Intersubband light absorption by holes in InAsSb/AlSb quantum well heterostructures

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Abstract. The absorption coefficients of intersubband optical transitions in the valence band of the AlSb/InAs₀.84Sb₀.16/AlSb quantum wells in framework of the four-band Kane model. It is established that the light absorption by holes may lead to the laser generation breakdown. It is shown that we need to decrease the quantum well width to range a<6 nm to neutralize the negative influence of this effect.

1. Introduction

One of the most important trends in modern semiconductor physics is creation of new optoelectronic devices in mid-infrared range (2-10 μm). This is due to the fact that there are the region of absorption of many toxic industrial gases, one of the windows of atmospheric transparency and maximum absorption tissues of the human body in this wavelength range. That can be applied to create a telecommunications and security systems, location and night vision equipment, gas analyzers, diagnostic and laser surgery devices. One of the most promising materials for solving this problem are deep quantum wells (QWs) based on InAsSb semiconductor compounds as the active region [1, 2]. These compounds are characterized by minimum values of the bandgap width \( E_g \) and effective electron mass \( m_e \) among A₃B₅ narrow-gap semiconductors [3, 4]. There are significant nonparabolicity of light (LH) and spin-orbit split-off (SH) holes energy spectrum in these heterostructures. This leads to significant corrections to the dimensional quantization levels energy and wave functions as compared to those in the case of the parabolic dispersion law even for the ground state in the valence band.

One of the basic mechanisms of internal light losses in semiconductor heterostructures is the light scattering by free charge carriers. The light scattering by free electrons in heterostructures based on A₃B₅ narrow-gap semiconductors is well studied. The light scattering by holes in quantum wells is studied within the Luttinger model for light and heavy holes (HH) but in order to take into account the spin- orbit split-off holes it is necessary to use the four-model Kane.

The aim of the present investigation is calculating of the optical absorption coefficient for HH-LH and HH-SH intersubband transitions in the AlSb/InAs₀.84Sb₀.16/AlSb heterostructure with a deep QW. The nonparabolicity is described with the four-band Kane model.

2. Basic Equations

We used the charge carriers wave functions of type \( \psi = \Psi_s |s\rangle + \Psi |p\rangle \), where \( |s\rangle \) and \( |p\rangle \) are the s- and p-type Bloch functions, respectively, and \( \Psi_s \) and \( \Psi \) are spinors. The Kane equations near the \( \Gamma \)-point in the spherical approximation are given by the following expressions [5]:

\[
(E_c - E)\Psi_s - iP\nabla\Psi = 0
\]

\[
(E_v - \delta - E)\Psi - iP\nabla\Psi_s + \frac{\hbar^2}{2m_0} (\gamma_1 + 4\gamma_2)\nabla(\nabla\Psi)
\]

\[
- \frac{\hbar^2}{2m_0} (\gamma_1 - 2\gamma_2)[\nabla \times [\nabla \times \Psi]] + i\delta[\sigma \times \Psi] = 0
\]
where $E_C$ and $E_V$ are the energy of the conduction band and the valence band edges, respectively, $P$ is the Kane matrix element, $\delta=\Delta_{so}/3$ is the spin-orbit split off constant, $m_0$ is the free electron mass, $\gamma_1$ and $\gamma_2$ are the generalized Lattinger parameters, $\sigma=(\sigma_x, \sigma_y, \sigma_z)$ are the Pauli matrices.

The charge carrier energy spectra in the valence band in the four-band Kane model are:

$$E_h = \delta - \frac{\hbar^2 (k_h^2 + q^2)}{2m_h},$$

$$E_{l_h,so} = -\frac{\delta}{2} - \frac{\hbar^2 (k_{l_h,so}^2 + q^2)}{4} (m_i^{-1} + m_h^{-1}) \pm \left\{2\delta^2 + \left[\frac{\delta}{2} - \frac{\hbar^2 (k_{l_h,so}^2 + q^2)}{4} (m_i^{-1} - m_h^{-1})\right]^2\right\}^{\frac{1}{2}},$$

where $m_i^{-1} = -\frac{2P_i^2}{\hbar^2 E_{l_h}} + m_0^{-1} (\gamma_1 + 4\gamma_2)$ and $m_h^{-1} = m_0^{-1} (\gamma_1 - 2\gamma_2)$, $E_{l_h}$, $E_h$ and $E_{so}$ are the HH, LH and SH energies, respectively, $k_h$, $k_l$ and $k_{so}$ are the quantized HH, LH and SH wave vector components, respectively, $q$ is the wave vector component in QW plane.

The number of transitions is given by formula:

$$Q = Q_0 \cos^2 \beta + Q_\perp \sin^2 \beta,$$

where $\beta$ is the angle between the vector potential amplitude $A_0$ and QW plane and

$$Q_{\perp} = \frac{4\pi^2 P^2 e^2 A_0^2}{\hbar^3 c^2} \sum_{k_0} \frac{qdq}{(2\pi)^2} \sum_{k(q)} \sigma_{\perp} f(E_h)(1 - f(E))\delta(E_h - E - \hbar\omega),$$

$$\sigma_{\perp} = \pi \left| I_{\perp}^2 \right|^2,$$

$I_i$ are the overlap integrals between $s$-component of final state wave function and $i$-component of initial state wave function, $i=x,y,z$. index $a$ denotes transitions with spin conversion, index $s$ denotes transitions without spin conversion, $\omega$ is the optical transition frequency, $k(q)$ is the wave vector of final state, $f$ is the Fermi function.

We considered the optical transitions where $A_0$ is parallel to the QW plane. The absorption coefficient of intersubband optical transitions can be calculated using the following equation:

$$\alpha_a = \frac{2\pi^2 e^2}{n c h^3} \frac{1}{\hbar\omega} \sum_{k_0} m_i(E)\sigma_a f(E_h)(1 - f(E)),$$

Where $m_i(E) = \frac{1}{m_i^{-1}(E) - m_h^{-1}}$, $m_{so}$ is the SH effective mass.

### 3. Results

In our calculations we used the following parameters: QW width $a=8$ nm, holes concentration $p=10^{12}$ cm$^{-2}$ and temperature $T=300$ K.

In Figures 1-3 the absorption coefficient of various intersubband optical transitions and total absorption coefficient by holes are presented.
Figure 1. The absorption coefficient of HH1-LH1 (a), HH1-LH2 (b), HH2-LH1 (c), HH2-LH2 (d) optical transitions.
Figure 2. The absorption coefficient of HH1-SH1 (a), HH1-SH2 (b), HH2-SH1 (c), HH2-SH2 (d)
optical transitions.

Figure 3. Total absorption coefficient of HH-LH (a) and HH-SH (b) optical transitions.

As can be seen, transition HH2-LH1 has the maximum absorption coefficient. It causes by HH2 and
LH1 energy levels resonance. Transition HH1-SH1 has large absorption coefficient that causes the fact
that \( m_\text{H} \approx m_\text{so} \).

Transitions HH1-SH1 and HH2-SH2 have the absorption coefficient value much higher than allowable
value of internal optical losses in laser heterostructures. Thus we need to increase the effective energy
gap value decreasing the QW width to achieve the conditions of the laser generation. The calculated
value of QW width according to laser generation is \( a < 6 \) nm.

4. Conclusions
Thus, it has been demonstrated that light absorption by holes is the very efficient way of internal
optical losses and may cause the laser generation breakdown in AlSb/InAs\(_{0.84}\)Sb\(_{0.16}\)/AlSb quantum
wells with QW width \( a > 6 \) nm.

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References

[1] Zegrya G G 1997 Mid-infrared strained diode lasers (Antimonide-Related Strained Layer Heterostructures) ed Manasreh M O (Gordon & Breach Science Publishers, Amsterdam) p 273

[2] Mikhailova M P, Danilov L V et al. 2013 Superlinear luminescence and enhancement of optical power in GaSb-based heterostructures with high conduction band offsets and nanostructures with deep quantum wells (The Wonder of Nanotechnology: Quantum Optoelectronic Devices and Applications) ed Razeghi M et al. (SPIE Press, Bellingham, WA) p 105

[3] Vurgaftman I, Meyer J R, Ram-Mohan L R 2001 Appl. Phys. 89 5815

[4] Cripps S A, Hosea T J C, Krier A et al. 2007 Appl. Phys. Lett. 90 172106

[5] Zegrya G G and Polkovnikov A S 1998 J. Exp. Theor. Phys. 86 815