/InP heterostructure with a QW width $a = 80$ A and a hole concentration $p = 10^{12}$ cm$^{-2}$. The solid curve shows the calculation result for $T = 300$ K, and the dotted curve shows the result for $T = 150$ K.

Figure 1(b). Dependence of the absorption coefficient $\alpha_{\text{per}}^c$ for the discrete levels of so-holes on the incident radiation frequency for different temperatures in the InGaAsP/InP heterostructure with a QW width $a = 80$ A and a hole concentration $p = 10^{12}$ cm$^{-2}$. The solid curve shows the calculation result for $T = 300$ K, and the dotted curve shows the result for $T = 150$ K.

Figures 2(a) and 2(b) show the frequency dependences of $\alpha_{\text{par}}^c$ and $\alpha_{\text{per}}^c$ at different temperatures in the InGaAsP/InP heterostructure at $a = 80$ Å and a hole concentration $p = 10^{12}$ cm$^{-2}$. First of all, it should be noted that the absorption maximum with the transition to the continuous spectrum is observed at a transition energy of about 0.7 eV, which is close to the value of the optical transition energy at a wavelength of 1.55 µm. Hence, the light absorption by heavy holes with the transition to the continuous spectrum of so-holes can make a large contribution to the value of internal radiation losses and explain the large value of the internal loss coefficient observed in experiment [7,8]. Another observation is that the predominance of absorption of radiation polarized in the QW plane is much stronger for the transitions to the continuous spectrum than for the transitions to the discrete spectrum.

Figure 3 shows the dependence of the absorption coefficient at the generation wavelength on the QW width at room temperature and a hole concentration $p = 10^{12}$ cm$^{-2}$. It can be seen that the maximum absorption is observed at values of the QW width from 40 to 60 Å, and the absorption is much weaker for values less than 30 Å and greater than 80 Å.
Figure 2(a). Dependence of the absorption coefficient $\alpha_{par}$ for the continuous spectrum of so-holes on the incident radiation frequency for different temperatures in the InGaAsP/InP heterostructure with a QW width $a = 80\text{Å}$ and a hole concentration $p = 10^{12}\text{ cm}^{-2}$. The solid curve shows the calculation result for $T = 300\text{ K}$, and the dotted curve shows the result for $T = 150\text{ K}$.

Figure 2(b). Dependence of the absorption coefficient $\alpha_{par}$ for the continuous spectrum of so-holes on the incident radiation frequency for different temperatures in the InGaAsP/InP heterostructure with a QW width $a = 80\text{Å}$ and a hole concentration $p = 10^{12}\text{ cm}^{-2}$. The solid curve shows the calculation result for $T = 300\text{ K}$, and the dotted curve shows the result for $T = 150\text{ K}$.

Figure 3. Dependence of the absorption coefficient to the continuous spectrum of spin-split holes on the width of a quantum well in the InGaAsP/InP heterostructure at room temperature and a hole concentration $10^{12}\text{ cm}^{-2}$. 
4. Conclusions

The mechanism of intraband radiation absorption by holes with a transition to the so-band for QWs based on A$_3$B$_5$ semiconductors is analyzed microscopically. The cases of the transverse and longitudinal polarizations of the incident radiation are considered separately. The analysis is performed for two cases: transitions to a discrete spectrum and to a continuous spectrum of so-holes. It is shown that the intraband absorption can be the main mechanism of internal optical losses for semiconductor lasers on QWs.

In quantum wells, the absorption that occurs with the transition to the discrete spectrum of so-holes is stronger than the absorption that occurs with the transition to the continuous spectrum. The frequency dependence of the absorption coefficient corresponding to the transitions to the discrete spectrum of so-holes has pronounced maxima, the position and magnitude of which depends on the temperature. With increasing temperature, the peak shifts towards higher energies, and the peak value of the absorption coefficient decreases. Also, the absorption of radiation polarized in the plane of the quantum well predominates over the absorption of the radiation of the transverse polarization.

The value of the absorption coefficient with the transition to the discrete spectrum decreases with increasing value of the energy of the forbidden band of the material. For the transitions to the continuous spectrum, its pronounced dependence on the width of the forbidden band is not observed. In this case, the inverse proportion of the absorption coefficient to the transition energy plays a more significant role.

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