Chapter 5

RESULTS AND DISCUSSIONS

5.1 Interpretation of Simulation Results

In this part of theoretical calculation, the simulation results presented include the material and mode gain over a specified spectral range of photon energy using the carrier concentration as a parameter. This is considered to be a measure of the injection level. The gains for TE and TM polarization are compared. The field distribution across the direction of the epitaxial growth of heterostructure is presented.

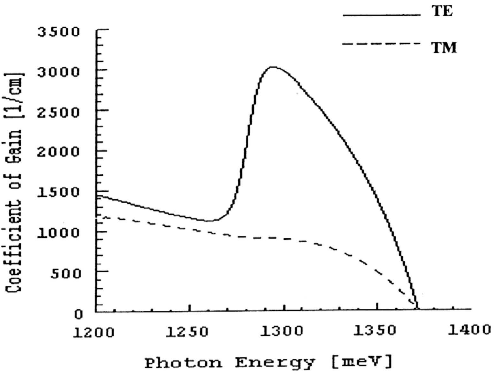
5.2 Material Gain Characteristics

The calculation of the optical gain in the active medium was performed using a known approach to the optical properties of a semiconductor laser first developed by Lasher and Stern. Optical gain is one of the most basic and important parameters that characterize the behavior of a semiconductor laser diode. The material gains are calculated for 300 K over a spectral range from 1.2 eV to 1.45 eV for the $In_{0.2}Ga_{0.8}As$/GaAs/GaAs QW laser diode with different carrier concentrations at $1\times10^{8} cm^{-3}$ and $2\times10^{18} cm^{-3}$. The radiation emitted from the laser diode consists of two polarization modes, i.e. transverse electric (TE) mode and transverse magnetic (TM) mode. The coefficients of gain for these two modes are compared in Figure 5.1(a) and (b) for these two particular different carrier concentrations, respectively.

The optical gain in the TE mode is much higher than that in the TM mode. This is due to the compressive strain induced in the QW region. The induced strain moves the edges of the valence bands. The top valence bands are pulled farther apart. This in turn extends the energy separation between the vh-band and the lh-band and vs-band increases. This means that a larger density of holes can be accommodated in the top band alone before the next band is also populated, resulting the number of holes transit from lh-band and vs-band to conduction band decreases. Since the TM mode mainly depends on the hole transition among these bands, thus it is depressed in a strained QW layer. However, TE mode is significantly enhanced as the top heavy valence band is increasingly populated by holes. Thus the optical output is mainly contributed by TE mode. The gain is polarization dependent and is controlled by strain in the QW layer. The performance of semiconductor lasers has been improved substantially by using strained quantum wells.

The following simulation events are calculations of the optical gain as functions of the level of injection that are measured in carrier concentration related to the width of the strained quantum layer. The gain spectrums in TE mode and TM mode at variety of net carrier concentration corresponding to 1, 2, 3, 4 and 5 in 10^{18} cm^{-3} units are shown in Figure 5.2(a) and (b), respectively. Positive gains appear at the concentrations above the inversion threshold and the material gains exceed 2500 cm^{-1} for TE mode and 800 cm^{-1}. The gain discussed here is called the material gain and comes only from the active region where the recombination is occurring. The maximum gain is apparently increased in both

(a)



(b)

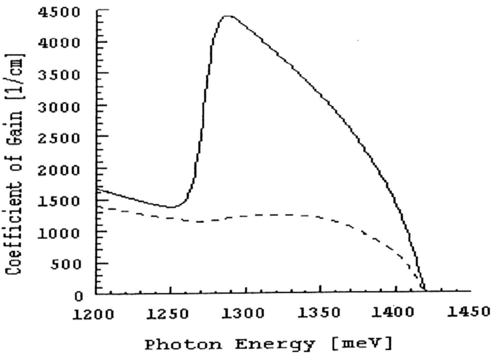
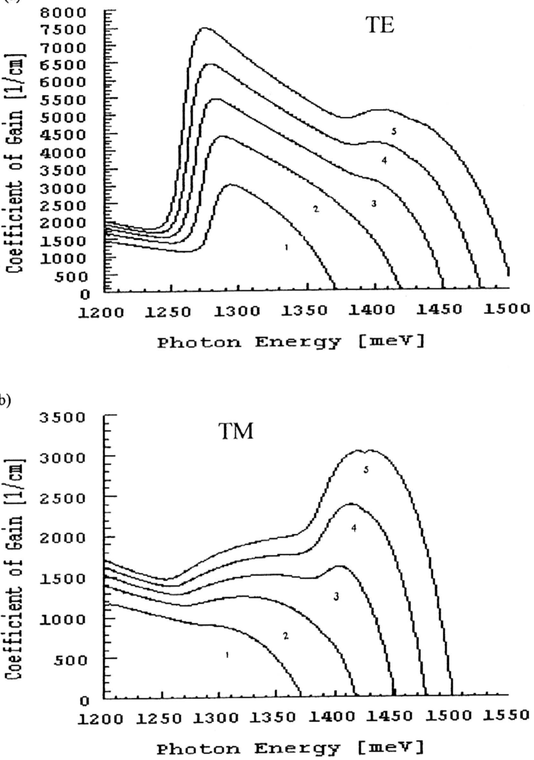


Figure 5.1 *Optical gain spectra at $T = 300\ K$ for* the $In_{0.2}Ga_{0.8}As/GaAs/GaAs$ 980 nm QW laser diode at carrier concentrations
(a) $N = 1\times10^{18}\ cm^{-3}$ (b) $N = 2\times10^{18}\ cm^{-3}$

(a)



(b)

Figure 5.2 *The $In_{0.2}Ga_{0.8}As/GaAs/GaAs$ strained quantum well optical gain spectrum in (a) TE mode and (b) TM mode versus the injected carrier concentration from 1 to 5 ($x10^{18}$) cm^{-3}*

the TE and TM modes when increasing the injected level of carrier concentration. This is due to when the injection level of carriers is increased, the occupation probabilities, f^e for bound electrons and f^h for bound holes in the quantum well layer increase, thus increasing the material gain. Figure 5.3 shows the relationship between the injected carrier (electron) concentrations and the 2D electron and hole concentrations in the quantum well at the photon wavelength measured at 980 nm. The linearly curves indicate the proportionality of these parameters.

In addition, the spectral evolution of the material gain in TE mode suggests that the injected carriers induce a longer wavelength shift in the maximum gain spectra. The physics behind this phenomenon is that the injected minority carriers induce band gap shrinkage of the electronic bands. This band gap shrinkage in QW is caused by the exchange-correlation interaction of free carriers. The conduction band edge is shifted up while the valence band edges are shifted down, causing an increase in the barrier height. The higher the concentrations of the free carriers, the larger the shift of the electronic bands is. This result in a decrease in the band gap energy and thus increasing the wavelength of the stimulated emission. The interconnection between the injected minority carrier (electron) concentration and the band gap energy is illustrated in Figure 5.4. The band gap energy can be considered decreasing linearly with the increasing injection level. This is consistent with the longer emission wavelength at higher injected carrier concentration. In view of this evolution, the maximum material gain and the emission wavelength are controllable through a variety of carrier injection levels.

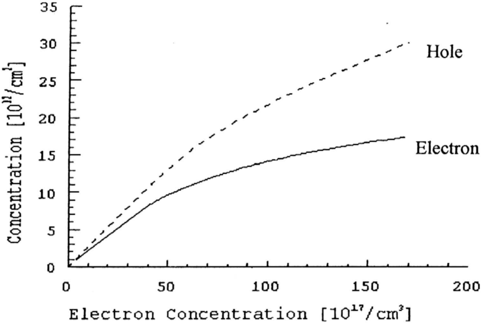


Figure 5.3 *Relationship between the injected carrier (electron) concentrations and the 2D QW electron and QW hole concentrations*

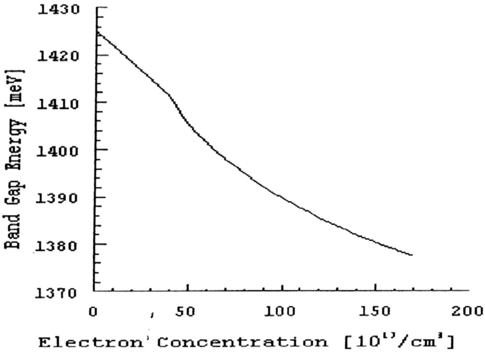


Figure 5.4 *The relationship between the injected minority carrier (electron) concentration and the band gap energy*

5.3 Strained and Unstrained Models

This simulation event is the comparison of optical properties between the strained quantum well design and the unstrained quantum well design. In $Ga_xIn_{1-x}As_yP_{1-y}$ material system for the quantum well, the induced strain is dependent on the mole fraction of Ga, x and As, y as expressed in equation (3.5.1). The default model consists of quantum well material $In_{0.2}Ga_{0.8}As$ with compressive strain 2.29%. The unstrained quantum well material is modified to be $In_{0.53}Ga_{0.47}As$ for x = 0.47 and y = 1 as calculated using equation (3.5.1). This is a practical example of unstrained material system which is lattice-matched to the substrate.

The graphical outputs of the optical gain in both TE mode and TM mode for these two designs are presented in Figure 5.5 (a) and (b), respectively. It is noticed that there is a substantial difference in the gain spectrum for TE mode between the strained and unstrained designs. The optical gain of the strained QW design is substantially enhanced in the TE mode. While in the TM mode, the difference is not apparent. This is due to the compressive strain induced in the QW region pulls the valence bands farther apart. This in turn extends the energy separation between the vh-band and the lh-band increases and a larger concentration of holes can be accommodated in the top heavy hole band alone before the next band is also populated. The increasing hole population in the heavy hole valence band results in the enhancement of the optical gain in TE mode and in turn lowers the injection level of carriers. Hence strain provides a powerful tool for the band structure engineering. The shifts of the band edges are incorporated as calculated in equations (3.6.13), (3.6.14) and (3.6.15).

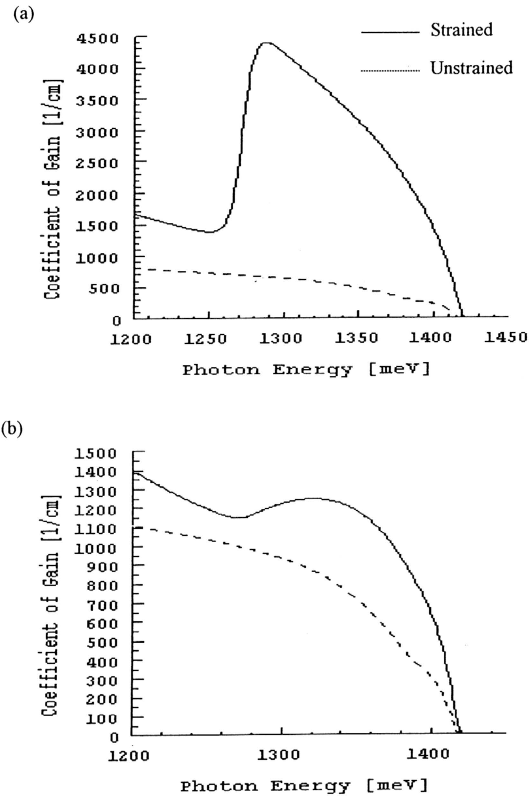


Figure 5.5 *The optical gain for the strained and unstrained quantum well designs in (a) TE mode (b) TM mode*

5.4 Mode Gain Characteristics

The material gain described above has to be used for the calculation of the mode gain, i.e. the amplification coefficient of the confined wave in the two dimensional (2D) optical structure of the laser. The mode gain is determined as twice the value of the imaginary part of the propagation constant of the guided fundamental mode. Figure 5.6 displays a propagation constant spectrum which is equivalent to the mode gain spectrum (twice the value of the propagation constant) at the carrier injection level of 2 (10^{18}) cm^{-3}. The mode gain is caused by the material gain of the active medium i.e. strained quantum well layer which occupies only a part of the mode volume. Since the absorbing mediums i.e. the doped cladding layers are included into the mode volume too, the mode gain is smaller than the material gain. In this case, the mode gain is only 200 cm^{-1} compared to the 4300 cm^{-1} in the material gain. The mode gain in the spectral peak appears to be the laser emission photon energy. This spectral distribution of the gain depends on waveguide propagation in a horizontal direction along the multi-layer structure particularly on the active layer i.e. the strained quantum well layer. From the spectra of the material gain and mode gain, it was found that the spectral positions of peak of these two parameters do not coincide. Hence considering the material gain alone is not sufficient to characterize the spectral properties of the laser diode.

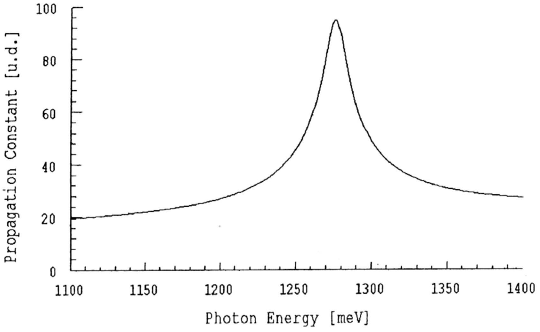


Figure 5.6 *Propagation Constant spectrum at the carrier injection level of 2×10^{18} cm^{-3}*

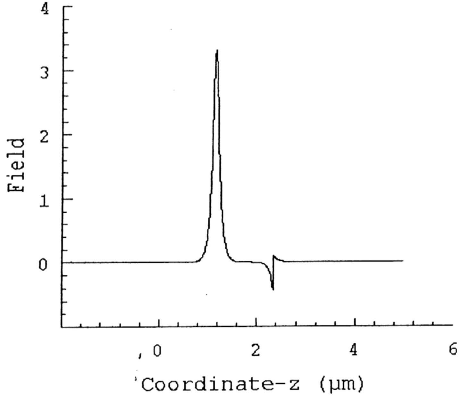


Figure 5.7 *The distribution of the scalar field over the multi-layer structure of the laser diode at carrier concentration of 2×10^{18} cm^{-3}*

5.5 Field Distribution

In this part, the distribution of the scalar field as calculated in equation (2.3.6) over the multi-layer structure of the laser diode is presented in Figure 5.7. This field distribution corresponds to TE_0-mode of the laser's waveguide and photon energy equal to 1.265 eV (wavelength 980 nm). The coordinates represent distance in the growth direction of the epitaxial structure, z-direction. They are measured in microns from the top of the substrate which is set with $z = 0\ \mu m$. From the graph presented, the peak of the field occur at $z = 1.3\ \mu m$ which corresponds to the active strained quantum well layer in the laser diode. In practice, this means that other layers (i.e. the cladding layers, substrate and cap layer) are either having low optical gain or their overlaps with a guide mode are small. This indicates that the strained quantum well layer acts as an optical cavity that the optical wave are confined in this region which dominates the stimulated emission process.

5.6 Threshold Current Density

The threshold current density, J_{th} of $In_{0.2}Ga_{0.8}As/GaAs$ QW laser is estimated by plotting the maximum optical gain of TE mode as a function of the radiative current density, J_{rad} calculated using equation (2.2.10). The total radiative lifetime, τ_r of $In_{0.2}Ga_{0.8}As$ is approximated to be 30 ns. The carrier densities in the active region for different carrier injection concentrations are tabulated in Table 5.1.

Injected Carrier Concentration ($1/cm^3$)	Carrier Concentration in Active Region ($1/cm^3$)
1×10^{18}	$63.64\ 0 \times 10^{17}$
2×10^{18}	81.525×10^{17}
3×10^{18}	96.895×10^{17}
4×10^{18}	111.401×10^{17}
5×10^{18}	125.657×10^{17}

Table 5.1 *The carrier densities in the active region for different carrier injection concentrations*

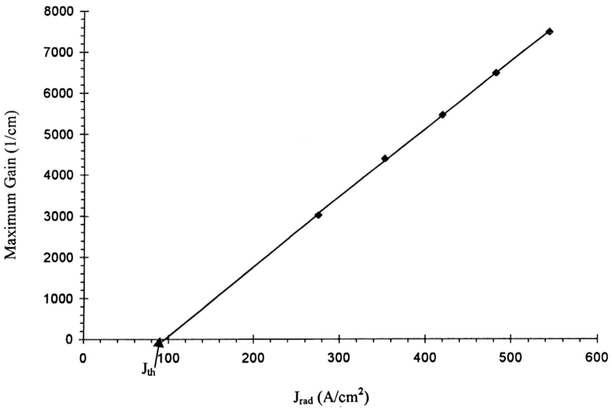


Figure 5.8 *The maximum optical gain of TE mode versus* the radiative current density, J_{rad}

In figure 5.8, a best fitting solid line is drawn and extended to the J_{rad} axis where the threshold current density can be determined from the crossing point between the line and the axis. A threshold current density of 90 A/cm^2 is obtained. The lowest threshold current densities reported to date are about 150 A/cm^2 for long-wavelength emission and 100 A/cm^2 for visible and near-infrared emission[27]. The value obtained here is very near to and even lower than the up-to-date best experimental result of 100 A/cm^2. The design of quantum well laser has enabled a decrease in the threshold current density of injection lasers reaching extremely low values of less than 50 A/cm^2 [28]. This indicates that further improvement of the threshold current density can be achieved in the semiconductor QW laser.

5.7 Summary

In this chapter, we have generated the generated the simulation results using the theoretical calculation in Chapter 2 and Chapter 3. The simulation results include the comparison of optical gain between the TE mode and TM mode, the material gain over a specified spectral range of photon energy using the carrier concentration as a parameter, the mode gain characteristics, the role of strain in quantum well and the field distribution across the direction of the epitaxial growth of heterostructure.

The results show that the optical output is mainly contributed by TE polarization since the TM is depressed in a compressive strained QW layer. The gain is polarization dependent, controlled by strain in the quantum well layer.

The concentration of injected carriers modified the optical gain spectrum. These minority carriers increase the peak material gain while all the rest of simulation parameters remain unchanged. On the other hand, the injected carriers also shifted the peak material gain to a longer emission wavelength.

The compressive strain induced in quantum well results in the enhancement of the optical gain in TE mode and in turn lowers the injection level of carriers.

The mode gain spectrum was also obtained from the propagation constant under a waveguide propagation in a horizontal direction along the multi-layer structure. The mode gain includes the absorption from layers other than the active quantum well layer too. Thus its value is lower than that of material gain and it is a more adequate parameter to characterize the spectral properties of the laser diode.

The field distribution across the direction of the epitaxial growth of heterostructure shows that the peak of the field occur in the active strained quantum well layer in the laser diode. The strained quantum well layer creates an optical cavity that guide the optical wave generated in this region that participates in the stimulated emission process.

A threshold current density of 90 A/cm^2 is predicted for this QW laser. The result shows that further improvement of the threshold current density can be achieved in the semiconductor QW laser.