STRAINED QUANTUM WELL HETEROSTRUCTURE: MODELING AND SIMULATION OF 980 nm LASER

HUNG YEW MUN

SUBMISSION OF DISSERTATION FOR THE PARTIAL FULFILLMENT OF MASTERS OF TECHNOLOGY (MATERIALS SCIENCE)

INSTITUTE OF POSTGRADUATE STUDIES UNIVERSITY OF MALAYA KUALA LUMPUR FEBRUARY 2002
ABSTRACT

This thesis concerns the study of a strained quantum well laser diode emitting at wavelength of about 980 nm which is suitable for pumping $\text{Er}^{3+}$ doped fiber amplifiers. The concept of a strained quantum well in the design of the active medium of the laser diode is discussed. A model is proposed that incorporates features of the physical structural factors and characteristics of the structure. The theoretical background linked directly to the simulation of the model is to provide calculations and derivations of the optical properties of the modeled structure. Theoretical calculations were made taking into account the variation of the optical gain due to the influence of the level of the carrier concentration and strain induced in the quantum well active medium. Based on the simulation, an analysis of the characteristics of the simulated model was performed and comprehensive description of the characteristics due to the structural behavior given. Within the spectral range of 1.20-1.40 eV (wavelength 886 – 1034 nm), the results are reasonable and consistent with the basic principles employed in the optical properties of quantum well lasers and will be useful for designing optimized strained quantum well lasers.
ABSTRAK

ACKNOWLEDGEMENT

I would like to express my indebtedness and appreciation to my supervisor, Professor Dr. Muhamad. Rasat Muhamad, for his continuing interest, guidance, supervision and encouragement in this endeavour. Many thanks to Mr. Mohd. Sharizal and Ms. Lim Chui Huah for their interest and many valuable suggestions. I also thank the staff in the Laboratory of Solid State in Physics Department, University of Malaya, who had been so helpful and cooperative. I am very grateful to my family for its forbearance and encouragement. Last but not leastt, I would like to express my sincere thanks to those who have contributed to this project in one way or another.
# CONTENTS

*Abstract*  
ii

*Abstrak*  
iii

*Acknowledgement*  
iv

*Contents*  
v

*List of Figures*  
vii

*List of Tables*  
ix

## 1 INTRODUCTION

1.1 Fiber Communication  
1

1.2 Erbium Doped Fiber Amplifiers (EDFAs)  
3

1.3 The Most Efficient Pump Light Source – 980 nm  
4

1.4 Summary  
7

## 2 THEORETICAL BACKGROUND

2.1 Basic Principles and Scope  
8

2.2 Complex Permittivity  
10

2.3 Transfer Matrix Method (TMM)  
13

2.4 The Rate of Stimulated Transitions  
17

2.5 The Kane Model  
19

2.5.1 Distribution Functions  
22

2.5.2 Direct Interband Transitions  
23

2.5.3 Indirect Intraband Transitions  
25

2.5.4 Many-Body and Collective Effects  
27

2.6 Summary  
29

## 3 QUANTUM WELL LASERS

3.1 Introduction  
30

3.2 Quantum Well Layer  
31
4 LASER DIODE MODEL AND COMPUTATIONAL TECHNIQUES

4.1 Simulation

4.2 980 nm Laser Diode Model

4.3 Computational Techniques

4.3.1 Simulation Conditions

4.3.2 Model Computations

5 RESULT AND DISCUSSIONS

5.1 Interpretation of Simulation Results

5.2 Material Gain Characteristics

5.3 Strained and Unstrained Models

5.4 Mode Gain Characteristics

5.5 Field Distribution

5.6 Threshold Current Density

5.6 Summary

6 CONCLUSIONS

Appendix A – Material Constants

Appendix B – Material Constants

Bibliography
LIST OF FIGURES

Figure 1.1  Schematic Optical Transmission  2
Figure 1.2  Erbium Doped Optical Fiber Amplifier  4
Figure 1.3  Energy Level States of Erbium  6
Figure 2.1  Schematic vertical structure of the injected semiconductor Laser diode  9
Figure 2.2  TE and TM polarization of the semiconductor laser diode  14
Figure 2.3  Schematic band structure of direct gap III-V semiconductor  21
Figure 3.1  Energy band diagramme of a nominal quantum well  31
Figure 3.2  Growth of InGaAs on GaAs substrate  35
Figure 3.3  Effect of strain on the bands of a semiconductor, showing the splitting of valence band  36
Figure 4.1  Schematic structure of In$_{0.2}$Ga$_{0.8}$As/GaAs/GaAs 980 nm QW laser diode  45
Figure 5.1(a) Optical gain spectra at $T = 300$ K for the In$_{0.2}$Ga$_{0.8}$As/GaAs/GaAs 980 nm QW diode at $1 \times 10^{18}$ cm$^{-3}$  52
Figure 5.1(b) Optical gain spectra at $T = 300$ K for the In$_{0.2}$Ga$_{0.8}$As/GaAs/GaAs 980 nm QW diode at $1 \times 10^{18}$ cm$^{-3}$  52
Figure 5.2(a) The In$_{0.2}$Ga$_{0.8}$As/GaAs/GaAs strained quantum well optical gain spectrum in TE mode versus the injected carrier concentration From 1 to 5 ($x 10^{18}$) cm$^{-3}$  53
Figure 5.2(b) The In$_{0.2}$Ga$_{0.8}$As/GaAs/GaAs strained quantum well optical gain spectrum in TM mode versus the injected carrier concentration From 1 to 5 ($x 10^{18}$) cm$^{-3}$  53
Figure 5.3  Relationship between the injected carrier (electron) concentrations and the 2D QW electron and QW hole concentrations  55
Figure 5.4  The relationship between the injected minority carrier (electron) concentration and the band gap energy 55

Figure 5.5(a)  The optical gain for the strained and unstrained quantum well designs in TE mode 57

Figure 5.5(b)  The optical gain for the strained and unstrained quantum well designs in TM mode 57

Figure 5.6  Propagation Constant spectrum at the carrier injection level of $2 \times 10^{18}$ cm$^{-3}$ 59

Figure 5.7  The distribution of the scalar field over the multi-layer structure of the laser diode at carrier concentration of $2 \times 10^{18}$ cm$^{-3}$ 59

Figure 5.8  The maximum optical gain of TE mode versus the radiative Current density, $J_{rad}$ 61
**LIST OF TABLES**

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table 2.1</td>
<td>Propagation constant in z-direction and electromagnetic field</td>
<td>15</td>
</tr>
<tr>
<td>Table 2.2</td>
<td>Characteristic cross-sections of the phonon assistant indirect intraband transitions</td>
<td>26</td>
</tr>
<tr>
<td>Table 4.1</td>
<td>Composition and layer thickness of In$<em>{0.2}$Ga$</em>{0.8}$As/GaAs/GaAs 980 nm QW structure</td>
<td>46</td>
</tr>
<tr>
<td>Table 5.1</td>
<td>The carrier densities in the active region for different carrier injection concentrations</td>
<td>61</td>
</tr>
<tr>
<td>Table A</td>
<td>Material constants for Ga$<em>x$In$</em>{1-x}$As$<em>y$P$</em>{1-y}$</td>
<td>66</td>
</tr>
<tr>
<td>Table B</td>
<td>Material constants for Al$<em>x$Ga$</em>{1-x}$As</td>
<td>67</td>
</tr>
</tbody>
</table>