Intraband light absorption by holes in InGaAsP/InP quantum wells

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Abstract. A microscopic analysis of the radiation intraband absorption mechanism 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

The mechanisms radiation intraband absorption mechanisms in QW lasers are studied both theoretically and experimentally for many years [6]. Experimental results [7,8] show that the laser radiation intraband absorption coefficient is substantially higher than predicted by the theory [9]. One of the candidates for explaining these results is the process radiation intraband absorption process by holes with the transition to the spin-split (so) zone. In this paper, we will use the modification of the four-band Kane model [10] proposed by Polkovnikov and Zegrya [11,12], which is based on the use of the $8 \times 8$ $kP$ Hamiltonian, and 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 study the radiation intraband absorption coefficient by holes with their transition to the so-zone for QWs based on A$_3$B$_5$ 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 based on the example of the InGaAsP/InP heterostructure, which is widely used in the construction of semiconductor lasers with a radiation wavelength of 1.55 μm, and the structure parameters are taken from [13].

2. Basic Equations

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

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

$$|s \uparrow\rangle,|s \downarrow\rangle,|x \uparrow\rangle,|x \downarrow\rangle,|y \uparrow\rangle,|y \downarrow\rangle,|z \uparrow\rangle,|z \downarrow\rangle$$

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

$$\psi = \Psi_s |s\rangle + \Psi_p |p\rangle$$

Where $\Psi_s$, $\Psi_p$ are spinors.

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

$$(E_C - E)\Psi_s - i\hbar\gamma\nabla\Psi_p = 0,$$
\[ (E_v - \delta - E)\Psi_p - i\hbar\gamma\nabla\Psi_p + \frac{\hbar^2}{2m_0}(\gamma_1 + 4\gamma_2)\nabla(\nabla\Psi_p) \cdot \frac{\hbar^2}{2m_0}(\gamma_1 - 2\gamma_2)[\nabla \times [\nabla \times \Psi_p]] + i\tilde{\delta}[\sigma \times \Psi_p] = 0 \]  

(1)

Here \( E_C \) and \( E_V \) are the energies of conduction and valence band edges, \( \gamma \) is the Kane matrix element with dimension of velocity, \( \tilde{\delta} = \Delta_{so} / 3 \) is the spin-orbit splitting constant, \( m_0 \) is the free electron mass, \( \gamma_1 \) and \( \gamma_2 = \gamma_3 \) 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:

\[ \alpha_p^d = \frac{2\gamma^2e^2}{\hbar^2c} \frac{1}{n_0a} \sum_{k} \sum_{k(h)} m^d m_p f(E_h), \]

(2)

for the transitions into so-holes discrete spectrum and

\[ \alpha_p^c = \frac{\gamma^2e^2}{2\pi\hbar^2c} \frac{m_h}{n_0a} \sum_{k} \sum_{k(h)} \sigma_p f(E_h) \frac{dE_h}{k} \left| \frac{\partial E(k^2)}{\partial k^2} \right|, \]

(3)

for the transitions into so-holes continuous spectrum.

Here, the index \( p \) denotes the polarization of light and takes on a value \( \perp \) 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 \( \parallel \) for a wave polarized in the QW plane, \( n \) is the refractive index, \( \omega \) is the optical transition frequency, \( a \) is the QW width, \( k \) and \( k_h \) are the wave vector \( x \) components of the so and heavy holes, respectively, \( E \) and \( E_h \) are the energy of the 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, \( m_s = \frac{m_h m_{so}}{m_h - m_{so}} \), \( m_{so} \) is the so-hole effective mass. The value of \( \sigma \) is determined by the overlap integrals of the wave functions:

\[ \sigma_\perp = 2\pi \left| I^{+d}_{s} \right|^2 \]

\[ \sigma_\parallel = \pi \left( \left| I^{+d}_{s} \right|^2 + \left| I^{+d}_{c} \right|^2 \right), \]

(4)

Where \( I_{s} = \int_{-a/2}^{a/2} \Psi_{h,s}^* \Psi_{s} dx \).

3. Results

In Fig. 1a and 1b the frequency dependences \( \alpha_p^d \) and \( \alpha_p^d \) at different temperatures in the InGaAsP/InP heterostructure at \( a = 80 \text{A} \) and the hole concentration \( p = 10^{12} \text{ cm}^{-2} \) are shown. It can be seen that at \( T = 150 \text{K} \) more sharp peaks with a larger amplitude are observed than at \( T = 300 \text{K} \). It is also clear that as the temperature is raised, the transition energy corresponding to the absorption peaks increases. It is also noticeable that the radiation polarized in the plane of the QW is absorbed more efficiently than the radiation of the transverse polarization. In the calculations, we assumed that the carrier concentration is constant.
Figure 1a. Dependence of the absorption coefficient $\alpha^d$ on the discrete levels of so-holes on the incident radiation frequency for different temperatures in the InGaAsP/InP heterostructure with the QW width $a=80\,\text{Å}$ and the hole concentration $p=10^{12}\,\text{cm}^{-2}$. The solid curve shows the calculation result for the temperature $T=300\,\text{K}$, dotted for the temperature $T=150\,\text{K}$.

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

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

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

In Fig. 2a and 2b the frequency dependences $\alpha^c$ at different temperatures in the InGaAsP/InP heterostructure at $a=80\,\text{Å}$ and the hole concentration $p=10^{12}\,\text{cm}^{-2}$ are shown. First, it should be noted that the absorption maximum with 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 it can be concluded that 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 the experiment [7,8]. Another result is that for transitions to the continuous spectrum, the predominance of absorption of radiation polarized in the QW plane is much stronger than for transitions to the discrete spectrum.

In Fig. 3 the dependence of the absorption coefficient at the generation wavelength on the QW width at room temperature and hole concentration \( p = 10^{12} \, \text{cm}^{-2} \) is shown. It can be seen that the maximum absorption will be observed at values of the QW width from 40 to 60 A, and for the values less than 30 A and greater than 80 A, the absorption will be much weaker.

4. Conclusion

A microscopic analysis of the radiation intraband absorption mechanism by holes with a transition to the so-band for QWs based on A3B5 semiconductors is performed. The cases of transverse and longitudinal polarization of the incident radiation are considered separately. The analysis is performed for the cases of transition to a discrete and 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 the so-holes is stronger than the absorption that occurs with the transition to the continuous spectrum. The frequency dependence of the absorption coefficient due to 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 transverse polarization.

The value of the absorption coefficient with transition to the discrete spectrum decreases with increasing value of the energy of the forbidden band of the material. For transitions to the continuous spectrum, a 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.

5. Acknowledgements

This work is supported in part by RFBR grant № 16-08-01130-A.
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