Studies on quantum well laser

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ABSTRACT

One-dimensional simulation on quantum-well laser diodes in steady-state had been studied in this work. The electrical behaviors are obtained by solving Poisson's equation and current continuity equations for electrons and holes using a self-consistent method. Band parameters are added in the continuity equations for compositional change in each layer. Different forms of band parameters are used in quantum well regime. The recombination model are revised in the quantum well regime. After the electron and hole profiles are obtained, the peak gain in the quantum well regime are then calculated. The model for the optical matrix element used in this study includes intraband relaxation but without band mixing effects. Wave equation is solved to obtain the optical field intensity and the optical confinement factor. Modal gain and total loss are then calculated. This procedure proceeds until the modal gain is greater than the loss. We use this model to simulate both graded-index separate-confinement heterostructure (GRIN-SCH) quantum-well laser and separate-confinement heterostructure (SCH) quantum-well laser for AlGaAs-GaAs system. Results show that the carriers are well-confined in GRIN-SCH laser, thus less recombination current density present outside the quantum well regime in GRIN-SCH than in SCH. The optical confinement factor depends strongly on the waveguide structures. It may be better confined in GRIN-SCH than in SCH for a set of layer thickness and poorly confined for another set of layer thickness. Thus, the threshold current density depends on the structure. The calculated threshold current density is slightly lower than the experimental result.

1. INTRODUCTION

The two dimensional nature of electron motion in quantum well heterostructures produces several important features in semiconductor lasers. For instance, quantum-size effects shorten the emission wavelength due to the radiative transition between the confined states and significantly reduce the threshold current density and its temperature dependence as a result of the modification in the density-of-states function.

Theoretical investigation on the gain of quantum well lasers have been carried out by several authors [1]–[9]. Some of the models are based on the energy levels calculated for an effective mass electron (or hole) in the potential well [1]–[6]. The energy versus momentum vector ($E-k$) dispersion curves for electron in the quantum well plane were assumed to be defined by parabolic bands with bulk material effective mass value. In addition, the magnitudes of the optical matrix elements were assumed to be constant for the transitions anywhere in the bands (no $k$ or $E$ dependence). Other studies based on detailed band structure analysis obtained a different optical matrix elements [7]–[9]. These analyses of the quantum well are based on techniques such as the tight binding method [7], the pseudopotential method [8], and the $k•p$ perturbation method [9]. These techniques show effects of the band mixing on the quantum well subband levels and on the matrix elements.

Laser modeling is a tool of great value, both to understand the operations seen in real laser diodes as well as to predict and possibly to optimize the behavior of as yet fabricated devices. Device modeling for semiconductor laser have been presented by many
authors[10]—[15], a review of these works before 1985 was summarized by J.Buss[13]. These models present either one—dimensional or two—dimensional simulation. The advantage for these models are that they considered the detailed structure of laser. Laser has a strong structure dependence. It exhibits different electrical and optical behavior for different structures. Thus, a good designed tool is needed to optimize the laser design.

In order to develop a design tool for quantum well laser, we study the quantum well laser following the idea of K.B.Kahen [14] and T.Ohtoshi et. al. [15], which was adopted for conventional double heterostructure (DH) laser. They used a self—consistent method by solving Poisson equation, current continuity equation to obtain carrier distribution in the device; and they solved wave equation to obtain the field intensity. But due to the two dimensional nature in quantum well, the density—of—states, the optical matrix, and thus the gain are different from those in the conventional laser. To avoid time consuming in calculating the band structure, band mixing effects are not considered in this work.

2. MODEL

2.1 Electrical equations:

To accurately analyze an arbitrary semiconductor structure which is intended for use under various operation conditions, a mathematical model has to be given. The basic semiconductor equations can be derived from Maxwell's equations and several relations obtained from solid—state physics under various assumptions. These equations are described as follows

(1) Poisson equation:
\[ \nabla \cdot (\epsilon \nabla V) = q \cdot (n - p - C) \]

q is the elementary charge, n is the negatively charged electron concentration and p is the positively charged hole concentration, C is the net ionized concentration.

(2) Continuity equation for holes and electrons:
\[ \nabla \cdot J_n - q \cdot \frac{\partial n}{\partial t} = q \cdot R(\psi, n, p) \]
\[ \nabla \cdot J_p + q \cdot \frac{\partial p}{\partial t} = q \cdot R(\psi, n, p) \]

(3) Boltzmann transport equation:
\[ J_n = -q \cdot (\mu_n \cdot n \cdot \nabla \psi - D_n \cdot \nabla n) \]
\[ J_p = -q \cdot (\mu_p \cdot p \cdot \nabla \psi + D_p \cdot \nabla p) \]

J_n is the conduction current density caused by electrons and J_p is that for holes. \( \mu_n \) and \( \mu_p \) are carrier mobility for electrons and holes respectively. D_n and D_p are the diffusion constants for electron and hole, respectively. D_n and D_p are related to \( \mu_n \) and \( \mu_p \) obey the Einstein relation.

2.2 Heterojunction equations

The heterojunction model follows from the formalism of Lundstrom and Schuelke [16] for heterostructure devices. Assuming steady—state conditions and using the drift—diffusion model, the Boltzmann transport equations are rewritten as

\[ J_p = -p \cdot q \cdot \mu_p \cdot V_p \cdot (V - V_p) - kT \cdot \mu_p \cdot \nabla p \]
\[ J_n = -n \cdot q \cdot \mu_n \cdot V_n \cdot (V + V_n) + kT \cdot \mu_n \cdot \nabla n \]

with
\[ V_p = -\frac{1}{q} \left( E_v - E_{vr} \right) + \frac{kT}{q} \ln \left( \frac{N_v}{N_{vr}} \right) + \frac{kT}{q} \ln \left( \frac{\mathcal{A}_2(\eta_v)}{\exp(\eta_v)} \right) \]
\[ V_n = -\frac{1}{q} (E_c - E_{cr}) + \frac{kT}{q} \ln \left( \frac{N_c}{N_{cr}} \right) + \frac{kT}{q} - \ln \left[ \mathcal{R}/2(\eta) \exp(\eta) \right] \]  

(9)

\[ \eta_c = (F_n - E_c)/kT \]  

(10)

\[ \eta_v = (E_v - F_p)/kT \]  

(11)

\[ \mathcal{R}/2(\eta) = \frac{2}{\sqrt{\pi}} \int_0^\infty \frac{\eta^{1/2}}{1 + \exp(\eta)} d\eta \]  

(12)

\( (E_v - E_{vr}) \) and \( (E_c - E_{cr}) \) are the valence band and conduction band discontinuity related to reference material. The discontinuity between \( Al_xGa_{1-x}As \) and GaAs is still controversial.

In this study, we use the results from capacitor–voltage (C–V) and current density–voltage (J–V) measurements[17–19]

\[ \Delta E_c = 0.75 \ x \quad (x \leq 0.45) \]  

(13)

\[ \Delta E_v = 0.55 \ x \]  

(14)

where \( x \) is the AlAs mole fraction. \( N_c, N_v, N_{cr}, N_{vr} \) in eq.(8) and eq.(9) are the effective density of states of conduction band and valence band in the material and reference material. The reference material chosen in this work is GaAs. \( V_p \) and \( V_n \) are band parameters arising from the fact that when electrons (holes) transport across the heterojunction, a discontinuity appear in the conduction (valence) band and different effective density of states gives an effective potential to electrons (holes). The last term in \( V_n \) and \( V_p \) account for the Fermi Dirac statistics whenever Boltzmann statistics is invalid. All these parameters except those for the reference material are position dependent.

2.3 Quantum well model

Due to the two dimensional nature, the carriers in the quantum well are restricted to move freely in the plane parallel to quantum well. The two dimensional density of states is \( \frac{m^*}{\pi \hbar^2} \) for each state. Thus the carrier concentration related to quasi Fermi level \( F_n \) or \( F_p \) in the quantum well can be written as

\[ n = \frac{m_c kT}{\pi \hbar^2 w} \sum \ln[1 + \exp(-F_n/E_c)] \]  

(15)

\[ p = \frac{kT}{\pi \hbar^2 w} \left[ m_{hh} \sum \ln[1 + \exp(-E_{hh}/kT)] + m_h \sum \ln[1 + \exp(-E_h/kT)] \right] \]  

(16)

where \( w \) is the well width, \( m_c, m_{hh} \) and \( m_h \) are the effective masses of electrons, heavy holes and light holes in the quantum well. \( E_{l} \) is the \( l \)-th eigen energy in the well. Following the heterojunction model described above, the band parameters in the quantum well can then be written as

\[ V_n = -\frac{1}{q} (E_{cb} - E_{cr}) + \]  

\[ \log \left[ \frac{N_{qw} \sum \ln[1 + \exp(-F_n/E_c)] + N_c \mathcal{R}/2(F_n - E_{cb})}{\exp(-F_n/E_{cb})} \right] \]  

(17)

with \( N_{qw} = \frac{m_c kT}{\pi \hbar^2 d} \)
Similar expression can be obtained for $V_p$.

2.4 Recombination model

(i) Stimulated-emission recombination rate:[15]

$$R_{st} = \frac{c_0}{n_{eff}} g S |E|^2$$

$E$ is the optical electric field, and $S$ is the photon energy.

(ii) Spontaneous-emission recombination rate:[15]

$$R_{sp} = B (n_p - n_0 n_0)$$

where $B = 5 \times 10^{-10}$ (cm$^3$/s) [14]

(iii) Shockley—Read—Hall recombination rate:[15]

$$R_{SRH} = \frac{n_p (n + n_t) + n_t (p + p_t)}{\tau_p (n + n_t) + \tau_n (p + p_t)}$$

where $\tau_p = \tau_n = 10 \text{ ns}$[15]

2.5 Schrödinger equation

In the active layer, wavefunctions obey the 1D Schrödinger equation,

$$-\frac{\hbar^2}{2m^*} \frac{\partial^2 \psi_n}{\partial z^2} + V(z) \psi_n = E_n \psi_n$$

where $V(z)$ is the potential that describes the band discontinuities. In eq.(21) the effective masses $m^*$ depend on $z$ since they are not the same in the quantum well and in barrier layer. The resulting boundary conditions describe the conservation of the probability density and probability current across the hetero—interfaces [20]

2.6 Optical model

The optical field distribution in the waveguide structure can be obtained from the wave equation:

$$\nabla^2 E + (n^2 k_0^2 - \beta^2) E = 0$$

$E$ is the normalized optical field distribution, $n$ is the refractive index, $k_0 = \lambda_0/2\pi$ is the wavevector and $\beta$ is the eigen mode in the waveguide.

Rate equation describes the photon density and oscillation condition[15]

$$\frac{dS}{dt} = \left[ \frac{c_0}{n_{eff}} G_m - \frac{1}{\tau_{ph}} \right] S + C \cdot R_{sp}$$

$$G_m = \int g |E|^2 \, dx$$

$G_m$ is the mode gain; $c_0$ is the light velocity in vacuum; $n_{eff}$ is the effective refractive index; $g$ is the local gain which will be discussed in the next section. $\tau_{ph}$ is the photon lifetime given by eq.(25)

$$\frac{1}{\tau_{ph}} = \frac{c_0}{n_{eff}} (\alpha_1 + \alpha_m)$$

At steady—state $dS/dt = 0$, and the $R_{sp}$ term is neglected, the threshold condition can be written as

$$G_m = \alpha_1 + \alpha_m$$

$\alpha_1$ represents the internal loss and is given by

$$\alpha_1 = \int \alpha_c |E|^2 dx + \alpha_s + \alpha_c$$
\( \alpha_{fc} \) (cm\(^{-1}\)) \( \simeq 3 \times 10^{-18} n + 7 \times 10^{-18} p \) \( \alpha_{fc} \) is the free carrier absorption loss; \( \alpha_{s} \) is the optical scattering loss due to irregularities at the heterointerfaces and can be negligible in epilayer grown by molecular beam epitaxy (MBE) or metal–organic chemical vapor deposition (MOCVD); \( \alpha_{c} \) is the coupling loss and is usually negligible when the Al\(_{x}\)Ga\(_{1-x}\)As cladding layers are thick (\( \sim 2\mu m \)) \( \alpha_{m} \) is the mirror loss term and is given by

\[
\alpha_{m} = \frac{1}{2L} \ln \left( \frac{1}{R_{1}R_{2}} \right)
\]

(29)

L is the cavity length and \( R_{1}, R_{2} \) are the reflectivity of the two facets. For uncoated cleaving facets, \( R_{1} = R_{2} = 0.32 \) \( \) \[21\]

2.7 Local gain

The linear gain model of M. Asada, et. al. \[2\] was used, which took into account the intraband relaxation process, such as the electron–electron scattering, electron–phonon scattering, etc., then broadening occurs in the gain spectrum of semiconductor lasers. Then the linear gain \( g \) in the quantum–well laser can be written as \[2\]

\[
g (\omega) = \omega \frac{\mu}{\epsilon} \frac{m_{c}^{*} m_{h}^{*}}{m_{c}^{*} + m_{c}^{*}} \frac{1}{\pi \hbar^{2} w}
\]

(28)

where \( E_{cn}, E_{hn} \) are the \( n \)-th electrons and holes eigen energies in the quantum well, respectively. The energy reference was chosen at the bottom of the conduction band, with one exception that \( E_{hn} \) is measured from the top of the valence band down to the quantized level. \( \omega \) is the angular frequency of light, \( \mu \) is the permeability constant, \( \epsilon \) is the dielectric constant, \( m_{h}^{*} \) and \( m_{c}^{*} \) are effective masses of hole and electron. \( E_{ch} = (\epsilon_{cn} - \epsilon_{hn}) \) is the transition energy, \( w \) is the well width, and \( f_{c} \) and \( f_{v} \) are the Fermi functions given by

\[
f_{c} = \frac{1}{1 + \exp\left(\left(\epsilon_{cn} - E_{tc}/kT\right)\right)}^{-1}
\]

(31)

\[
f_{v} = \frac{1}{1 + \exp\left(\left(\epsilon_{hn} - E_{tv}/kT\right)\right)}^{-1}
\]

(32)

\[
\epsilon_{cn} = \frac{\hbar^{2}}{2m_{c}^{*}}(k_{x}^{2} + k_{y}^{2}) + E_{cn}
\]

(33)

\[
\epsilon_{hn} = -\frac{\hbar^{2}}{2m_{h}^{*}}(k_{x}^{2} + k_{y}^{2}) - E_{hn} - E_{g}
\]

(34)

\( R_{ch} \) is the matrix element of the dipole moment formed by an electron in subband \( n \) and a hole in subband \( m \), \( R_{ch} \) can be written as

\[
R_{ch} = \langle \psi_{cnk_{cn}} | e \cdot r | \psi_{hnk_{hn}} \rangle
\]

\[
\simeq \left[ \int_{-\infty}^{\infty} \phi^{*}_{cn} \phi^{*}_{hn} dy \right] \delta_{k_{cn}k_{hn}} R
\]

(35)

where

\[
R = \int_{\text{unit cell}} u_{c}^{*} e \cdot r u_{h} dr
\]

(36)

For TE–mode electromagnetic waves, the square of \( R \) parallel to \( E \) is averaged for one subband as

\[
<R^{2}n> \simeq R^{2}(1 + E_{cn}/\epsilon_{cn})/2
\]

(37)

\[
R \simeq (\hbar^{2}/2E_{ch})[E_{g}(E_{g} + \Delta_{0})/(E_{g} + 2\Delta_{0}/3)/m_{c}^{*}]^{1/2}
\]

(38)

\( E_{g} \) is the bulk energy gap; \( \Delta_{0} \) is the spin–orbit splitting.
3. NUMERICAL METHODS

3.1 Self-consistent calculation

The program flowchart is shown in Fig.1. The grids are generated nonuniform because the dependent variables (V, n, and p) change rapidly near the hetero-interface. Schrödinger equation is solved to obtain eigen-energies and wavefunctions in the well by inverse power method[22]. The electrical equations are solved using Gummel Algorithm. And all the equations are solved using the finite difference method[23]. The gain spectrum is calculated to obtain the peak gain and the lasing wavelength using the calculated carrier concentrations injected in the quantum well. To save computing time, this procedure is done after the difference of the quasi-Fermi levels for electrons and holes in the quantum well is greater than the bandgap in the well. Using the obtained wavelength, wave equation is then solved to obtain the light intensity distribution in the waveguide structure.

3.2 Simplified model

This simplified model is based on the assumption that space charge neutrality is preserved in the quantum well regime. Using this assumption and note that the quantum well is usually undoped, and the carrier concentrations for both holes and electrons are almost the same. The simplified model prevails by giving the injection carrier concentration rather than solving the Poisson equation and continuity equations.

Whenever threshold carrier density is obtained, spontaneous emission rate at photon energy $\hbar \omega$ can be calculated using eq.(39)

$$r_{sp}(\hbar \omega) = \frac{8\pi \hbar^2 (\hbar \omega)^2}{\hbar \omega^2} \omega \frac{\mu}{\epsilon} \frac{m_e m_h^*}{m_e^* m_h} \frac{1}{\pi \hbar^2 \omega} \cdot$$

$$\sum_{n=0}^{\infty} \int_{E_{ch+n}}^{\infty} R_{ch} \frac{f_c(1-f_c)(\hbar/\tau_n) dE_{ch}}{(E_{ch}-\hbar \omega)^2 + (\hbar/\tau_n)^2} (39)$$

The total spontaneous emission rate $R_{sp}$ is obtained by integrating over all possible photon energies, with the result expressed in s$^{-1}$ cm$^{-3}$

$$R_{sp} = \int_{0}^{\infty} r_{sp}(\hbar \omega) \cdot d(\hbar \omega) (40)$$

The radiative component of the current density $J_{rad}$ is related to the total spontaneous emission rate by[24]

$$J_{rad} = e d R_{sp} (41)$$

where $d$ is the active layer thickness. And the threshold current due to spontaneous emission can then be calculated as

$$I_{th} = w L J_{rad} (42)$$

4. RESULTS AND DISCUSSION

4.1 Gain spectrum calculation

The structure considered here is: GaAs substrate with (1) 1.5µm n-type (2 x 10$^{18}$ cm$^{-3}$) Al$_x$Ga$_{1-x}$As ($x = 0.4$) (2) 0.1µm p-type (1 x 10$^{15}$ cm$^{-3}$) Al$_x$Ga$_{1-x}$As ($x = 0.2$ or graded from 0.4 to 0.2) (3) GaAs layer as the quantum well (4) 0.1µm p-type (1 x 10$^{18}$ cm$^{-3}$) Al$_x$Ga$_{1-x}$As ($x = 0.2$ or graded from 0.2 to 0.4) (5) 1.5µm p-type (2 x 10$^{18}$ cm$^{-3}$) Al$_x$Ga$_{1-x}$As ($x = 0.4$). The gain spectrum was calculated with well width 50Å, 75Å, 100Å, 125Å,
150Å, and 175Å. For each well width, gain was calculated under different injection carrier concentration (from $1.6 \times 10^{18}$ to $1.3 \times 10^{19}$ cm$^{-3}$). The gain spectra for the well width 100Å under different carrier concentrations are shown in Figs.2. When the injection carriers become higher, the peak gain is shifted toward short wavelength. These shifts due to the broaden effects used in the gain spectrum model (small shifts within a few to a few tens Å). Another shifts may be occurred due to higher sublevel transition (for greater well width). The peak gain under different carrier concentrations for different well widths is shown in Fig.3. Under low injection carriers, the smallest peak gain is obtained at a well width of 50Å. This is due to higher sublevels in the thinner quantum well, the population is small and absorption is larger than emission. When injection carrier increases, peak gain rises faster in thin quantum well for its fewer sublevels in quantum well and smaller density of states. And under high injection, peak gains for well width greater than 100Å are very close.

Optical confinement factor $\Gamma$ for well width 50Å is about 0.011. The threshold gain $g_{th}$ is calculated for different cavity length. Then the threshold carrier density is calculated. A tabulation on these quantities are given in Table. 1. Threshold current density due to spontaneous emission is calculated using eq.(41). This current density become very high at short cavity length.

4.2 Results on self–consistent calculation

Simulation results on separate confinement heterostructure (SCH) with well width 150Å and cavity length 500 μm are shown in Figs. 4–7. These figures are calculated using some recombination data discussed next paragraph. Fig.4 and Fig.5 show the carrier concentration for electrons and holes at voltage 1.55 V, just above the threshold, respectively. The carrier concentrations are about $3.4 \times 10^{18}$ cm$^{-3}$. Using simplified model discussed above, the spontaneous emission rate is $1.5 \times 10^{27}$ s$^{-1}$cm$^{-3}$. The radiative current density is then 360 A⋅cm$^{-2}$. The current density is about 450 A⋅cm$^{-2}$ using this self–consistent calculation, i.e. an amount of 90 A⋅cm$^{-2}$ is leaky to the quantum well. This leakage current will become more important when more carriers are leaky from the active region. For the spontaneous emission rate is proportional to the square of the carrier concentration in the three–dimensional case, and the carriers required to inject in the quantum well is very high in very thin quantum well with short cavity length, thus leakage current becomes very important. A notable feature on Fig.4 and Fig.5 is that a spike is observed at the heterointerface. These spikes come from the abrupt change of the bandgap at the hetero–interface. Current density vs applied voltage is shown in Fig.6.

Fig.8 shows the current density for the same structure with different recombination models used in the quantum well region. Current density is higher in three–dimensional case than in the two–dimensional case. Recombination rate using eq.(19) and eq.(20) for spontaneous–emission recombination and Shockley–Read–Hall recombination in the three–dimensional case shows an overestimation on current density. From eq.(19), the spontaneous emission $R_{sp}$ is proportional to the square of the carrier concentration at high applied voltage whenever $n\cdot p$ product is greater than that of $n_0\cdot p_0$. But using the results of spontaneous emission rate calculated from eqs.(39) and (40), it is almost a linear dependence on higher carrier concentration as shown in Fig.9 (for carrier density from $3 \times 10^{17}$ cm$^{-3}$ to $1.3 \times 10^{19}$ cm$^{-3}$ with well width 150Å). Thus, the recombination rate must be revised for carrier recombination in the quantum well. Using these data as recombination rate in the quantum well, a significant reduction on the current density are observed at the same bias voltage.

The simulated results on graded–index separate confinement heterostructure (GRIN–SCH) are discussed as followed. The differences between SCH and GRIN–SCH are the AlAs mole fraction graded from 0.4 to 0.2 for optical confinement layer. The cavity length is 500 μm. No spikes was observed on the edge of quantum well for these bandgaps do not change.

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abruptly. Due to the "funnel" type of band diagram, when carriers are injected to the graded region, they tend to go further to the lower bandgap region. Thus, the lack of carriers in graded regions near the cladding layers results in a barrier for holes on the valence band and electron on the conduction band. When carriers injected to these layers of SCH case, there are no additional force for them to go further. On the other hand, there are forces due to the ionized impurity to make the carriers accumulated at the interface and it forms a two—dimensional electron gas at this interface.

The current density calculated as a function of applied voltage. The threshold current density is higher in GRIN—SCH than in SCH. The reason is that the optical field confined in the waveguide structure is poor in the GRIN—SCH. The optical confinement factor increases as well width increase and almost varies nearly. To increase the thickness of optical confinement layer results a better confinement of wave intensity in the waveguide, however, it reduces the fraction of wave in the active layer. Such effects are plotted in Fig.10. Thus, the optimized thickness of these layer is around 0.11 μm. In this structure, the mirror loss is 22.56 cm⁻¹; the total loss calculated from eqs.(24), (25), (26), and (27) are 29.774 cm⁻¹. Thus an internal loss of 7.214 cm⁻¹ due to the free carrier absorption. The injection carriers density in the quantum well region is ~ 3.8 x 10¹⁸ cm⁻³. Thus the spontaneous emission rate is ~ 1.8 x 10²⁷ s⁻¹·cm³. As a result, radiative current density is 432 A/cm². The threshold current density is 490 A/cm². Thus, the non—radiative current density is 48 A/cm² less than the non—radiative current density 96 A/cm² in the structure B. This is due to carriers are confined near the quantum well region for the sake of "funnel" type band diagram.

4.4 Results compared with published data

In this section, we use this model to simulate the SCH structure which had been fabricated by S.D.Horsee et.al.[25]. Although several structures were considered in that paper, only the Neet structure described in Table. 2 will be considered in this work. For this structure, the threshold current densities from experiments are about 600 A/cm² and 530 A/cm² for different runs. In our simulation, the bias voltage increases 0.01 V at each update when applied voltage greater than 1.5 V, the threshold current density obtained by this model is between 469.7 A/cm² and 530.7 A/cm² at bias voltages 1.545V and 1.555V, respectively. The total loss is 32.711 cm⁻¹ and the mode gain (peak gain times optical confinement factor) is 25.64 cm⁻¹ at 1.555V and the total loss is 32.711 cm⁻¹ and the mode gain is 34.38 cm⁻¹ at 1.555 V. The small difference between these two loss is due to the free carrier absorption. The threshold current density is then about 518 A/cm² for interpolated on the data given above. This value is smaller than the experiment data. The underestimation on threshold current density may due to the gain calculated in this study.

4.4 Summary

The main problems for the complicated simulations come from many reasons. First, the gain calculated in this model is higher than that calculated from band structure including the band mixing effects[9]. The calculation of band structure is another big problem and time—consuming. Thus, it is nearly impossible to impose such model in a simulator. It needs an analytical expression for such model to be used in a simulator, if it exists. Second, for laser is operating at high injection and the density of states in the quantum well regime is usually small, it is easy to fill the sublevels in the well. Whether the states above well will affect the performance of laser is needed to be investigated. Carrier concentrations in the quantum well region includes two—dimensional density—of—states and three—dimensional density—of—states by assuming continuous states with bulk three—dimensional effective density—of—states above the well. Third, Gummel algorithm fails to converge at high level injection, it needs another
method to simulate the behaviors above threshold. Usually, Newton method is recommended, but it has another problem of convergence.

5. CONCLUSIONS

In this studies, we derived the band parameters in quantum well regime, and then applied them in the self-consistent model to study the threshold current density on quantum well laser. The gain and spontaneous emission rate are calculated using a model which included the intraband relaxation process in the quantum well regime in stead of three-dimensional case. The threshold current density calculated based on this model is smaller than the experiment data. This may be due to the gain model used in this simulation. We also compare the structure of SCH and GRIN—SCH. Differences on these structure were pointed out.

The poor optical confinement on quantum well laser results that higher carrier density is required to inject in the quantum well. Thus, spontaneous emission and other recombination mechanisms are enhanced — effects to increase threshold current density. The optical confinement can be improved by introducing multi—quantum wells as the active region. This also increases the density of states in the quantum well regime. But asymmetric injections for both carriers will occur.

Although one—dimension case was considered in this study, it can be extended to the two—dimensional one to simulate more complex structures. For a more detailed and accurate simulation on quantum well lasers, it is necessary to learn more information about the quantum well and more physics about the quantum well should be involved.

6. REFERENCES

Table 1: Total loss, threshold gain, and threshold carrier density for different cavity lengths with well width 50 Å.

<table>
<thead>
<tr>
<th>Cavity Length (µm)</th>
<th>Total Loss (cm⁻¹)</th>
<th>Threshold Gain (cm⁻¹)</th>
<th>Threshold Carrier Density (× 10¹⁸ cm⁻³)</th>
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Table 2. Structure D to be simulated

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<th>Material</th>
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<th>AlAs Mole Fraction</th>
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<tbody>
<tr>
<td>layer 1</td>
<td>AlₓGa₁₋ₓAs p</td>
<td>2.0 µm</td>
<td>x = 0.4</td>
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<td>layer 2</td>
<td>AlₓGa₁₋ₓAs p</td>
<td>0.2 µm</td>
<td>y = 0.48</td>
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<tr>
<td>layer 3</td>
<td>GaAs</td>
<td>120 Å</td>
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<tr>
<td>layer 4</td>
<td>AlₓGa₁₋ₓAs p</td>
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<td>y = 0.48</td>
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<tr>
<td>layer 5</td>
<td>AlₓGa₁₋ₓAs n</td>
<td>2.0 µm</td>
<td>z = 0.4</td>
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</tbody>
</table>

Cavity length = 300 µm

Fig. 1 Program flowchart

Fig. 2. Gain spectrum for different injection carriers: 2×10¹⁸ to 2×10¹⁹ for structure A with well width 100 Å.
Fig. 3. Prox. gain versus injection currents for different well widths for structure A at 76.1, 155.1, 155.1, and 155.1.

Fig. 4. Electron carrier concentrations profile at bias voltage 1.55V for structure B.

Fig. 5. Hole carrier concentrations profile at bias voltage 1.55V for structure B.

Fig. 6. Simulation results on current density versus applied voltage for structure B.
Fig. 7 Simulation results on band diagram profiles at bias voltage 1.35V for structure A with voltage profile between them.

Fig. 8 Simulation results on current density versus applied voltage for different spontaneous emission rate model 3D recombination rate and 3D recombination for structure B.

Fig. 9 Spontaneous emission rate versus carrier concentration with well width 150Å for structure B.

Fig. 10 Optical confinement factor versus confinement layer thickness for structure C.