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Study of Modulation Doping and Ridge Height Effects in InAs/GaAs Quantum Dot Lasers

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“Few people are successful unless a lot of other people want them to be.”

— Charles Brower

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Table of Contents

Statement of Originality	i
Acknowledgments	ii
Table of Contents	iii
Abstract	v
List of Figures	vi
List of Abbreviations	xi
Chapter 1 Introduction	1
1.1 Background	1
1.2 Motivation and Research Gaps	2
1.3 Objectives	6
1.4 Major Contributions of the Thesis	8
1.5 Publications	10
1.5.1 First Author Publications	10
1.5.2 Co-author Publications	11
1.6 Research Methodology	13
1.7 Overview of the Thesis	14
Chapter 2 Literature Review	15
2.1 Overview of QD Lasers	15
2.1.1 Quantum Mechanics in QD Lasers	15
2.1.2 Growth of QD Structures	18
2.1.3 Current State of QD lasers	22
2.2 Gain of QD Lasers	23
2.2.1 Stacked QD Structures	23
2.2.2 <i>p</i> -type Modulation Doping	25
2.2.3 Two-State Competition	30
2.2.4 Geometrical Effect	33
2.2.5 Self-Heating Effect	36
Chapter 3 Fabrication and Characterization	38
3.1 Fabrication Process	38
3.2 Pulsed Anodic Oxidation (PAO)	42
3.3 Characterization Tools	46
Chapter 4 Results and Discussion	48
4.1 <i>p</i> -type Modulation Doping Effect	48
4.1.1 Background	48
4.1.2 Objectives and Main Results	49
4.1.3 Basic Characterization	50
4.1.4 Theoretical Model of Modal Gain and Differential Gain	59
4.1.5 Results and Analysis of Modal Gain and Differential Gain	67
4.1.6 Summary	78

4.2	The p-Doping Effect on Two-State Lasing.....	79
4.2.1	Background.....	79
4.2.2	Objectives and Main Results	79
4.2.3	Experiments, Results, and Analysis.....	80
4.2.4	Summary.....	85
4.3	Geometrical Effect on QD Laser Gain	85
4.3.1	Background.....	85
4.3.2	Objectives and Main Results	86
4.3.3	Experiments, Results, and Analysis.....	86
4.3.4	Summary.....	97
4.4	The Self-Heating Effect in QD Lasers	97
4.4.1	Background.....	97
4.4.2	Objectives and Main Results	98
4.4.3	Experiments, Results, and Analysis.....	98
4.4.4	Summary.....	106
Chapter 5	Conclusions and Recommendations	107
5.1	Conclusions	107
5.2	Recommendations for Future Research	110
Bibliography		114

Abstract

Recently, the rapid development of the networks requires fast and stable laser sources. Since quantum dot (QD) lasers are expected to have low threshold current, high characteristic temperature, high material gain, and high differential gain over conventional quantum well (QW) lasers, they have been studied intensively. However, the actual performance of QD lasers has not achieved high speed advantage over QW lasers due to several factors such as the low density of QDs and the closely spaced energy states of the QD holes. Therefore, the use of multiple stacked QD layers and *p*-type modulation doping has been proposed to improve the gain properties and the temperature sensitivities of QD lasers.

In this thesis, we study the 1.3 μ m ten-layer InAs/InGaAs/GaAs quantum dot lasers with different doping concentrations. The main focus of the study is the modal gain characterization. The objective is to investigate the various factors affecting the laser modal gain and, hence, to suggest conditions for the laser growth and fabrication that will improve the QD laser performance. The temperature dependent modal gain of QD lasers with different doping levels was investigated for a better understanding regarding the *p*-type modulation doping effect. The modal gain of the lasers with different ridge heights was also measured to optimize the fabrication process. In addition, experiments conducted in the continuous wave and pulsed modes on the lasers with different doping densities help us to understand the doping effect on the device self-heating.

List of Figures

Figure 1.1	Road map of the research methodology used in this research study.	13
Figure 2.1	Diagrams of the density of states for semiconductor lasers with different structures: bulk, QW, and QD (from left to right).	16
Figure 2.2	Schematic diagram of the energy states in a QD. E_g is the bandgap energy. The GS and the ES lasing correspond to the ground-state and the excited-state lasing from the QD.	18
Figure 2.3	(a) A micrograph of the etching mask. (b) A micrograph of QDs [41].	19
Figure 2.4	(a) A schematic diagram of the fabrication process of selective growth. (b) A micrograph of the GaAs QDs [41].	20
Figure 2.5	(a) Top view and (b) cross-sectional view of self-assembled QDs[45].	22
Figure 2.6	TEM image of vertically coupled multiple stacked QD layers [19].	24
Figure 2.7	A graph of modal gain at threshold vs. threshold current density at room temperature for four laser structures with stacked QD layers (1, 3, 5, and 7 layers) [57].	25
Figure 2.8	A graph of calculated gain vs. injected electron number per QD for different numbers of built-in holes (N_a) and inhomogeneous linewidth ($\Delta\omega$) of 10meV and 30meV [20].	26
Figure 2.9	A graph of the calculated 3dB frequency response vs. square root of current density [20].	27
Figure 2.10	Peak modal gain plotted as a function of the drive current density at 300K for the undoped (circles), p -doped (15 acceptors/QD) (squares), and p -doped (50 acceptors/QD) (triangles) lasers [24].	29
Figure 2.11	Plots of the peak gain vs. the injection current density at (a) room temperature and at (b) 350K for the undoped and p -doped QD lasers [23].	30
Figure 2.12	A graph of the electroluminescence spectra on logarithmic scale of a 1.5mm-long InAs/GaAs QD laser at various injection current densities (J) [25].	31
Figure 2.13	The ratio of the ES and the GS threshold current as a function of temperature for as-grown 600°C annealed and 650°C annealed InAs/GaAs QD lasers with a cavity length of 1mm. The inset shows this ratio for as-grown and annealed devices with different cavity lengths [28].	32

Figure 2.14	A graph of the transparency threshold current density (J_{tr}) of InGaAs/GaAs lasers with ridge heights (h) of 0.39, 0.80, 1.23, 1.55, and 1.77 μm [34].	34
Figure 2.15	A graph and a diagram showing the temperature dependence of threshold current density (J_{th}) and external quantum efficiency (η_d) for device (A) a deep etched device and device (B) a shallow etched device [33].	35
Figure 2.16	A graph of the maximum output power at different duty cycles and oxide apertures for InAs/GaAs QD vertical cavity surface emitting lasers [66].	37
Figure 2.17	Plots of experimental and theoretical results of linewidth enhancement factors at different duty cycles for InAs/GaAs QD lasers [38].	37
Figure 3.1	(a) Schematic illustration of the 1.3 μm InAs/GaAs 10-layer QD laser structure. (b) TEM scan of the InAs QD active region. The scale bar is 100nm.	39
Figure 3.2	A flow chart of the fabrication process of the QD laser.	41
Figure 3.3	(a) SEM image of the top view of the laser device. The stripe width is about 4 μm as shown. (b) SEM image of the cross-sectional view of the laser device. The ridge height is about 1.5 μm .	41
Figure 3.4	Schematic diagram of the experimental setup for the pulsed anodic oxidation.	43
Figure 3.5	Diagram of typical waveforms displayed on the oscilloscope. Channel 1 (upper) monitors the input pulse signal and Channel 2 (lower) monitors the output voltages across the small impedance.	44
Figure 3.6	A diagram of the oscilloscope traces of the input and output signals across the small series resistor in the time domain.	45
Figure 3.7	Photographs of the laser testing equipment setup, which involved a laser parameter analyzer, a pulsed current source, a device testing holder, and an optical spectrum analyzer.	47
Figure 4.1	A graph of light output power vs. injection current density characteristics of the undoped, p -doped (8 acceptors/QD, and p -doped (16 acceptors/QD) InAs/GaAs QD lasers.	51
Figure 4.2	A graph of the emission spectra of the InAs/GaAs QD lasers with different doping densities (undoped, p -doped with 8 and 16 acceptors/QD) measured at $J = 1.1J_{th}$ at 20°C.	52
Figure 4.3	Graphs of the L - J characteristics of the undoped, p -doped (8 acceptors/QD), and p -doped (16 acceptors/QD) lasers ($4 \times 1500\mu\text{m}^2$) at the temperature range of 20°C-120°C.	53
Figure 4.4	A graph of the temperature dependent threshold current density (J_{th}) in a logarithm scale of the undoped, p -doped (8 acceptors/QD), and p -doped (16 acceptors/QD) lasers ($4 \times 1500\mu\text{m}^2$) in the temperature range of 20-120°C.	55

Figure 4.5	A graph of inverse external efficiency (η_d^{-1}) vs. cavity length (L) of the undoped, p -doped (8 acceptors/QD), and p -doped (16 acceptors/QD) lasers at room temperature.	56
Figure 4.6	Schematic diagram of the relaxation processes in a QD system with three discrete levels.	63
Figure 4.7	An energy band diagram of the InAs/GaAs QD structure [74].	64
Figure 4.8	A graph of the theoretical simulations of the modal gain profiles from 20°C to 120°C.	66
Figure 4.9	A graph of theoretical simulations of differential gain vs. injection current density from 20°C to 120°C.	67
Figure 4.10	A graph of the spectra of the amplified spontaneous emission (ASE) of the p -doped (16 acceptors/QD) laser measured at 20°C under an injection current of 30mA. (a) is a magnification of the FP resonances in the red rectangle in (b).	68
Figure 4.11	A graph of the net modal gain spectra of the p -doped (16 acceptors/QD) laser measured under an injection current from 25mA to 37mA at 20°C.	70
Figure 4.12	Plots of the peak net modal gain vs. the injection current density from 20°C to 120°C for the (a) undoped, (b) p -doped (8 acceptors/QD), and (c) p -doped (16 acceptors/QD) InAs/GaAs QD lasers.	71
Figure 4.13	Plots of the peak net modal gain vs. the injection current density at 20°C, 80°C and 120°C for the undoped laser (solid symbol), p -doped (8 acceptors/QD) laser (open symbol), and p -doped (16 acceptors/QD) laser (cross-open symbol).	73
Figure 4.14	Graphs of differential gain (dG/dJ) vs. injection current density from 20°C to 120°C for the (a) undoped, (b) p -doped (8 acceptors/QD), and (c) p -doped (16 acceptors/QD) InAs/GaAs QD lasers. The solid lines are guides to the eye.	74
Figure 4.15	A graph of the trends of differential gain as a function of injection current density for the undoped, p -doped (8 acceptors/QD), and p -doped (16 acceptors/QD) QD lasers.	76
Figure 4.16	Linewidth enhancement factors as a function of wavelength for the unoped, p -doped (8 acceptors/QD), and p -doped (16 acceptors/QD) lasers measured near threshold at 20°C.	78
Figure 4.17	A graph of the lasing spectra of the 1.3 μ m undoped InAs/GaAs QD laser at 20°C.	81
Figure 4.18	The peak net modal gain profiles for the undoped, p -doped (8 acceptors/QD), and p -doped (16 acceptors/QD) lasers measured around the ES lasing threshold at 20°C.	82
Figure 4.19	A graph of the ratio of ES and GS threshold current ($I_{th,ES}/I_{th,GS}$) as a function of temperature for the undoped, p -doped (8 acceptors/QD), and p -doped (16 acceptors/QD) lasers.	83

Figure 4.20	The logarithm of temperature dependent GS threshold current ($I_{th,GS}$) of the undoped, p -doped (8 acceptors/QD), and p -doped (16 acceptors/QD) lasers ($4 \times 1000 \mu\text{m}^2$) within the temperature range of 20°C - 120°C	84
Figure 4.21	Three cross-sectional SEM images of the InAs/GaAs QD lasers with different ridge heights (h) of $0.90 \mu\text{m}$, $1.36 \mu\text{m}$, and $1.75 \mu\text{m}$	87
Figure 4.22	A diagram of a simplified laser structure with different etching depths.	87
Figure 4.23	The light output power vs. injection current density for InAs/GaAs QD lasers with different ridge heights (h) of $0.90 \mu\text{m}$, $1.36 \mu\text{m}$, and $1.75 \mu\text{m}$	88
Figure 4.24	A graph of inverse external efficiency (η_d^{-1}) vs. cavity length (L) for InAs/GaAs QD lasers with the different ridge heights of $0.90 \mu\text{m}$ (triangles), $1.36 \mu\text{m}$ (squares), and $1.75 \mu\text{m}$ (circles).....	90
Figure 4.25	The logarithm of the threshold current density vs. temperature (from 20°C to 120°C) for the InAs/GaAs QD lasers with different ridge heights of $0.90 \mu\text{m}$ (triangles), $1.36 \mu\text{m}$ (squares), and $1.75 \mu\text{m}$ (circles). The solid lines are linear fittings to the data points of the three lasers over the same temperature range for easy comparison.	92
Figure 4.26	The calculated ratio of J_{eff} to J_{total} as a function of temperature for lasers with different ridge heights of $0.90 \mu\text{m}$, $1.36 \mu\text{m}$, and $1.75 \mu\text{m}$	95
Figure 4.27	Peak net modal gain vs. injection current density at 20°C (squares), 80°C (circles), and 120°C (triangles) for InAs/GaAs QD lasers with different ridge heights of $0.90 \mu\text{m}$ (cross-open symbols), $1.36 \mu\text{m}$ (solid symbols), and $1.75 \mu\text{m}$ (open symbols), respectively.....	96
Figure 4.28	A graph of the CW spectra of the p -doped (16 acceptors/QD) laser as a function of injection current from 40mA to 150mA at 20°C	99
Figure 4.29	The CW spectra of the p -doped (16 acceptors/QD) laser as a function of heat sink temperatures from 20°C to 100°C under constant injection current of 100mA	100
Figure 4.30	A graph of the emitted peak wavelength vs. the total heating power (P_{heat} in Equation (4.33)) for the undoped (squares), p -doped (8 acceptors/QD) (circles), and p -doped (16 acceptors/QD) (triangles) InAs/GaAs QD lasers.	101
Figure 4.31	A graph of the emitted peak wavelength vs. the heat sink temperature for the undoped (squares), p -doped (8 acceptors/QD) (circles), and p -doped (16 acceptors/QD) (triangles) InAs/GaAs QD lasers.	102

Figure 4.32	The threshold current density (J_{th}) vs. temperature (from 20°C to 120°C) for the undoped (squares), <i>p</i> -doped (8 acceptors/QD) (circles), and <i>p</i> -doped (16 acceptors/QD) (triangles) InAs/GaAs QD lasers measured in CW (solid symbols) and pulsed (open symbols) modes.....	103
Figure 4.33	Graphs of peak net modal gain vs. injection current density at 20°C (squares), 80°C (circles), and 120°C (triangles) for (a) undoped, (b) <i>p</i> -doped (8 acceptors/QD), and (c) <i>p</i> -doped (16 acceptors/QD) InAs/GaAs QD lasers measured in CW (solid symbols) and pulsed (open symbols) modes.....	105
Figure 5.1	Diagram of the energy band of a tunnelling injection QD laser [104].	111
Figure 5.2	Schematic drawing of the layout and electrical connection of a mode-locked QD laser [108].	112
Figure 5.3	Emission spectra of 1.5μm InAs–InP(113)B QD laser [110].	113

List of Abbreviations

1ES First Excited State

A

ASE Amplified Spontaneous Emission

C

CL Cap Layer

CW Continuous Wave

D

DI De-Ionized

DWELL Dot-in-a-Well

E

ES Excited State

F

FP Fabry-Perot

G

GS Ground State

I

IPA Isopropanol

L

L-I-V Light-Current-Voltage

L-J Light-Current Density

M

MBE	Molecular Beam Epitaxy
ML	Monolayer
MOCVD	Metal-Organic Chemical Vapor Deposition

O

OSA	Optical Spectrum Analyzer
-----	---------------------------

P

PAO	Pulsed Anodic Oxidation
-----	-------------------------

Q

QD	Quantum Dot
QW	Quantum Well

R

RT	Room Temperature
RWG	Ridge Waveguide

S

SEM	Scanning Electron Microscope
SK	Stranski-Krastanow

T

TEC	Thermoelectric Controller
TEM	Transmission Electron Microscopy

W

WL	Wetting Layer
----	---------------

Chapter 1 Introduction

1.1 Background

In 1917, Albert Einstein explained the concepts of absorption, spontaneous emission, and stimulated emissions in his paper “Zur Quantentheorie der Strahlung” (“On the Quantum Theory of Radiation”) with his famous Einstein’s Coefficients. Einstein’s Coefficients built the theoretical foundation for the invention of the laser. Almost half a century later, in 1960, Theodore Maiman discovered the first laser [1]. The word “laser” is the acronym of “Light Amplification by Stimulated Emission of Radiation” [2]. The semiconductor laser was realized simultaneously by several research groups in 1962 [3-6]. However, the first useful semiconductor lasers were demonstrated independently by two groups in 1970 [7, 8]. Ever since then, research and development on semiconductor lasers has never ceased and today, they are produced in volumes of 10s of millions/month and have not only revolutionized telecommunications and enabled the Internet, but are ubiquitous in many everyday consumer products like CD and DVD players and computer mice.

During the 1980s, the rapid development of material growth techniques offered great opportunities to the research of semiconductor lasers. First, the quantum well (QW) laser was realized [9-11]. Subsequently, quantum wire and quantum dot (QD) structures were experimentally studied [12-14]. Among the three quantum structures, the QD structure has the most advantages due to its three-dimensional

quantum confinement. The first QD laser was demonstrated at a low temperature in 1994 [15]. Since then, intensive studies have been conducted on QD lasers.

Today, semiconductor lasers have a wide range of applications such as optical fibre communications, optical memories, sensors, optical storage, printers, optical information processing, pumping sources, device processing, and medical inspection. This wide range of applications is due to the excellent properties of semiconductor lasers including their small size, high efficiency, high modulation speed, long-life, relatively low price, wide range of wavelengths, and low power consumption. Recently, the rapid development of the networks has required the use of fast and stable laser sources. Needless to say, QD semiconductor lasers are one of the best choices due to their unique properties such as their extremely low threshold current [16] and their temperature insensitivity over a wide range of temperature [17].

1.2 Motivation and Research Gaps

Since QD lasers are expected to have low threshold current, high characteristic temperature, high material gain, and high differential gain over conventional bulk and QW lasers, they have been widely studied. Among the various QD material systems, the InAs/GaAs QD material system attracts the most attention because the approximately 7% lattice mismatch between InAs and GaAs is suitable to implement the self-assembled QD growth technique. In addition, the emission wavelength of InAs/GaAs QD laser is around $1.3\mu\text{m}$, which is appropriate for short distance light transmission in the application of fibre-optics communications

due to the zero-dispersion in optical fibers [18]. However, several limitations hamper the performance of InAs/GaAs QD lasers.

First, the performance of 1.3 μm InAs/GaAs QD lasers is limited by their gain saturation due to the low dot density (on the order of $10^{10}/\text{cm}^2$). In order to enlarge their laser gain, the growth of stacked QD structures has been developed to increase the total density of the QDs [19].

Another limitation in the InAs/GaAs QD lasers is the closely spaced energy states of the QD valence band. Recent theoretical research [20] indicates that the introduction of *p*-type modulation doping in the active region of QD lasers can improve the modal gain, the modulation bandwidth, and the temperature sensitivity of the devices. In particular, temperature-insensitive 10Gbps direct modulation has been demonstrated in 1.3 μm *p*-doped InAs/GaAs QD lasers [21]. This makes the QD laser promising as a light source for future high-speed fibre-optics communication systems.

Motivated by the bright future of the InAs/GaAs QD lasers, we propose to study the gain characteristics of 1.3 μm 10-layer stacked InAs/GaAs QD lasers with different doping concentrations. Laser gain is the key parameter to determine the threshold current, the maximum light output power, and the modulation speed of a laser device. In this project, the main focus is on the modal gain characterization in QD lasers. The objective is to investigate the various factors affecting the laser modal gain and, hence, to provide an in-depth understanding of the performance of QD lasers.

Several research issues regarding the QD laser gain are worth investigating. First, the effect of p -type modulation doping on the QD laser gain is not clear. A theoretical study [20] conducted by Shchekin and Deppe showed clear improvements due to p -type modulation doping on the modal gain and the 3dB bandwidth of QD lasers. They reported that the improvements were mainly attributed to the large number of built-in excess holes in the QD active region, which saturated the energy levels in the valence band and reduced the thermal hole broadening. However, in the experimental studies, although p -doping improved the characteristic temperature [22] even to infinity [17], the improvement on the modal gain was not clearly demonstrated. At a low current injection, the p -doped QD laser showed either a smaller or a similar modal gain compared to the undoped laser. At high current injection, p -doped QD lasers have been shown to have higher modal gain than undoped lasers by some research groups [22, 23]. On the other hand, Sandall *et al.* [24] reported that undoped QD lasers have a larger modal gain than p -doped QD lasers at high current injection, which was attributed to excited-state lasing. Therefore, studying the p -doping effect to understand the reason for the inconsistency between the theory and experiments is merited. In addition, a lack of studies exists on the differential gain of QD lasers with different doping concentrations. Therefore, a study of the differential gain with different doping concentrations could provide an insight into the high speed modulation behaviour of QD lasers.

Second, the competition between the excited-state (ES) and the ground-state (GS) gain is an interesting topic. Recently, simultaneous two-state lasing [25-30] and even three-state lasing [31, 32] was demonstrated in QD lasers with a relatively

short cavity length (typically below 2mm) at high injection current. The simultaneous lasing from both the ES and the GS is attributed to the relatively long relaxation time between the two states, which is governed by the Pauli exclusion principle [25]. The presence of a higher carrier population in the GS causes a longer relaxation time from the ES into the GS. This leads to an accumulation of carriers in the ES and results in simultaneous two-state lasing. By further increasing the amount of injected carriers, the ES lasing will eventually surpass the GS lasing and reduce the GS modal gain. Therefore, an understanding of the two-state lasing behaviour in QD lasers is highly desired. In addition, the p -doping effect on the competition between the ES lasing and the GS lasing has not been reported.

Third, the p -doping effect on the QD laser performance has attracted intensive studies, but only a little effort has been put into the study of the geometrical effect on the QD laser performance [33]. In the laser fabrication process, the geometrical shape of the laser device mainly depends on the etching process, which is very critical to the laser's performance because it determines the current spreading profile and the laser waveguide in the device. Researchers have reported that the threshold current density and the transparency current density are dependent on the ridge height [33, 34]. However, the dependence of the QD laser gain properties on the laser ridge height remains undetermined. In addition, there is also a lack of study regarding the effect of the ridge height on the temperature sensitivity in QD lasers.

Fourth, a self-heating effect always exists in electronic devices. Previous studies

[35] have shown that the thermal conductivity of QD materials is about one order lower than that of the quantum well (QW) materials and it is two orders lower than that of the bulk materials due to the incoherent phonon scattering by the QDs. These findings imply that a more serious self-heating effect could be present in QD devices. However, only a few investigations on the self-heating effect in QD lasers have been reported [36-38] and none of them examined the self-heating effect on the modal gain of QD lasers with different doping levels. Therefore, a study of the modal gain measured in different operating modes (continuous wave or pulsed) will help to identify how self-heating affects the laser gain and how p -doping affects the self-heating in the device.

1.3 Objectives

In view of these research gaps in the InAs/GaAs QD laser studies, the objectives of this project are to:

- Experimental investigation and analysis of the p -type modulation doping effect on the gain characteristics of 1.3 μm 10-layer stacked InAs/GaAs QD lasers, including both the GS and the ES gain and the competition between them.
 - Conduct a literature review on the concepts of p -type modulation doping effect in QD lasers.
 - Based on the theoretical understanding, establish a self-consistent model to analyze the modal gain and differential gain of QD lasers.
 - Experimentally fabricate and characterize QD lasers with different

- doping concentrations.
 - Analyze the experimental observations of the doping effect in QD lasers based on the theoretical model.
 - Suggest the optimum doping concentration for the InAs/GaAs QD lasers.
- Experimental investigation and analysis of the geometrical effect in 1.3 μ m 10-layer stacked InAs/GaAs QD lasers.
- Conduct a literature review on the concepts of the geometrical effect in QD lasers.
 - Experimentally fabricate and characterize QD lasers with different ridge heights controlled by the etching time.
 - Analyze the experimental observations of the geometrical effect in QD lasers with the assistance of a theoretical model of temperature dependent current spreading.
 - Suggest the optimum etching depth for fabricating QD lasers.
- Experimental investigation and analysis of the self-heating effect in 1.3 μ m 10-layer stacked InAs/GaAs QD lasers with different doping concentrations.
- Conduct a literature review on the concepts of self-heating effect in QD lasers.
 - Experimentally characterize QD lasers with different doping concentrations operating in continuous wave and pulsed modes.
 - Analyze the self-heating effect in QD lasers by comparing the performance of the devices operating in different modes with the

assistance of device thermal resistances.

- Suggest the optimum doping concentration to suppress the self-heating effect in QD lasers.

1.4 Major Contributions of the Thesis

This section describes the significant contributions of this project. According to the objectives of this project, this research study is divided into three main parts. Each part involves both theoretical and experimental investigations. Regarding the *p*-type modulation doping effect in QD lasers, we first studied the temperature dependent threshold current density, the modal gain, and the differential gain of the devices with different doping concentrations. The results show that, compared to the undoped QD laser, the laser with the doping concentration of 8 acceptors/QD had a lower threshold current density and better temperature stability due to the interaction between increased internal loss and improved carrier confinement induced by *p*-doping. Notably, the *p*-doped QD lasers showed larger differential gain compared to the undoped devices, implying that *p*-doping can enhance the high speed modulation performance in QD lasers.

For the *p*-doped laser with a high doping density of 16 acceptors/QD, it showed temperature-insensitive behaviour at the temperature range of 20°C to 80°C. However, this laser had a significantly larger threshold current density and the improvement in the differential gain of the device was quite limited due to the side effects of *p*-doping. The results indicated that an optimum condition could be achieved in QD lasers by carefully choosing the *p*-doping density. In this study,

compared to the undoped QD laser, the device with a doping concentration of about 8 acceptors/QD could provide larger modal gain and differential gain coupled with a low threshold current and a relatively large characteristic temperature value. In addition to the p -doping effect in the GS gain of QD lasers, we also investigated the GS and ES gain competition in the QD devices with different doping densities. Our results indicated that the ES lasing could be suppressed in QD lasers with p -type modulation doping. Compared to the undoped QD laser, the device with a doping density of 8 acceptors/QD could mostly suppress the ES lasing with a lower GS threshold current.

Next, regarding the geometrical effect in QD lasers, we studied the temperature dependent threshold current density and the modal gain of QD lasers with different ridge heights, which was defined by different etching depth. The results show that QD lasers with ridge heights corresponding to their etching surfaces located right above the laser active region have lower threshold currents and larger characteristic temperatures due to the suppression of lateral carrier spreading and their moderate sidewall area, which limits the interface recombination. Comparison of the net modal gain profiles of the lasers with different ridge heights further proved that the laser with the ridge height corresponding to the etching surface located right above the laser active region had the best temperature stability. Overall, the results suggested that an optimum ridge height corresponding to the etched surface located right above the active region could reduce the threshold current and improve the laser modal gain and temperature sensitivity, which is important for achieving high performance QD lasers.

Finally, we studied the self-heating effect on the threshold current density and modal gain of QD lasers with different doping densities. The results show that a QD laser with a doping density of 8 acceptors/QD exhibited a weaker self-heating effect compared to the undoped laser due to their lower threshold current and thermal resistance. Further increasing the doping density to 16 acceptors/QD will lead to an infinite or even negative characteristic temperature, which will significantly reduce the self-heating effect. However, the drawback in this device was its large threshold current. The results indicated that a light p -doping density of around 8 acceptors/QD in a QD laser could suppress the self-heating effect to achieve the same modal gain as the undoped laser with a low injection current. This may provide good guidance to future studies on arresting the self-heating effect in QD lasers.

1.5 Publications

The contributions discussed in the previous section were published in the following papers.

1.5.1 First Author Publications

1. R. Wang, S. F. Yoon, H. X. Zhao, and C. Y. Liu, "Self-Heating Effect on Modal Gain of 1.3 μ m InAs/GaAs QD Lasers with Different p -Doping Levels," *IEEE Photonics Journal*, vol. 3, no. 4, pp. 713-717, Aug 2011.
2. R. Wang, S. F. Yoon, H. X. Zhao, and C. Y. Ngo, "Geometrical Effects on Characteristic Temperature and Modal Gain of InAs/GaAs Quantum Dot Lasers," *IEEE Photonics Technol. Lett.*, vol. 23, no. 13, pp. 863-865, Jul 2011.

3. R. Wang, S. F. Yoon, H. X. Zhao, C. Z. Tong, C. Y. Liu, and a. Q. Cao, "Doping effect on two-state lasing in 1.3 μ m InAs/GaAs quantum dot lasers," in *22nd IEEE International Semiconductor Laser Conference (ISLC)*, Kyoto, Japan, pp. 73-74, Sep 2010.
4. R. Wang, S. F. Yoon, H. X. Zhao, C. Z. Tong, C. Y. Liu, and Q. Cao, "Temperature Dependent Study on Modal Gain and Differential Gain of 1.3 μ m InAs/GaAs QD Lasers with Different p -Doping Levels," *IEEE Photonics Technol. Lett.*, vol. 22, no. 14, pp. 1045-1047, Jul 2010.
5. R. Wang, C. Z. Tong, S. F. Yoon, C. Y. Liu, H. X. Zhao, and Q. Cao, "Temperature Characteristics of Gain Profiles in 1.3 μ m p -doped and Undoped InAs/GaAs Quantum Dot Lasers," *IEEE Electron. Device Lett.*, vol. 30, no. 12, pp. 1311-1313, Dec 2009.

1.5.2 Co-author Publications

6. H. X. Zhao, S. F. Yoon, C. Y. Ngo, and R. Wang, "Improved Ground State Characteristics of 1.3 μ m InAs/GaAs Quantum Dot Lasers by Optimum Rapid Thermal Annealing," in *38th International Symposium on Compound Semiconductors (ISCS)*, Berlin, Germany, May 2011.
7. H. X. Zhao, S. F. Yoon, C. Y. Ngo, and R. Wang, "Improved Ground-state Modulation Characteristics in 1.3 μ m InAs/GaAs Quantum Dot Lasers by Rapid Thermal Annealing," *Nanoscale Res. Lett.*, vol. 6, art. no. 382, May 2011.
8. H. X. Zhao, S. F. Yoon, C. Y. Ngo, R. Wang, Q. Cao, and C. Y. Liu, "Effects of Annealing and p -doping on the Two-state Competition in 1.3 μ m InAs/GaAs Quantum Dot Lasers," *IEEE Trans. Nanotechnol.*, vol. 10, no. 6, pp. 1211-1213, Mar 2011.
9. H. X. Zhao, S. F. Yoon, C. Z. Tong, C. Y. Liu, R. Wang, and Q. Cao, "Thermal Effects and Small Signal Modulation of 1.3 μ m InAs/GaAs Self-Assembled Quantum-Dot Lasers," *Nanoscale Res. Lett.*, vol. 6, art. no. 37, Dec 2010.

10. C. Y. Ngo, S. F. Yoon, S. Y. Lee, H. X. Zhao, R. Wang, D. R. Lim, Vincent Wong, and S. J. Chua, "Electroabsorption Characteristics of Single-Mode 1.3 μ m InAs–InGaAs–GaAs Ten-Layer Quantum-Dot Waveguide," *IEEE Photonics Technol. Lett.*, vol. 22, no. 23, pp. 1717-1719, Dec 2010.
11. H. X. Zhao, S. F. Yoon, C. Y. Ngo, R. Wang, C. Z. Tong, C. Y. Liu, and Q. Cao, "Effects of thermal annealing on the dynamic characteristics of InAs/GaAs quantum dot lasers," *IEEE Photonics Journal*, vol. 2, no. 4, pp. 630-635, Aug 2010.
12. Q. Cao, S. F. Yoon, C. Z. Tong, C. Y. Ngo, C. Y. Liu, R. Wang, and H. X. Zhao, "Two-state competition in 1.3 μ m multilayer InAs/InGaAs quantum dot lasers," *Appl. Phys. Lett.*, vol. 95, no. 19, pp. 191101, Nov 2009.
13. H. X. Zhao, R. Wang, Q. Cao, C. Y. Liu, C. Z. Tong, M. L. Nai, J. Wei, and S. F. Yoon, "Quantum Dot Laser Diodes with Native Oxide Injection Current Confinement: Static and Dynamic Properties," *International Conference on Materials for Advanced Technologies, Symposium O – Compound Semiconductor Photonics: Materials, Devices and Integration*, O-S11.59(P) A01953-04208, July 2009, Singapore.
14. C. Y. Liu, S. F. Yoon, R. Wang, Q. Cao, and H. X. Zhao, "Comparison of Optical Properties from GaAs-based 1.3 μ m InAs Quantum Dot Lasers and InGaAsN quantum Well Lasers," *International Conference on Materials for Advanced Technologies, Symposium O – Compound Semiconductor Photonics: Materials, Devices and Integration*, O-S11.11(P) A00275-00745, July 2009, Singapore.
15. C. Y. Liu, S. F. Yoon, R. Wang, Q. Cao, and H. X. Zhao, "Designing Distributed Bragg Reflectors for Short-Cavity Edge Emitting Quantum Dot Lasers by Transfer Matrix Method and FDTD," *International Conference on Materials for Advanced Technologies, Symposium O – Compound Semiconductor Photonics: Materials, Devices and Integration*, O-S11.10(P) A00275-00738, July 2009, Singapore.

1.6 Research Methodology

In this project, both experimental and theoretical studies are involved. Theoretical models explain the physics and provide guidance to the design of experiments, whereas experimental measurements feed the practical results back to justify the models. The road map of the research methodology is shown in Figure 1.1.

Figure 1.1 Road map of the research methodology used in this research study.

1.7 Overview of the Thesis

In this thesis, Chapter 1 described the potential applications of QD lasers, the motivation for conducting this project, and the research gaps in the particular research field. The main objectives, contributions, publications, and research methodology of this project were also stated in Chapter 1.

In Chapter 2, a theoretical review on QD physics and growth is stated. The various factors affecting the QD laser gain, including multiple stacked QD structures, *p*-type modulation doping, geometrical shapes, and self-heating, are also reviewed in this chapter.

The device structures, fabrication process, and experimental setups are presented in Chapter 3. The experimental results and theoretical models are discussed in Chapter 4. The last chapter, Chapter 5, concludes the thesis and provides recommendations for future research.

Chapter 2 Literature Review

In this chapter, the basic theory of the quantum dot laser is reviewed first. Second, the chapter contains descriptions of the various growth techniques used so far. Third, a review of recent literature on the gain properties of QD lasers is provided.

2.1 Overview of QD Lasers

2.1.1 Quantum Mechanics in QD Lasers

In a laser device, the most important characteristic is coherent light emission. This light can be achieved by confining the electron-hole pairs in a narrow energy spectrum through size quantization. According to the fundamental laws of quantum physics, the quantized dimensions should be comparable to the de Broglie wavelength, which is on the order of a nanometre scale. As shown in Figure 2.1, the quantized structures increase the density of the states for the charge carriers near the band edges.

Figure 2.1 Diagrams of the density of states for semiconductor lasers with different structures: bulk, QW, and QD (from left to right).

For a bulk laser, the density of states is a parabolic curve as a function of energy. At a low temperature, the injected electrons fill all of the available states but, as the temperature increases, the carriers begin to spread to higher energy states according to the Fermi-Dirac distribution. In order to satisfy the lasing condition, a number of states must be filled before achieving the ground-state population inversion. Therefore, high threshold currents are required in a bulk semiconductor laser.

In addition, as the temperature increases, an even higher threshold current is required to maintain a constant Fermi level, which implies that a bulk laser is very temperature sensitive. In a QW laser, the density of states is a step function that is dependent on the energy. If a high concentration of injected carriers has the same stepped energy, population inversion can be achieved at an earlier stage with a lower threshold current. However, because of the nature of two-dimensional quantization in QW, it makes QW lasers very temperature sensitive. Therefore, in

some applications, maintaining a constant output power requires a complicated and expensive circuitry.

In QD lasers, the laser active regions are formed by small enough volume of material to approach atom-like behaviours. In a QD structure, the carriers are confined in three dimensions and the parabolic density of states in bulk lasers or the step-like density of states in QW lasers change to a Dirac delta function in QD lasers as shown in Figure 2.1. Due to the smaller physical volume of the active region and reduced density of states, a reduction in the threshold current density can be expected in QD structures. The discrete density of states in QD lasers lead to an easier population inversion, because fewer carriers are needed to invert the carrier population, which results in a significantly lower threshold current density and high quantum efficiency in QD lasers. In addition, the carriers are confined in a very narrow energy state, theoretically in a single energy state. If the separation of these energy states in the dot is greater than $\sim 3k_B T$, the carriers are no longer thermally excited into the higher energy levels and the laser threshold could be temperature insensitive [39]. Due to the increase in the quantization dimension and decrease of density of states, the material gain and differential gain of QDs also increases, which will lead to potentially high modulation speed or large bandwidth in telecommunication applications.

A typical energy state diagram of the QD is shown in Figure 2.2. An optical transition between the two energy states labelled E_0 involves the recombination of an electron and a hole occupying the ground state (GS). At high injections, optical transitions between the first excited states (ES) (labelled E_1) are possible. In

realistic applications, one would normally prefer to avoid the ES lasing and achieve the GS lasing only in the laser diode because the GS lasing has a lower threshold current and it generates light at the desired wavelength.

Figure 2.2 Schematic diagram of the energy states in a QD. E_g is the bandgap energy. The GS and the ES lasing correspond to the ground-state and the excited-state lasing from the QD.

2.1.2 Growth of QD Structures

In the 1980s, researchers first theoretically predicted that the three-dimensional charge confinement in the laser active region could improve the characteristic temperature [12] and the material gain [14]. Since then, numerous techniques have been employed to create QDs in semiconductor materials. As stated in the previous section, the quantized dimensions should be in the range of the de Broglie wavelength, which is very challenging to implement. In addition, since the QD is used in the active region of the laser, it should be comprised of a very high quality,

defect-free material.

Several techniques were introduced to manufacture QDs. The earliest method of manufacturing QDs involved employing lithographical etching [40]. In this method, a sample containing one or more QWs is prepared. Following patterning and etching, QDs (or quantum boxes) in a square-shape are formed. In this way, the motion of electrons, which is initially confined in the plane of the QW, is further restricted to a small square-shaped QD with a diameter on the scale of 10-100 nm. Since the simplicity of the production of thin QWs, GaAs is the most commonly used material for creating QDs by the means of etching. Figure 2.3 presents a photograph of the real dots obtained using this method [41].

Figure 2.3 (a) A micrograph of the etching mask. (b) A micrograph of QDs [41].

The second method is the selective growth of a semiconducting compound with a narrower bandgap (e.g. GaAs) on the surface of another compound with a wider bandgap (e.g. AlGaAs) [42]. The restriction of the growth to chosen areas is obtained by covering the surface of the sample with a mask (SiO_2) and by etching miniature triangles on it. On the surface not covered by the mask, the growth is carried out using the metal-organic chemical vapour deposition (MOCVD) method at a temperature of 700°C - 800°C . The crystals that are created have the shape of tetrahedral pyramids and, hence, it is possible to obtain a dot with an effective size under 100 nm when the first crystallized layers are the layers of the substrate compound (AlGaAs) and only the top of the pyramid is created of GaAs. The fabrication process and a micrograph of the QDs grown via this method are shown in Figure 2.4.

Figure 2.4 (a) A schematic diagram of the fabrication process of selective growth. (b) A micrograph of the GaAs QDs [41].

The QD growth techniques described previously are *ex situ* methods, which always have a possibility of contamination and are time consuming and complicated due to the multiple steps involved in the process. From a technological point of view, the most effective way to create QDs so far is by a third method: self-assembly, *in situ* growth technique in a highly strained material. This method is known as Stranski-Krastanow (SK) growth [43].

In this method, QDs are spontaneously formed during epitaxial crystal growth. This type of formation was first observed by Goldstein [44]. When the lattice constants of the substrate and the crystallized material have a considerable difference (7% in the case of GaAs and InAs, the most commonly used pair of compounds), only the first deposited monolayers crystallize in the form of strained layers with a lattice constant equal to that of the substrate. When the critical thickness is exceeded, the significant strain which occurs in the layer leads to the breakdown of the ordered structure and to the spontaneous formation of randomly distributed QDs of a regular shape and a similar size. The shape and the average size of the QDs depend on the strain intensity in the layer related to the misfit of lattice constants, the growth temperature, and the growth rate. Typical micrographs of the self-assembled QDs are shown in Figure 2.5 [45].

Figure 2.5 (a) Top view and (b) cross-sectional view of self-assembled QDs[45].

2.1.3 Current State of QD lasers

To date, InAs/GaAs QD lasers with emission wavelength of $1.3\mu\text{m}$ have shown low threshold current, high quantum efficiency, high temperature stability, and great potential for high speed applications. Liu *et al.* [27] has shown a low threshold transparency current density of $5.9\text{A}/\text{cm}^2$ per QD layer with a high internal efficiency of 93.5% in $1.3\mu\text{m}$ 10-layer InAs/GaAs QD lasers. As for the characteristic temperature (T_0), several research groups [17, 46, 47] have reported an infinite T_0 in p -doped QD lasers. The dramatic improvement in characteristic temperature is attributed to the interaction between increased internal loss and improved carrier confinement induced by p -doping. Another important parameter, linewidth enhancement factor, which influences several fundamental performances in semiconductor lasers, such as the laser linewidth and the sensitivity to external optical feedback or to optical injection, has been improved in QD lasers as well. Near zero linewidth enhancement factor has been reported by different research groups [48, 49]. However, the high speed performance of QD lasers still needs

further improvement. So far, the highest cut-off frequency in QD lasers is around 20GHz for direct modulation [50], while mode-locked QD lasers can enhance the cut-off frequency to 40GHz [51], which provides a possible solution to achieve large bandwidth in telecommunication applications. In addition, an interesting phenomenon, two-state lasing in QD lasers, has been demonstrated by different groups [25, 28, 52]. Recently, Naderi *et al.* [30] have demonstrated a multi-section distributed feedback QD laser with two-state lasing with 8THz separation between the two lasing modes, which shows an optimum way to produce a compact and low-cost THz laser source for future applications.

2.2 Gain of QD Lasers

The general threshold condition for a semiconductor laser can be written as

$$\Gamma g_{th} = \alpha_i + \alpha_m = \alpha_i + \frac{1}{2L} \ln \left(\frac{1}{R_1 R_2} \right) \quad (2.1)$$

where Γ is the optical confinement factor, g_{th} is the threshold gain, and α_i and α_m are the internal and mirror losses, respectively. α_m can also be expressed in terms of the reflectivity of the resonator mirrors (R_1 and R_2) and the cavity length L . The lasing operation starts when the threshold condition is satisfied (i.e. when the modal gain (Γg) compensates for the sum of all losses). $(\Gamma g - \alpha_i)$ is defined as the net modal gain, which is equal to the mirror loss α_m at the lasing condition.

2.2.1 Stacked QD Structures

The first multiple aligned stacked QD layers were demonstrated by Solomon [53]

and Ledentsov [19] in 1996. The purpose of the multiple stacked layers is to increase the modal gain in QD lasers, which is limited by the density of QDs. The use of multiple layers of QDs is necessary, therefore, to allow the fabrication of devices with a reasonable cavity length without assistance by high reflection coatings on the facets. Using this approach, GS lasing at room temperature was realized at a reduced threshold current density of $90\text{A}/\text{cm}^2$ [19]. After that, several research groups put much effort into fabricating defect-free multiple layers of QDs by [19, 54-56]. A typical structure of multiple stacked QDs is shown in the transmission electron microscope (TEM) image in Figure 2.6.

Figure 2.6 TEM image of vertically coupled multiple stacked QD layers [19].

The multiple stacked QD structure can increase the modal gain of QD lasers dramatically. A linear increase of the modal gain with the number of QD layers was demonstrated in the multiple stacked QD laser structures shown in Figure 2.7.

A saturation modal gain of 5.5cm^{-1} , 15.2cm^{-1} , 30.4cm^{-1} and 42cm^{-1} was obtained from four laser structures containing 1, 3, 5, and 7 QD layers, respectively (corresponding to $\sim 6\text{cm}^{-1}$ per QD layer).

Figure 2.7 A graph of modal gain at threshold vs. threshold current density at room temperature for four laser structures with stacked QD layers (1, 3, 5, and 7 layers) [57].

2.2.2 *p*-type Modulation Doping

The actual high frequency performance of QD lasers over QW lasers has not achieved due to several factors such as the closely spaced energy states of the QD holes. Therefore, the use of *p*-type modulation doping has been proposed to improve the gain properties [23, 58] and the temperature sensitivities [17, 22, 47]

of QD lasers. Figure 2.8 and Figure 2.9 show the theoretical study conducted by Shchekin and Deppe [20, 59]. These researchers showed clear improvements in the modal gain and the 3dB bandwidth of QD lasers with p -type modulation doping. In their simulation, the improvements were mainly attributed to the large number of built-in excess holes in the QD active region, which saturated the energy levels in the valence band and reduced the thermal hole broadening.

Figure 2.8 A graph of calculated gain vs. injected electron number per QD for different numbers of built-in holes (N_a) and inhomogeneous linewidth ($\Delta\omega$) of 10meV and 30meV [20].

Figure 2.9 A graph of the calculated 3dB frequency response vs. square root of current density [20].

In experiments, while the p -doping improved the characteristic temperature (T_0) even to infinity [17], the improvement in the modal gain was not clearly demonstrated. As shown in Figure 2.10, the peak gain versus the current density curves were plotted for p -doped (15 and 50 acceptors/QD) and undoped samples at 300K. At low injections, the p -doped QD laser showed a similar modal gain compared to the undoped laser. At high injections, the undoped laser provided the largest gain, which is attributed to the excited-state (ES) lasing [24]. However, in Figure 2.11 (a), the peak net gain of the p -doped device was much less than that for

the undoped device at a low injection. As the injection current increased, the net modal gain of the p -doped device became larger than that of the undoped device.

Both types of lasers tended towards similar behaviour at 350 K (see Figure 2.11(b)). Compared to the peak gain at room temperature, the peak gain saturated at a lower value at 350K and the first excited state (1ES) can be observed in the p -doped devices at a low peak gain. At 350 K, the peak net gain of the p -doped laser was less than that of the undoped laser at low injections. However, the difference was less than that at room temperature. This was likely due to the improved carrier redistribution but shows that the p -doped devices did not fully reach thermal equilibrium even at 350 K [23, 60]. In summary, conflicting results of the p -type modulation effect on the QD laser gain were observed from [23] and [24], and more experiments need to be conducted in order to identify the reasons.

Figure 2.10 Peak modal gain plotted as a function of the drive current density at 300K for the undoped (circles), p -doped (15 acceptors/QD) (squares), and p -doped (50 acceptors/QD) (triangles) lasers [24].

Figure 2.11 Plots of the peak gain vs. the injection current density at (a) room temperature and at (b) 350K for the undoped and *p*-doped QD lasers [23].

2.2.3 Two-State Competition

In QD lasers, ground-state lasing resulting from the recombination of electrons and holes in the GS generally occurs at a low injection current. As the injection current increases, a second lasing peak is often observed due to the excited-state recombination, especially for a QD laser with a relatively short cavity length (below 2mm). Recently, researchers from different groups have demonstrated two-state lasing [25-29] (as shown in Figure 2.12) and even three-state lasing [31, 32] in QD lasers. The simultaneous lasing from both the ES and the GS is attributed to the relatively long relaxation time between the two states, which is

mainly induced by the Pauli exclusion principle [25]. A higher carrier population in the GS causes a longer relaxation time from the ES into the GS. This leads to an accumulation of carriers in the ES and results in simultaneous two-state lasing. Further increasing the concentration of injected carriers, the ES lasing will eventually surpass the GS lasing and reduce the GS modal gain. Therefore, an understanding of the two-state lasing behaviour in QD lasers is required.

Figure 2.12 A graph of the electroluminescence spectra on logarithmic scale of a 1.5mm-long InAs/GaAs QD laser at various injection current densities (J) [25].

Figure 2.13 The ratio of the ES and the GS threshold current as a function of temperature for as-grown 600°C annealed and 650°C annealed InAs/GaAs QD lasers with a cavity length of 1mm. The inset shows this ratio for as-grown and annealed devices with different cavity lengths [28].

Recent research has demonstrated that GS and ES lasing can be enhanced or suppressed by the proper choice of anneal temperature [28]. As shown in Figure 2.13, the 600°C annealed laser shows a higher value of the ratio of the ES threshold current to the GS threshold current ($I_{th,ES}/I_{th,GS}$) compared to the as-grown device. The difference between the $I_{th,ES}/I_{th,GS}$ value of the 600°C annealed and the as-grown device is larger at higher temperature, which suggests that optimized annealing can enhance the GS lasing and suppress the ES lasing. In addition,

researchers have also found that the facet coating design with the central wavelength of 1480 nm can delay the ES lasing until 100°C for the laser diodes with a cavity length of 1.2 mm [29]. However, the p -doping effect on the competition between the ES and the GS lasing has not been reported.

2.2.4 Geometrical Effect

The geometrical shape of a ridge waveguide laser device is defined in the etching process, which controls the laser ridge height. For a QD laser with a narrow ridge, the ridge height is crucial to the performance of the device. Previous studies have shown that the laser with a shallow ridge will have a large lateral spreading current, which will affect the device performance in the transparency threshold current, internal efficiency, etc [61, 62].

Figure 2.14 shows the ridge height dependent transparency current density (J_{tr}) of a QW laser. An optimum ridge height h of 1.23 μm corresponding to the etching depth right above the laser active region was observed to minimize J_{tr} [34] because, in lasers with shallower ridges, the injected carriers spread out laterally and the effective carrier density in the active regions was lower and, thus, a higher J_{tr} was required. However, for lasers with ridges that were too high (i.e. $h > 1.23\mu\text{m}$), the sidewall area of the ridge was large and this resulted in a heavy carrier loss due to surface recombination.

Figure 2.14 A graph of the transparency threshold current density (J_{tr}) of InGaAs/GaAs lasers with ridge heights (h) of 0.39, 0.80, 1.23, 1.55, and 1.77 μm [34].

A similar behaviour was observed in QD lasers [33]. As shown in Figure 2.15, device (A) with its ridge etched through the whole active region shows a larger threshold current than device (B) in which the etching had stopped just above the active region. However, the researchers were not able to define whether the current spreading or the changes in the waveguide played the major role in the changes in laser performance. In addition, no investigation on how the ridge height affected the laser modal gain was reported.

Figure 2.15 A graph and a diagram showing the temperature dependence of threshold current density (J_{th}) and external quantum efficiency (η_d) for device (A) a deep etched device and device (B) a shallow etched device [33].

2.2.5 Self-Heating Effect

A self-heating effect always exists in electronic devices. Previous studies have shown that devices with multiple QW structures have a serious intrinsic heating effect due to the phonon dispersion effect [63, 64]. The thermal conductivity of QD materials is about one order lower than that of the QW materials and two orders lower than that of the bulk materials due to the incoherent phonon scattering by the QDs [35, 65]. This lower thermal conductivity implies that a more serious self-heating effect might be present in QD devices.

A recent study on QD vertical cavity surface emitting laser devices showed a reduced emission power in continuous wave (CW) mode [66]. As shown in Figure 2.16, the maximum output power of the laser device decreased as the duty cycle of the injection current increased. For the device with oxide apertures of $15\mu\text{m}\times 15\mu\text{m}$, the maximum power reduced more than 20% when the duty cycle of the injection current increased to 100% (in CW mode). However, only a few investigations on the self-heating effect in QD lasers have been reported [36-38]. As shown in Figure 2.17, both the theoretical and the experimental results show that an injection current with a high duty cycle will show an artificial decrease in the linewidth enhancement factor due to the Joule heating in the device. Nevertheless, a lack of studies exists on the self-heating effect on the modal gain of QD lasers. In addition, how *p*-doping affects the device self-heating is not clear. Therefore, a study of the modal gain measured in different operating modes (CW or pulsed mode) is needed in order to identify how intrinsic heating affects the modal gain of QD lasers with different doping concentrations.

Figure 2.16 A graph of the maximum output power at different duty cycles and oxide apertures for InAs/GaAs QD vertical cavity surface emitting lasers [66].

Figure 2.17 Plots of experimental and theoretical results of linewidth enhancement factors at different duty cycles for InAs/GaAs QD lasers [38].

Chapter 3 Fabrication and Characterization

In this chapter, the structures and the fabrication process of InAs/GaAs QD lasers are described followed by a detailed description of the pulsed anodic oxidation process. Finally, the measurement systems utilized in this project are introduced.

3.1 Fabrication Process

In this research project, we used three types of devices, which had similar structures but different doping concentrations. The InAs/In_{0.15}Ga_{0.85}As/GaAs wafers were grown on Si-doped GaAs (100) substrates by molecular beam epitaxy (MBE). The active region was sandwiched between 1.5μm-thick Al_{0.35}Ga_{0.65}As cladding layers for optical confinement. The bottom and top cladding layers were doped with Si and C for *n*- and *p*-type conductivity, respectively. The active region was comprised of ten layers of self-assembled InAs (2.32ML)/In_{0.15}Ga_{0.85}As (5nm) QDs separated by a 33nm-thick GaAs spacer. For the *p*-doped QD laser structures, the doping consisted of carbon atoms incorporated into a 10nm GaAs layer, which was situated in the middle of each 33nm-thick spacer between the QD layers. The doping concentration was about $2.5 \times 10^{17} \text{ cm}^{-3}$ and $5 \times 10^{17} \text{ cm}^{-3}$ corresponding to 8 acceptors/QD and 16 acceptors/QD, respectively. The dot density per QD layer was about $3 \times 10^{10} \text{ cm}^{-2}$. The growth was finished with a 200nm-thick carbon doped GaAs ($\sim 1 \times 10^{20} \text{ cm}^{-3}$). A schematic illustration of the QD laser structures is shown in Figure 3.1(a). A cross-sectional transmission electron microscopy (TEM) image of the QD active region is shown in Figure 3.1(b).

Figure 3.1 (a) Schematic illustration of the 1.3 μm InAs/GaAs 10-layer QD laser structure. (b) TEM scan of the InAs QD active region. The scale bar is 100nm.

The fabrication process of the edge emitting ridge lasers is briefly described by the flow chart shown in Figure 3.2. The QD wafer was first cleaned by HCl to remove any possible oxide on the surface followed by the standard cleaning process using acetone, IPA, and de-ionized (DI) water solutions. Thereafter, the wafer proceeded to the standard photolithography and wet chemical etching process.

The photoresist (AZ 1518) was spun uniformly on the wafer surface followed by exposure under UV light. The stripe pattern was formed after developing for 70 seconds. The width of the stripe was defined by the mask used at the photolithography step. In this project, a stripe width of 4 μm was established to realize a narrow ridge waveguide (RWG) laser structure. The wet etching ($\text{H}_3\text{PO}_4\text{:H}_2\text{O}_2\text{:DI water} = 1\text{:}1\text{:}5$) process followed and good control of the etch

depth was necessary to achieve a narrow RGW structure since the refractive index step between the ridge and trench region was determined by the etch depth. According to previous studies [34, 67] regarding the optimization of the ridge height, the entire p -doped layers outside the ridge region were etched through to the QD active region.

Before removal of the photoresist, the wafer was subjected to a dielectric oxidation process for better electrical and optical confinement. A 200nm-thick oxide layer was formed by the pulsed anodic oxidation (PAO) process [68], which was conducted at room temperature to form a native oxide for both electrical and optical confinement. The details of this process will be discussed in next section.

Subsequently, p -type ohmic contact layers (Ti/Au, 50/300nm) were deposited by electron beam evaporation. Thereafter, the device was lapped down to about 100 μ m to ease the cleaving step. The n -type ohmic contact layers (Ni/Ge/Au/Ni/Au, 5/20/100/25/300nm) were deposited on the backside of the substrate after the lapping process. The wafer was annealed at 410°C for 3 minutes in a nitrogen ambient chamber after each metal deposition. Finally, the wafer was cleaved into laser devices of various cavity lengths for further testing. Each laser only contained one stripe. Scanning electron microscope (SEM) images of a typical top view and the cross-sectional view of a single QD laser are shown in Figure 3.3.

Figure 3.2 A flow chart of the fabrication process of the QD laser.

Figure 3.3 (a) An SEM image of the top view of the laser device. The stripe width is about $4\mu\text{m}$ as shown. (b) An SEM image of the cross-sectional view of the laser device. The ridge height is about $1.5\mu\text{m}$.

3.2 Pulsed Anodic Oxidation (PAO)

The PAO technique was carried out at room temperature to produce a native oxide, which functions as the isolation layer of the ridge waveguide QD lasers. Compared to the conventional oxide deposition techniques, the PAO technique is simple and reliable [68, 69].

Figure 3.4 illustrates the setup scheme of the PAO technique. The setup consisted of a function generator, a power amplifier, an oscilloscope, and a vacuum pump. The function generator generated a pulse signal with the frequency of 144Hz, a duty cycle of 10%, and an amplitude of 2V. After going through the power amplifier, the amplitude of the pulse signal was amplified 40 times to 80V. This voltage was the dominant factor that determined the final thickness of the oxide formed by the PAO. The sample was held by a vacuum chuck, which also functioned as the conductive wire connecting the anode of the power source to the backside of the sample. A palladium (Pd) pad was connected to the cathode and put into the electrolyte, which was composite of ethylene, DI water, and phosphoric acid (40:20:1 in volume). The oxidation took place when the sample surface was dipped in to the electrolyte.

The total anodization time was around 4 minutes and the final anodic oxide thickness was about 200nm. A thicker oxide layer could be obtained by setting a higher voltage from the power source or a larger pulse duty cycle. The overall reactions of the anodization process are described by the chemical formula below:

Figure 3.4 Schematic diagram of the experimental setup for the pulsed anodic oxidation.

As shown in Figure 3.4, the oscilloscope monitored the time-dependent output voltage across the small resistor (10Ω) in the circuit and it also monitored the input signal. The typical waveforms displayed on the oscilloscope are shown in Figure 3.5, where Channel 1 and Channel 2 monitor the input and output signals, respectively. The current in the circuit decreased as the oxide became thicker. However, the magnitude of the leading edge of the pulse signal remained unchanged since the reading was across the small resistor.

Figure 3.5 Diagram of typical waveforms displayed on the oscilloscope. Channel 1 (upper) monitors the input pulse signal and Channel 2 (lower) monitors the output voltages across the small impedance.

Figure 3.6 shows representative oscilloscope traces for the time-dependent input and output pulse signals. In the figure, T_0 and T_n represent the initial and final pulse signals, respectively, while T_1 and T_2 are the intermediate pulse signals. The leading edges of the pulses remained constant for all of the waveforms whereas the trailing edges of the pulses decreased with time corresponding to the growth of the oxide.

Figure 3.6 A diagram of the oscilloscope traces of the input and output signals across the small series resistor in the time domain.

The pulse shape can be explained by modelling the solution/oxide/semiconductor system as a Schottky barrier diode which transitions to a metal-oxide-semiconductor capacitor as the oxide thickens [69]. At the beginning of each pulse, the capacitance of the oxide acted to short out the oxide resistance. As the capacitor charged, the current decreased to a steady-state value within the pulse, which resulted in a decreasing trailing edge. As the oxide thickness increased, the resistance increased. Therefore, the steady-state current decreased from pulse to pulse (i.e. T_0 , T_1 , T_2 , etc). As long as the pulse was long enough for the capacitor to achieve quasi-steady state, this performance was invariantly repeated. The oxide growth terminated when the oxide resistance was large enough to render the

available voltage pulse insufficient to drive the anodic reactions further, reaching the final pulse T_n . The pulsed nature of the process allowed the formation of a uniform oxide with a high growth rate at room temperature since the pulse process was a combination of oxidation and etching steps. When the pulse was off, the solution acted as a mild etchant for the oxide. When the pulse was stabilized, a quasi-steady state was achieved in which the oxide dissolution rate at the oxide/solution interface equalled the oxide formation rate at the oxide/semiconductor interface. In this manner, the oxide film was grown uniformly and the ridge was defined at the same time.

3.3 Characterization Tools

Several characterization tools were involved in this project. The ILX laser diode parameter analyzer is the essential equipment to obtain the basic characteristics of the QD laser devices. In the experimental setup for this research study, the laser bar was placed on a copper heat sink with the *p*-side down. This expedited the heat dissipation and protected the laser ridge against damage by the probe of the test jig. Underneath the test platform was the thermoelectric controller (TEC), which adjusted the test temperature from 10°C to 120°C and which enabled temperature dependent testing for the QD laser devices. Therefore, the ILX laser diode parameter analyzer collected the temperature dependent light-current-voltage (*L-I-V*) characteristics of the devices. In addition, a digital current source was implemented, which provided pulse signals with duty cycles of 0.01% to 10%. The digital current source is useful in obtaining pulsed mode measurements. However, the measured data of the pulse source had to be recorded manually.

The Yakogawa optical spectrum analyzer (OSA), a classical optical tool for the characterization of semiconductor emitters, is a very useful tool. The OSA's detection range is 650nm-1750nm. In this project, we mainly used the 1100nm-1500nm range. In our setup, the laser light was guided through an optical fibre to the OSA. Working together with the current source and TEC in the ILX analyzer, it provided laser spectra at various temperatures and injection currents. By adjusting the resolution and sensitivity of the OSA, we obtained the amplified spontaneous emission (ASE) spectrum from the laser, from which we calculated the laser modal gain. In this thesis, the resolution was set to 0.02nm and the sensitivity was set to "HIGH 1". Photographs of the main characterization tools are shown in Figure 3.7.

Figure 3.7 Photographs of the laser testing equipment setup, which involved a laser parameter analyzer, a pulsed current source, a device testing holder, and an optical spectrum analyzer.

Chapter 4 Results and Discussion

In this research project, 1.3 μm InAs/GaAs QD lasers with different p -doping levels were fabricated based on the fabrication process described in the previous chapter. The device structures were shown in Figure 3.1. The laser first went through basic characterizations, such as light-current-voltage (L - I - V) and temperature dependent tests to determine the laser performance and characteristic temperature (T_0). These basic characterizations were followed by optical spectrum measurements using the OSA to study the gain properties of the device.

A detailed analysis on the laser performance and the modal gain versus the various parameters are divided into four sections in this chapter. The first section presents the p -doping effect on the ground-state modal gain and the differential gain of QD lasers with doping concentrations of 0, 8, and 16 acceptors/QD. A theoretical model of the modal gain-based rate equations and the net modal gain measurement technique are described in detail. The following section discusses the modal gain competition between ground-state lasing and excited-state lasing. The geometrical effect and self-heating effect on the QD laser gain are presented in the last two sections.

4.1 p -type Modulation Doping Effect

4.1.1 Background

As stated in Section 2.2.2, the use of p -type modulation doping had been proposed

to improve the gain properties and the temperature sensitivity behaviour of QD lasers. The theoretical studies [20] showed obvious enhancements in modal gain and 3dB bandwidth of the p -doped QD lasers due to the large number of built-in excess holes in the QD active region, which saturated the energy levels in the valence band and reduced the thermal hole broadening. However, the experimental studies did not clearly demonstrate improvements on modal gain and differential gain in the p -doped QD lasers. Some researchers reported [22, 23] that, at a low current injection, p -doped QD lasers showed either a smaller or an equivalent modal gain compared to undoped lasers. At high injection levels, p -doped QD lasers showed higher modal gain than undoped lasers. On the contrary, Sandall *et al.* demonstrated that p -doped QD lasers had a smaller modal gain than the undoped QD lasers at high injection levels, which was attributed to excited-state lasing [47]. Furthermore, studies on the temperature dependent p -doping effect on the differential gain of QD lasers are absent. A study of this effect could provide insight into the high speed modulation behaviour of such devices.

4.1.2 Objectives and Main Results

The main objective of this study is to investigate the temperature dependent modal gain and the differential gain of the InAs/GaAs QD lasers with different doping concentrations. We first conducted a basic characterization of the undoped and p -doped QD lasers including the L - I - V , characteristic temperature, internal loss, and efficiency measurements. A theoretical model based on rate equations was developed to simulate the modal gain and the differential gain of QD lasers at various temperatures. An effective approach to measure QD laser differential gain was developed and implemented. The results show clear enhancements in the

characteristic temperature, the modal gain, and the differential gain in the p -doped lasers compared to the undoped laser. Notably, the results indicated that an optimum doping density in QD lasers could be obtained to increase the characteristic temperature, modal gain, and differential gain and to reduce the threshold current density. This phenomenon has not been reported before.

4.1.3 Basic Characterization

In order to study the p -type modulation doping effect on the QD laser, we fabricated a batch of p -doped and undoped lasers with ridge widths (w) of $4\mu\text{m}$ under the same condition. The device structure was described in Section 3.1.

The doping concentrations of the two p -doped lasers were 8 and 16 acceptors per QD while the dot density was about $3 \times 10^{10} \text{cm}^{-2}$. The three types of devices with a similar cavity length (L) of 1.5mm were measured at 20°C in continuous wave (CW) mode. The light output power of the undoped (black line), p -doped (8 acceptors/QD) (red line), and p -doped (16 acceptors/QD) (blue line) lasers is plotted as a function of the injection current density in Figure 4.1. The p -doped (8 acceptors/QD) laser showed a threshold current density (J_{th}) of 132A/cm^2 (corresponding to a threshold current (I_{th}) of 7.9mA), which was lower than the undoped and p -doped (16 acceptors/QD) lasers (181A/cm^2 and 573A/cm^2 , corresponding to I_{th} of 10.9mA and 34.4mA, respectively). The reason for the low J_{th} obtained in the p -doped (8 acceptors/QD) laser should be due to the counteracting effect caused by increased internal loss and improved carrier confinement, which will be explained in detail later.

Figure 4.1 A graph of light output power vs. injection current density characteristics of the undoped, p -doped (8 acceptors/QD), and p -doped (16 acceptors/QD) InAs/GaAs QD lasers.

The ground-state lasing spectra ($J = 1.1J_{th}$ at 20°C) centred at 1291.8nm (undoped laser), 1296.9nm (p -doped (8 acceptors/QD) laser), and 1302.6nm (p -doped (16 acceptors/QD) laser) are shown in Figure 4.2. These spectra are good evidence of CW GS lasing in the 1.3 μm range in these QD laser structures. The shift in the emitted peak wavelengths in the three devices is likely due to changes in the band gap energy. A higher doping density will shrink the device band gap energy, resulting in a longer emission wavelength. Therefore, the p -doped lasers may show longer emission wavelengths compared to the undoped devices.

Figure 4.2 A graph of the emission spectra of the InAs/GaAs QD lasers with different doping densities (undoped, p -doped with 8 and 16 acceptors/QD) measured at $J = 1.1J_{th}$ at 20°C.

The temperature dependent light-current density (L - J) characterization was carried out for the undoped, p -doped (8 acceptors/QD), and p -doped (16 acceptors/QD) devices and is shown in Figure 4.3 (from top to bottom). All of the devices were able to exhibit CW lasing up to 120°C, which showed good temperature stability. The high temperature GS lasing should be attributed to the high available GS gain from the ten stacked QD layers.

Figure 4.3 Graphs of the L - J characteristics of the undoped, *p*-doped (8 acceptors/QD), and *p*-doped (16 acceptors/QD) lasers ($4 \times 1500 \mu m^2$) at the temperature range of 20°C-120°C.

As depicted in Figure 4.3, the kinks in the L - J curves became more obvious as the temperature increased. The kinks shown at the high temperature under high injection current density are due to lasing from the excited-state (ES). The competition of the two-state lasing will be discussed in the next section.

From Figure 4.3, we can extract the J_{th} at each temperature. Hence, the characteristic temperature (T_0), which is an essential parameter to determine the laser temperature sensitivity, can be calculated by the formulae below:

$$J_{th} = J_0 \exp(T / T_0) \quad (4.1)$$

$$T_0 = \frac{\Delta T}{\Delta \ln(J_{th})} \quad (4.2)$$

The plots of $\ln(J_{th})$ versus the temperature of the three laser devices with different doping levels are shown in Figure 4.4. The characteristic temperatures of the undoped laser were 77K from 20°C to 50°C and 58K from 60°C to 120°C while the characteristic temperatures of the p -doped (8 acceptors/QD) laser were 97K and 64K in the same temperature ranges. The p -doped (16 acceptors/QD) laser exhibited a much larger T_0 than the other two lasers (an almost infinite T_0 was observed from 20°C to 80°C).

Figure 4.4 A graph of the temperature dependent threshold current density (J_{th}) in a logarithm scale of the undoped, *p*-doped (8 acceptors/QD), and *p*-doped (16 acceptors/QD) lasers ($4 \times 1500\mu\text{m}^2$) in the temperature range of 20-120°C.

In order to analyze the reason for the drastic improvement in characteristic temperature of the *p*-doped (16 acceptors/QD) laser, the internal loss (α_i) and the internal efficiency (η_i) were calculated based on cavity-length dependent measurements. The differential quantum efficiency (η_d) of the three devices with different doping levels is plotted as a function of the device cavity length (L) in Figure 4.5.

Figure 4.5 A graph of inverse external efficiency (η_d^{-1}) vs. cavity length (L) of the undoped, p -doped (8 acceptors/QD), and p -doped (16 acceptors/QD) lasers at room temperature.

The values of η_d for the three types of QD lasers with various cavity lengths ($L=0.8\text{mm}-3\text{mm}$) were calculated from the following formula.

$$\eta_d = \frac{dP_{out}/dI}{\hbar\omega/q} \quad (4.3)$$

where the light output power (P_{out}) is expressed as [70]:

$$P_{out} = \frac{\hbar\omega}{q} \frac{\alpha_m}{\alpha_m + \alpha_i} \eta_i (I - I_{th}) \quad (4.4)$$

where $\hbar\omega$ is the photon energy, q is the elementary charge, α_m is the mirror loss, I

is the injection current, and I_{th} is the threshold current. Combining Equation (4.3) and Equation (4.4), we have:

$$\eta_d = \eta_i \frac{\alpha_m}{\alpha_m + \alpha_i} \quad (4.5)$$

where the mirror loss α_m is determined by the device cavity length and the reflectivity (R) of the two cleaved facets, which is estimated to be 0.32. The relationship is expressed as:

$$\alpha_m = \frac{1}{L} \ln \frac{1}{R} \quad (4.6)$$

Hence, Equation (4.5) can be written in the following form:

$$\eta_d^{-1} = \alpha_i \eta_i^{-1} \ln(R)L + \eta_i^{-1} \quad (4.7)$$

Therefore, the values of η_i and α_i can be derived from the above equation based on the plots in Figure 4.5. The internal losses of the three devices are 4.2cm^{-1} (undoped laser), 4.7cm^{-1} (p -doped (8 acceptors/QD) laser), and 7.2cm^{-1} (p -doped (16 acceptors/QD) laser), respectively, while the internal efficiencies are 90.2%, 94.8%, and 87.4%, respectively.

As shown in Figure 4.4, the p -doped (8 acceptors/QD) laser had a smaller J_{th} than the undoped QD laser within the temperature range of measurements. This could be explained by the counteracting effect caused by the increased internal loss and the improved carrier confinement induced by the p -doping in the laser active region. Although p -doping increased the internal loss due to inter-valence band absorption [60] and non-radiative recombination [71, 72] which increased the threshold current of the device, p -doping also improved the hole thermalization and shortened the intraband carrier relaxation time [20, 71, 73] which decreased

the threshold current. Therefore, by choosing a relatively light doping concentration, the factors which decreased the J_{th} will dominate, leading to a smaller threshold current density in the p -doped laser. When the doping density was increased to 16 acceptors/QD, the doping effect on the internal loss dominated. As shown in Figure 4.5, the p -doped (16 acceptors/QD) laser showed a much larger internal loss than the other two lasers, which resulted in a larger J_{th} in this laser.

In terms of the characteristic temperature, the p -doped (16 acceptors/QD) laser exhibited an almost infinite T_0 from 20°C to 80°C (as shown in Figure 4.4), which is much larger than the characteristic temperatures of the other two lasers. The large improvement in the characteristic temperature of the p -doped lasers may be due to the increase in both the Auger recombination and the carrier thermalization between dots with increasing temperature. The increase in Auger recombination will increase the threshold current but this is compensated by an increase in the carrier thermalization. This is because the increase in the carrier thermalization between the dots increases the efficiency of radiative recombination and reduces the threshold current [46]. In the p -doped laser, the electrostatic attraction of the excess holes increased the effective barrier for electron escape. Hence, this limited the electron thermalization until a relatively higher temperature compared to the undoped device and resulted in a larger T_0 for the p -doped lasers [46]. Therefore, by choosing the appropriate doping density, the effects of Auger recombination and carrier thermalization cancel each other out around room temperature, leading to an almost temperature insensitive J_{th} within a large temperature range. These results suggested that QD lasers with light p -doping (8 acceptors/QD in our case)

could improve both the J_{th} and the T_0 in the devices. In order to achieve higher temperature insensitivity, a higher doping density is required. However, at a high doping density, the devices exhibited a larger threshold current density.

4.1.4 Theoretical Model of Modal Gain and Differential Gain

In order to analyze the modal gain and the differential gain in multilayer QD lasers, a theoretical model based on a rate-equation model of one QD layer [74] was developed. In this model, we considered the following factors:

- All possible relaxation paths were considered;
- The relaxation time was assumed to be the same as long as the initial and final relaxation states remain the same;
- Electrons were injected into the QDs from the wetting layer (WL) and escaped from the InGaAs cap layer (CL);
- Holes were injected from the CL into the QDs and escaped from the WL;
- The multilayer QDs were distributed symmetrically in the active region of the QD laser.
- The electrons and holes are in pairs, and the carrier dynamics is the same in both conduction and valence bands

Under the above conditions, the rate equations for the multilayer QD laser are:

$$\frac{dN_B}{dt} = \frac{J}{qb} + \frac{1}{t_{ewb}} \frac{g_w f_w}{b/n} (1 - f_B) - \left(\frac{1}{t_{bw}} + \frac{1}{t_{rB}} \right) N_B \quad (4.8)$$

$$\begin{aligned} \frac{df_w}{dt} = & \frac{(1-f_w)}{g_w} \left(\frac{N_B b / n}{t_{bw}} + \frac{N_d d}{t_{bd}} \right) - \frac{f_w}{t_{ewb}} \\ & + \sum_{i=0}^2 \left[\frac{2p_i \rho}{g_w} Es_{iw} f_i (1-f_w) - R_{wi} f_w (1-f_i) \right] - \frac{f_w}{t_{rw}} \end{aligned} \quad (4.9)$$

$$\begin{aligned} \frac{df_2}{dt} = & \frac{g_w}{2p_2 \rho} R_{w2} f_w (1-f_2) - Es_{2w} f_2 (1-f_w) \\ & + \sum_{i=0}^1 \left[\frac{p_i}{p_2} Es_{i2} f_i (1-f_2) - R_{2i} f_2 (1-f_i) \right] - \frac{f_2}{t_{r2}} \end{aligned} \quad (4.10)$$

$$\begin{aligned} \frac{df_1}{dt} = & \frac{g_w}{2p_1 \rho} R_{w1} f_w (1-f_1) - Es_{1w} f_1 (1-f_w) \\ & + \left[\frac{p_2}{p_1} R_{21} f_2 (1-f_1) - Es_{12} f_1 (1-f_2) \right] \\ & + \left[\frac{p_0}{p_1} Es_{01} f_0 (1-f_1) - R_{10} f_1 (1-f_0) \right] - \frac{f_1}{t_{r1}} - PG_1 \end{aligned} \quad (4.11)$$

$$\begin{aligned} \frac{df_0}{dt} = & \sum_{i=1}^2 \left[\frac{p_i}{p_0} R_{i0} f_i (1-f_0) - Es_{0i} f_0 (1-f_i) \right] \\ & + \left[\frac{g_w}{2p_0 \rho} R_{w0} f_w (1-f_0) - Es_{0w} f_0 (1-f_w) \right] - \frac{f_0}{t_{r0}} - PG_0 \end{aligned} \quad (4.12)$$

The respective symbols and the parameters of the above equations (Equations (4.8)-(4.12)) are shown in Table 4.1.

Table 4.1 The meanings of the symbols in the rate equations.

Symbol	Meaning
N_B	The carrier concentration in the barrier layer.
J	The injected current density.
q	The electronic charge.
b	The total thickness of the GaAs barrier in the active region.
t_{ewb}	The carrier escape time from WL (CL) to the GaAs barrier, which is a function of temperature.
g_w	The parameter describing the carrier concentration in the WL (CL).
f_i ($i=B,w,2,1,0$)	The carrier occupation probability in the barrier, WL (CL), QD ground state, first excited state, and second excited state, respectively.
n	The number of QD layers.
t_{bw}	The carrier transport time from cladding layer to the nearest WL (CL).
t_{ri} ($i=B,w,2,1,0$)	The carrier lifetime in the barrier, WL (CL), QD ground state, first excited state, and second excited state, respectively.
N_d	The doping concentration in the laser active region.
d	The thickness of the doped layer.
t_{bd}	The carrier transport time from the doped GaAs layer to WL (CL).
p_i ($i=2,1,0$)	The degeneracy of the QD levels.
ρ	The QD surface density.
Es_{ji} ($j<i=w,2,1,0$)	The escape rate from the j^{th} energy level to the i^{th} energy level.
R_{ij} ($j<i=w,2,1,0$)	The relaxation rate from the i^{th} energy level to the j^{th} energy level.
PG_i ($i=1,0$)	The emission term of the i^{th} energy level

In order to solve the rate equations, the relaxation rates $R_{ij}(j < i = w, 2, 1, 0)$ and the escape rates $Es_{ji}(j < i = w, 2, 1, 0)$ of the carriers had to be determined. The subscript $w, 2, 1$, and 0 represent the lowest state in the WL, the second excited state (ES), the first ES, and the ground state (GS), respectively. A schematic diagram depicting the electron relaxation paths is shown in Figure 4.6. The carrier relaxation rates can be expressed by the following equation [75]:

$$R_{ij}(j < i = w, 2, 1, 0) = A_{ij} + C_{ij}N_w \quad (4.13)$$

where A_{ij} and C_{ij} are the phonon-assisted relaxation rate and the Auger relaxation coefficient corresponding to the relaxation path between the i^{th} and j^{th} energy levels, respectively. N_w is the carrier density in the WL. The expressions of the phonon-assisted relaxation rate and the carrier density are [76, 77]:

$$A_{ij}(j < i = w, 2, 1, 0) = F_{ij} \left[\frac{1}{\exp(E_{ph}/k_B T) - 1} + 1 \right]^{n_{ph}} \quad (4.14)$$

$$N_w = \frac{m^* k_B T [1 - \exp(-E_{bw}/k_B T)]}{\pi \hbar^2} \equiv \frac{g_w}{L_w} f_w \quad (4.15)$$

In Equation (4.14), F_{ij} is the j^{th} state fill rate at absolute temperature, E_{ph} is the phonon energy, k_B is the Boltzmann's constant, and n_{ph} is the number of phonons. In Equation (4.15), m^* is the effective mass of the carriers in the WL, E_{bw} is the effective energy barrier, $\hbar$ is the reduced Planck's constant, and L_w is the width of the WL.

Figure 4.6 Schematic diagram of the relaxation processes in a QD system with three discrete levels.

By assuming that the system is in quasi-Fermi equilibrium, the escape rates of the carriers from the QD states to the WL and from a lower energy state to a higher one inside the QD can be expressed as [78, 79]:

$$Es_{iw}(i = 2, 1, 0) = \left[\frac{g_w}{2p_i \rho} \exp\left(-\frac{E_{iw}}{k_B T}\right) \right] R_{wi} \quad (4.16)$$

$$Es_{ji}(j < i = 2, 1, 0) = \frac{p_i}{p_j} \exp\left(-\frac{E_{ij}}{k_B T}\right) R_{ij} \quad (4.17)$$

where E_{iw} is the energy separation between the energy levels in the QDs and the WL while E_{ij} is the energy difference between the energy levels in QDs. The detailed band structure of the InAs/GaAs QDs is shown in Figure 4.7.

Figure 4.7 An energy band diagram of the InAs/GaAs QD structure [74].

Based on the weak guiding approximation, the maximum modal gain of a QD laser can be expressed as [80]:

$$G_{max} = \frac{hq}{cn_r m_0 \varepsilon_0} \frac{|P_{cv}|^2}{m_0 E_{cv}} \frac{1}{\sqrt{2\pi}} \left(\frac{2.35}{F_{in}} \right) \frac{\Gamma n \rho}{D_{ac}} (f_{0e} + f_{0h} - 1) \quad (4.18)$$

where h , c , n_r , m_0 and ε_0 are Planck's constant, velocity of light, refractive index, electron mass, and absolute permittivity in vacuum, respectively. E_{cv} is the centre of the energy distribution function of the ground-state transition. P_{cv} is the transmission matrix element and $|P_{cv}|^2$ is $\sim 2m_0 E_{cv}$ for the InAs/GaAs QD [80]. F_{in} is the inhomogeneous broadening of QDs, which describes the size uniformity of QDs. Γ is the optical confinement factor and D_{ac} is the total thickness of the active region. $(f_{0e} + f_{0h} - 1)$ is the population inversion term, which is determined by the rate equations that were described previously. Here, f_{0e} and f_{0h} are the electron and

the hole occupation probabilities, respectively, at the ground state. Obviously, the modal gain and differential gain are proportional to the population inversion term $(f_{0e} + f_{0h} - 1)$ in Equation (4.18).

In the calculation, three electron and hole energy levels are assumed in a QD and the separations of the QD energy levels are 64meV and 10meV for the electrons and the holes [74], respectively. The detailed band structure is shown in Figure 4.7. The phonon-assisted and Auger-assisted relaxations were taken into account and the relaxation parameters were selected according to the experimental and theoretical results reported in [81, 82]. Our calculation assumed the values of the optical confinement factor and the QD density as 0.05 [83] and $3 \times 10^{10} \text{ cm}^{-2}$, respectively. A relatively small inhomogeneous broadening value of 35meV was used. A larger inhomogeneous broadening leads to a lower material gain, as well as lower differential gain and 3dB bandwidth [20, 59], therefore uniform QDs are always preferred to achieve high performance in QD lasers. However, currently it is still a big challenge to grow QD structures with good uniformity. The calculated modal gain of the ten-layer InAs/GaAs QD laser at different temperatures is shown in Figure 4.8, which shows evidence of gain saturation under high injection current density. The increase in temperature reduced the saturation value of the gain.

The simulated differential gain (dG/dJ) is shown in Figure 4.9. As the injection current increased, the differential gain decreased exponentially. However, the temperature did not affect the differential gain significantly, which suggests that the differential gain measured in the temperature range of 20°C-120°C could be plotted together to describe the differential gain of QD lasers at room temperature.

This approach is implemented to identify improvements in the differential gain of the p -doped QD lasers in the following section.

Figure 4.8 A graph of the theoretical simulations of the modal gain profiles from 20°C to 120°C.

Figure 4.9 A graph of theoretical simulations of differential gain vs. injection current density from 20°C to 120°C.

4.1.5 Results and Analysis of Modal Gain and Differential Gain

A number of techniques are used for laser modal gain measurements, such as the Hakki-Paoli method [84] and the segmented contact method [85]. Among these gain measurement techniques, the Hakki-Paoli method is the easiest technique to employ with accuracy. Hence, decades after the technique was invented, it is still widely used in research studies regarding laser gain measurements [86, 87].

The Hakki-Paoli method requires high resolution spectroscopy. The method calculates the net modal gain (G_{net}) by the modulation depth of the Fabry-Perot (FP) resonances in the amplified spontaneous emission (ASE) spectrum. Consequently,

a fully resolved optical spectrum is required to show the peaks and the valleys of the FP resonances clearly (as shown in Figure 4.10(a)).

Figure 4.10 A graph of the spectra of the amplified spontaneous emission (ASE) of the *p*-doped (16 acceptors/QD) laser measured at 20°C under an injection current of 30mA. (a) is a magnification of the FP resonances in the red rectangle in (b).

In order to achieve this high resolution, the Optical Spectrum Analyzer (OSA) was set to a resolution of 0.02nm with the sensitivity grade on “HIGH 1” in our

measurements. An ASE spectrum of the p -doped (16 acceptors/QD) laser is shown in Figure 4.10, which was measured at 20°C under an injection current of 30mA. Figure 4.10(a) shows the magnification of the FP resonances centred around 1.3μm in Figure 4.10(b). The modulation depth S was determined by the intensity of the two adjacent peaks (p_i and p_{i+1}) and the valley (v_i) in-between, which is expressed as:

$$S = \frac{p_i + p_{i+1}}{2v_i} \quad (4.19)$$

Following the Hakki-Paoli method, the net modal gain was determined by the following equation [84]:

$$G_{net} = \Gamma g - \alpha_i = \frac{1}{L} \left[\ln \left(\frac{\sqrt{S} - 1}{\sqrt{S} + 1} \right) - \frac{1}{2} \ln(R_1 R_2) \right] \quad (4.20)$$

where Γ is the optical confinement factor, g is the material gain, α_i is the internal loss, L is the cavity length, and R_1 and R_2 are the reflectivity of the two facets in the lasers. Since the facets of our devices are as-cleaved, $R_1 = R_2 = R$. The reflectivity R is dependent on the refractive index (n) of the laser facets. According to the Fresnel equations, the expression is:

$$R = \left(\frac{n-1}{n+1} \right)^2 \quad (4.21)$$

where n is determined by the following equation [70]:

$$n = \frac{\lambda^2}{2\Delta\lambda L} \quad (4.22)$$

where $\Delta\lambda$ is the mode spacing (the wavelength difference between the two adjacent intensity maxima in the ASE spectrum) as shown in Figure 4.10(a).

Figure 4.11 A graph of the net modal gain spectra of the *p*-doped (16 acceptors/QD) laser measured under an injection current from 25mA to 37mA at 20°C.

The net modal gain spectra of the *p*-doped (16 acceptors/QD) laser calculated by the above equations are shown in Figure 4.11. As the injection current increased from 20mA to 35mA, the net modal gain spectrum rose with a higher peak value. After the injection current reached the threshold current of the device, which is 37mA in this device, the net modal gain pinned at its threshold value ($\sim 7.6\text{cm}^{-1}$).

Figure 4.12 Plots of the peak net modal gain vs. the injection current density from 20°C to 120°C for the (a) undoped, (b) *p*-doped (8 acceptors/QD), and (c) *p*-doped (16 acceptors/QD) InAs/GaAs QD lasers.

The peak net modal gain extracted from the gain spectra of the undoped, p -doped (8 acceptors/QD), and p -doped (16 acceptors/QD) laser devices from 20°C to 120°C is plotted versus injection current density in Figure 4.12. As shown in the figure, the peak net modal gain curves shifted to a higher injection current density as temperature increased. This shift occurred because the increase in the temperature increased the non-radiative recombination. Consequently, the device needed a higher injection current density to reach the same gain level. However, for the p -doped (16 acceptors/QD) laser, the gain profiles were similar to each other from 20°C to 80°C as shown in Figure 4.12(c), which implies that this device was temperature insensitive. This was inconsistent with the characteristic temperature behaviour observed at the same temperature range shown in Figure 4.4.

In order to ease the comparison of the modal gain properties in the undoped, p -doped (8 acceptors/QD), and p -doped (16 acceptors/QD) lasers, the peak gain profiles of the three devices at 20°C, 80°C, and 120°C are plotted in Figure 4.13. Comparing the undoped laser (solid symbols) with the p -doped (8 acceptors/QD) laser (open symbols) as the temperature increased from 20°C (squares) to 120°C (triangles), the difference between the peak net modal gain of both lasers became larger. This implies that the modal gain of the p -doped (8 acceptors/QD) laser was less sensitive to temperature variation. For the p -doped (16 acceptors/QD) laser (cross-open symbols), the thermal effect on the net modal gain was quite limited since the net modal gain profiles were almost the same at 20°C and 80°C (circles). Furthermore, the p -doped (16 acceptors/QD) laser modal gain showed better performance than that of the undoped laser at 120°C since the undoped laser gain tended to saturate faster. The results further prove that the p -doped laser had better

temperature stability than the undoped laser.

Figure 4.13 Plots of the peak net modal gain vs. the injection current density at 20°C, 80°C and 120°C for the undoped laser (solid symbol), *p*-doped (8 acceptors/QD) laser (open symbol), and *p*-doped (16 acceptors/QD) laser (cross-open symbol).

Figure 4.14 Graphs of differential gain (dG/dJ) vs. injection current density from 20°C to 120°C for the (a) undoped, (b) *p*-doped (8 acceptors/QD), and (c) *p*-doped (16 acceptors/QD) InAs/GaAs QD lasers. The solid lines are guides to the eye.

In order to investigate the doping effect on differential gain (dG/dJ) of QD lasers, we differentiated the modal gain curves of the undoped, p -doped (8 acceptors/QD), and p -doped (16 acceptors/QD) lasers in Figure 4.12 and plotted the dG/dJ of the three lasers as a function of injection current density at different temperatures in Figure 4.14. As shown in Figure 4.14(a)-(c), the differential gain decreased as the injection current density increased for all of the devices. The lines are guides to the eye and are plotted jointly in Figure 4.15 for comparison. As shown in Figure 4.14, the experimental differential gain showed a similar current dependence to the calculated results in Figure 4.9 (i.e. it decreased following an increase in the injection current and then reached a stable minimum which corresponded to the region of gain saturation). Based on the weak guiding approximation and the rate equation model, which was described in the previous section, the effect of temperature on differential gain was relatively small at a low injection current, whereas a negligible effect of temperature on the differential gain was observed at high injection current. Therefore, the dependence of dG/dJ on injection current density obtained under different operating temperatures should be accurate enough to reflect the characteristics of the differential gain in QD lasers. This also suggests that the measurement method used and described in this study is an effective experimental approach to obtain modal gain and differential gain characteristics of QD lasers.

Figure 4.15 clearly shows that the p -doped (8 acceptors/QD) laser has a larger differential gain compared to the undoped laser, once again proving that p -type doping can improve the laser differential gain. However, it is noted that, for the p -doped (16 acceptors/QD) laser, the improvement in the differential gain is quite

limited. The device showed a differential gain value which was comparable to that of the p -doped (8 acceptors/QD) laser. This could be due to the side effects of p -doping, which increase internal losses, decrease the carrier lifetime [71, 73], and increase the gain compression factor [88] and, hence, limit the improvement in differential gain.

Figure 4.15 A graph of the trends of differential gain as a function of injection current density for the undoped, p -doped (8 acceptors/QD), and p -doped (16 acceptors/QD) QD lasers.

Instead of using dG/dJ , dG/dN is frequently used to express the differential gain of lasers. The following equation is used to convert dG/dJ to dG/dN [89],

$$dG/dN = \frac{dG/dJ \times dJ/dN}{\Gamma} = dG/dJ \times \frac{qd}{\pi\Gamma} \quad (4.23)$$

where q is the electronic charge, d is the thickness of the active layer, τ is the

carrier life time, and Γ is the optical confinement factor. In our calculation, we use the following values: d is 400nm, τ is 0.5ns, and Γ is 0.03. After calculation, dG/dN is in the order of 10^{-16}cm^{-2} , which is consistent with the reported values [89, 90].

From the amplified spontaneous emission spectra, we can extract another important laser parameter, the linewidth enhancement factor (α_H) introduced by Henry in 1982 [91]. The expression of α_H can be written as follows [92, 93]:

$$\alpha_H \cong -\frac{4\pi}{\lambda} \frac{dn/dN}{dg/dN} \cong -\frac{2\pi}{\Delta\lambda \times L} \frac{\delta\lambda/\delta I}{\delta G_{net}/\delta I} \quad (4.24)$$

where n is the refractive index, N is the carrier density, g is the material gain, $\Delta\lambda$ is the mode spacing in the ASE spectrum, L is the laser cavity length, $\delta\lambda/\delta I$ is the change in wavelength with injection current, and $\delta G_{net}/\delta I$ is the change in net modal gain with injection current. The linewidth enhancement factors calculated by the above equation for the undoped and p -doped lasers are shown in Figure 4.16. All of the three curves in the figure were measured in near threshold condition at 20°C. As one can see, the p -doped (8 acceptors/QD) laser shows a near zero α_H , which is smaller than the undoped laser by a value of 1 at their emission wavelength, this may be due to the smaller carrier density in the excited states of the p -doped QDs near threshold [83, 94]. For the p -doped (16 acceptors/QD) laser, the linewidth enhancement factor was measured at a much higher current than the other two lasers, because the threshold current of the p -doped (16 acceptors/QD) laser is about three times higher than the other two devices. Therefore, the negative linewidth enhancement factor in the p -doped (16 acceptors/QD) laser may be caused by the thermal effect due to Joule heating.

Figure 4.16 Linewidth enhancement factors as a function of wavelength for the undoped, *p*-doped (8 acceptors/QD), and *p*-doped (16 acceptors/QD) lasers measured near threshold at 20°C.

4.1.6 Summary

In summary, we studied the temperature dependent threshold current density, modal gain, and differential gain of QD lasers with different doping densities. The results show that a QD laser with a doping density of 8 acceptors/QD has a lower threshold current density and a larger characteristic temperature due to the interaction between the increased internal loss and improved carrier confinement induced by *p*-doping. Notably, the *p*-doped QD lasers showed a larger differential gain compared to the undoped device, implying that *p*-doping can enhance the high speed modulation performance in QD lasers. The *p*-doped laser with a high doping

density of 16 acceptors/QD showed an almost infinite T_0 value. However, its threshold current increased significantly and the improvement in differential gain is quite limited due to the parasitic effects of p -doping. The results indicated that an optimum condition could be achieved in QD lasers by carefully choosing the p -doping density. In this study, compared to the undoped QD laser, the device with about 8 acceptors/QD provides larger modal gain and larger differential gain coupled with low threshold current and relatively large T_0 value. This may provide guidance to future studies of the p -doping effect on QD lasers.

4.2 The p -Doping Effect on Two-State Lasing

4.2.1 Background

Recently, QD lasers have shown extremely low threshold current, high internal efficiency, and superior characteristic temperature compared to conventional QW lasers. However, these characteristics were only achieved at a relatively low injection current (especially for QD lasers with a short cavity length). On the other hand, a large injection current will lead to a second lasing peak attributed to the ES emission. As reviewed in Section 2.2.3, the ES lasing will eventually surpass the GS lasing and reduce the GS modal gain [25, 28]. Therefore, an understanding of the two-state lasing behaviour in QD lasers is highly desired. In addition, the p -doping effect on the competition between the ES and the GS lasing is not clear.

4.2.2 Objectives and Main Results

In this section, we investigate the two-state lasing competition in the InAs/GaAs

QD lasers with different doping levels. The competition between the ES and the GS lasing is explained based on the modal gain behaviour in the lasers. In the experiments, we measured the lasing spectra and the net modal gain around the ES lasing threshold. Simultaneous two-state lasing behaviour was clearly demonstrated for QD lasers with different doping densities. The results show that QD lasers with a relatively light doping density can largely suppress the ES lasing, which could provide guidance to future studies on the p -doping effect in QD lasers.

4.2.3 Experiments, Results, and Analysis

The same three laser structures described in the previous section were investigated in this study. The doping densities of the three lasers were 0, 8 and 16 acceptors/QD. The wafers were fabricated into 4 μ m-wide ridge waveguide lasers with the pulsed anodic oxidation method and were cleaved into laser diodes with a cavity length of 1mm.

The lasing spectra of an undoped laser measured at 20°C are depicted in Figure 4.17. At an injection current of 270mA, only GS lasing was observed. As the injection current increased to 290mA, two simultaneous lasing peaks were present in the spectra. The peak centred at around 1250nm corresponded to the ES emission, which had a larger transition energy compared to the GS transition. After further increasing the injection current to 310mA, the GS emission was totally suppressed by the ES emission and, hence, only the ES lasing peak was observed in the spectra. Similar phenomena were observed in the two p -doped laser devices. The observation in Figure 4.17 could be explained by gain competition in the device.

Figure 4.17 A graph of the lasing spectra of the 1.3μm undoped InAs/GaAs QD laser at 20°C.

The GS and the ES modal gain profiles measured around the ES threshold current ($I_{th,ES}$) are plotted in Figure 4.18. When the injection current was above the GS threshold current ($I_{th,GS}$), the GS gain was pinned to its threshold value of 11.4cm^{-1} . Further increase in the injection current increased the stimulated emission rate from the GS, hence requiring a larger relaxation rate from the ES to the GS [95]. However, the carrier relaxation from the ES to the GS was slower than that from the barrier to the ES [71], which resulted in the accumulation of carriers in the ES (hence increasing the ES gain). Eventually, the ES lasing threshold condition was reached and simultaneous two-state lasing was observed as shown in Figure 4.17.

Figure 4.18 The peak net modal gain profiles for the undoped, *p*-doped (8 acceptors/QD), and *p*-doped (16 acceptors/QD) lasers measured around the ES lasing threshold at 20°C.

After ES lasing, the GS gain gradually decreased because the number of carriers relaxing from the ES to the GS kept decreasing upon ES lasing. This behaviour was reflected in the lasing spectra that the GS lasing was totally suppressed by the ES lasing. The ES threshold was reached earlier in the two *p*-doped lasers compared to the undoped laser. This may be due to the large number of built-in excess holes in the valence bands of the *p*-doped lasers, which may lead to an earlier population inversion in the ES transition in the *p*-doped lasers.

Figure 4.19 A graph of the ratio of ES and GS threshold current ($I_{th,ES}/I_{th,GS}$) as a function of temperature for the undoped, p -doped (8 acceptors/QD), and p -doped (16 acceptors/QD) lasers.

In order to further verify the competition between the ES and the GS lasing in QD lasers with different doping levels, we plot the ratio of the ES threshold current to the GS threshold current ($I_{th,ES}/I_{th,GS}$) for the three lasers as a function of temperature in Figure 4.19. The value of $I_{th,ES}/I_{th,GS}$ decreased as temperature increased, implying that the ES lasing is easier to achieve at high temperature. Among the three lasers, the p -doped (8 acceptors/QD) laser showed the largest $I_{th,ES}/I_{th,GS}$, implying the largest ES lasing suppression in the device. This is because the relatively light doping in QD lasers can reduce the $I_{th,GS}$. As shown in Figure 4.20, the p -doped (8 acceptors/QD) laser showed a smaller I_{th} than the other two

lasers. The reduction in I_{th} was due to the interaction between the increased internal loss and improved carrier confinement induced by p -doping, which was discussed in the previous section. When the doping density increased to 16 acceptors/QD, a nearly infinite characteristic temperature was obtained, which led to a nearly temperature insensitive $I_{th,ES}/I_{th,GS}$. However, the value of $I_{th,ES}/I_{th,GS}$ was quite small due to the large increase in $I_{th,GS}$ in the p -doped (16 acceptors/QD) laser. Therefore, the QD laser with a relatively light doping (8 acceptors/QD in our case) can largely suppress the ES lasing due to the reduction in the $I_{th,GS}$ and relatively small increase in the $I_{th,ES}$ compared to the undoped laser.

Figure 4.20 The logarithm of temperature dependent GS threshold current ($I_{th,GS}$) of the undoped, p -doped (8 acceptors/QD), and p -doped (16 acceptors/QD) lasers ($4 \times 1000 \mu\text{m}^2$) within the temperature range of 20°C-120°C.

4.2.4 Summary

In summary, we demonstrated simultaneous two-state lasing in InAs/GaAs QD lasers with different doping densities of 0, 8, and 16 acceptors/QD. The observation of the two-state lasing is explained by the modal gain profiles of the three laser devices. Our results indicate that the ES lasing could be suppressed in QD lasers by carefully choosing the p -doping density. In this study, in the p -doped laser, the ES lasing was shift to a relatively higher injection level compared its GS lasing threshold. This is helpful in reducing the linewidth enhancement factor in the device, which has been shown in Figure 4.16. In addition, the ES emission is not always a handicap, in recent studies [30], a two-state laser with an 8-THz frequency difference was realized in a two-section distributed feedback laser, which has significant potential applications as a compact and low-cost CW THz source. This may provide guidance to future studies of two-state emission QD lasers.

4.3 Geometrical Effect on QD Laser Gain

4.3.1 Background

Within the various investigations on QD lasers, only a little effort has been put into studying the geometrical effects on laser performance [33]. The few existing studies have shown that the laser ridge height, which is controlled by the etch depth during fabrication, is an important parameter for the lateral spreading current to achieve low threshold current in QW ridge waveguide lasers [34, 61, 62]. A similar effect was observed in QD lasers [33]. However, the dependence of the QD

laser gain properties on the laser ridge height is still absent. In addition, there is a lack of study regarding the effect of the ridge height on the temperature sensitivity in QD lasers.

4.3.2 Objectives and Main Results

The main objective of this study is to investigate the geometrical effect on QD laser gain and temperature sensitivity. In this research project, we systematically studied the temperature dependent threshold current density and the modal gain of QD lasers with different ridge heights. We demonstrated that the laser ridge height not only affected the threshold current, but also significantly affected the laser modal gain and the temperature sensitivity, which could be due to different lateral current spreading profiles and non-radiative surface recombination in QD lasers with different ridge heights. A theoretical model was developed to simulate the temperature dependent current spreading in the cladding layers of QD lasers. In addition, we showed that the laser ridge height also affects the injection efficiency and the internal loss in QD lasers.

4.3.3 Experiments, Results, and Analysis

Three *p*-doped (16 acceptors/QD) lasers with ridge heights (h) of 0.90 μm , 1.36 μm , and 1.75 μm were prepared by varying the etching time under the same fabrication conditions. The ridge widths of the three lasers are 4 μm with 0.2 μm variation. Figure 4.21 shows cross-sectional micrographs of the laser ridges captured by the scanning electron microscope (SEM). The devices show similar ridge shapes with different ridge heights. Figure 4.22 illustrates the position of the etch stop surface

in a simplified device structure. The devices with h of $0.90\mu\text{m}$, $1.36\mu\text{m}$, and $1.75\mu\text{m}$ correspond to the etched surface located at the middle of the top cladding layer, close to the active region, and in the active region, respectively.

Figure 4.21 Three cross-sectional SEM images of the InAs/GaAs QD lasers with different ridge heights (h) of $0.90\mu\text{m}$, $1.36\mu\text{m}$, and $1.75\mu\text{m}$.

Figure 4.22 A diagram of a simplified laser structure with different etching depths.

Figure 4.23 shows the light-output power vs. the injection current density characteristics of three QD lasers with the same cavity length (1.5mm) operating under continuous wave (CW) mode at 20°C. The laser with a ridge height of 1.36 μm exhibited the lowest threshold current density ($J_{th}=615\text{A}/\text{cm}^2$) and the highest differential efficiency ($\eta_d=41.7\%$) compared to the lasers with ridge heights of 0.90 μm ($J_{th}=1340\text{A}/\text{cm}^2$ and $\eta_d=31.4\%$), and 1.75 μm ($J_{th}=970\text{A}/\text{cm}^2$ and $\eta_d=39.8\%$). This implies that the ridge height of QD lasers plays an important role in the device performance.

Figure 4.23 The light output power vs. injection current density for InAs/GaAs QD lasers with different ridge heights (h) of 0.90 μm , 1.36 μm , and 1.75 μm .

The internal loss (α_i) and the internal efficiency (η_i) of the three devices were derived from the relationship between the inverse of external efficiency (η_d^{-1}) and laser cavity length (from 1mm to 3mm) as shown in Figure 4.24. The laser with a shallow ridge ($h=0.90\mu\text{m}$) had a much smaller η_i (~50%) than the other two lasers with higher ridges (~90%). The large difference was due to the lateral current spreading in the laser with a shallow ridge. Since the internal quantum efficiency was defined as the ratio of the carriers that contribute to the radiative recombination to the total injected carriers, the carriers that spread out laterally in the doped cladding layer were also taken into account in the total injected carriers. Therefore, the measured η_i depends on the lateral spreading current (I_{spread}) and the relationship could be expressed as [61]:

$$\eta_i = \eta_{i,act} \left(\frac{I_{total} - I_{spread}}{I_{total}} \right) = \eta_{i,act} \frac{I_{eff}}{I_{total}} \quad (4.25)$$

where $\eta_{i,act}$ is the actual internal efficiency depending only on the carrier loss due to non-radiative recombination and current leakage in the active region, which is also defined as the transverse current injection efficiency (η_t) [61]. I_{eff} is the effective current in the active region and I_{total} is the total injection current applied to the device.

For lasers with ridge heights of $1.36\mu\text{m}$ and $1.75\mu\text{m}$, I_{spread} is negligible due to the deep etching depth, which removed most of the conductive cladding layer above the active region. Hence, the measured η_i of the two lasers with a high ridge is approximated to $\eta_{i,act}$. For the laser with a ridge height of $0.90\mu\text{m}$, almost half of the cladding layer was left after the etching process. Consequently, a large number of carriers spread out laterally without contributing to radiative recombination.

Therefore, I_{eff} was small, leading to a small η_i . In addition to the internal efficiency, we also obtained the internal loss based on Equation (4.7) from Figure 4.24. The internal loss of the three devices increased as the ridge height increased. This was because the laser with the higher ridge had a larger sidewall area, which may have resulted in a relatively larger optical loss due to the light scattering at the sidewall.

Figure 4.24 A graph of inverse external efficiency (η_d^{-1}) vs. cavity length (L) for InAs/GaAs QD lasers with the different ridge heights of 0.90 μm (triangles), 1.36 μm (squares), and 1.75 μm (circles).

A temperature dependent study was conducted to investigate the effect of the ridge height on the temperature sensitivity of QD lasers. Figure 4.25 plots the logarithm of J_{th} as a function of temperature ranging from 20°C to 120°C. The laser with a ridge height of 0.90μm showed a much larger J_{th} than the laser with a ridge height of 1.36μm in the whole temperature range. This is because the injected carriers could spread out laterally in the doped cladding layer of the laser with a shallower ridge, resulting in a lower effective carrier density in the active region compared with the laser with a higher ridge. Hence, the laser with a ridge height of 0.90μm needs a larger injection current to lase. However, if the laser ridge is too high ($h=1.75\mu\text{m}$), it will expose the active region, resulting in a high carrier loss due to the non-radiative surface recombination [33, 34]. Therefore, the laser with a ridge height of 1.75μm exhibited a larger J_{th} than the laser with a ridge height of 1.36μm. In terms of the characteristic temperature, the laser with a ridge height of 1.36μm had an almost infinite T_0 from 50°C to 80°C and operated up to 120°C, while the laser with a ridge height of 0.90μm only operated below 80°C and exhibited a relatively lower T_0 of 325K from 50°C to 80°C.

Figure 4.25 The logarithm of the threshold current density vs. temperature (from 20°C to 120°C) for the InAs/GaAs QD lasers with different ridge heights of 0.90 μm (triangles), 1.36 μm (squares), and 1.75 μm (circles). The solid lines are linear fittings to the data points of the three lasers over the same temperature range for easy comparison.

The results shown in Figure 4.25 could be explained by the temperature dependent behaviour of the current spreading characteristics. The effective current density (J_{eff}) in the active region was approximated by [62, 96]:

$$J_{eff} = J_{total} (2l_s/w + 1)^{-1} \quad (4.26)$$

where w is the width of laser ridge and l_s is the current spreading length expressed as [62, 96]:

$$l_s = \sqrt{\frac{4k_B T d}{q \rho J_{eff}}} \quad (4.27)$$

where k_B is the Boltzmann constant, T is the temperature, q is the elementary charge, ρ is the cladding layer resistivity, and d is the distance between the etched surface and active region, which was equal to $(1.7\mu\text{m} - h)$ in our case. In the calculation, ρ is determined by the hole concentration p and the hole mobility μ_h , which are both temperature dependent, and the relationship is expressed as:

$$\rho = \sigma^{-1} \cong (pq\mu_h)^{-1} \quad (4.28)$$

where σ is the conductivity. The hole concentration p is determined by the approximate formula of the Fermi-Dirac integral:

$$p = N_V \exp\left(-\frac{E_F - E_V}{k_B T}\right) \quad (4.29)$$

where E_F and E_V are the energy of the Fermi level and the valence band-edge, respectively. N_V is the valence band-edge density of states and is defined by the following equation:

$$N_V = 2 \left(\frac{m_h^* k_B T}{2\pi \hbar^2} \right)^{3/2} \quad (4.30)$$

where m_h^* is the hole effective mass and $\hbar$ is the reduced Planck's constant.

The temperature dependence of the hole mobility was estimated from experimental results in the literature [97]. This relationship is expressed as:

$$\mu_h = A \left(\frac{T}{300} \right)^m \quad (4.31)$$

where A is a constant and m is estimated to be 1.3 from experimental measurements [97]. Therefore, combining Equations (4.28)-(4.31), we have an expression of the temperature dependent resistivity:

$$\rho = \rho_0 \left(\frac{300}{T} \right)^{1/5} \exp \left[\left(\frac{E_F - E_V}{k_B} \right) \left(\frac{1}{T} - \frac{1}{300} \right) \right] \quad (4.32)$$

where ρ_0 is the resistivity of the top cladding layer at room temperature and is estimated to be $0.25\Omega\cdot\text{cm}$ from the literature [62, 98]. By combining Equations (4.26), (4.27), and (4.32), the ratio of J_{eff} to J_{total} was calculated as a function of temperature for the lasers with different ridge heights, which are plotted in Figure 4.26. For the laser with a ridge height (h) of $1.75\mu\text{m}$, we assumed that there was no spreading current since the cladding layer was completely removed. Hence, $J_{eff}/J_{total} = 1$ for this laser. As depicted in Figure 4.26, the curve of the laser with a ridge height of $0.90\mu\text{m}$ shows a larger slope than the other two lasers, which implies that this laser is more sensitive to temperature. This is consistent with the observation of characteristic temperature in Figure 4.25, where the lasers with ridge heights of 1.75 and $1.36\mu\text{m}$ have larger T_0 than the laser with a ridge height of $0.90\mu\text{m}$. From 90°C to 120°C , the laser with a ridge height of $1.75\mu\text{m}$ showed a smaller T_0 (150K) than the laser with a ridge height of $1.36\mu\text{m}$ (270K). The difference of the characteristic temperature values may be due to a larger increase of the surface recombination rate at the exposed active region of the laser with a higher ridge at high temperature.

Figure 4.26 The calculated ratio of J_{eff} to J_{total} as a function of temperature for lasers with different ridge heights of $0.90\mu m$, $1.36\mu m$, and $1.75\mu m$.

The peak net modal gain characteristics of the three lasers measured using the Hakki-Paoli method [84] at $20^\circ C$, $80^\circ C$, and $120^\circ C$ are compared in Figure 4.27. At $80^\circ C$, the laser with a ridge height of $0.90\mu m$ showed gain saturation while the laser with a ridge height of $1.36\mu m$ exhibited a similar modal gain at $20^\circ C$ and $80^\circ C$. The modal gain saturation in the laser with a ridge height of $0.90\mu m$ could be due to the presence of a large lateral spreading of carriers in the p -doped cladding layers at high temperature. As shown in Figure 4.26, J_{eff}/J_{total} decreased faster in the laser with a shallow ridge as the temperature increased, which meant that more carriers spread out laterally instead of being injected into the active region. Hence, the laser with a ridge height of $0.90\mu m$ had a lower carrier density

in the active region compared to the other two lasers under the same injection level, resulting in a slower increase in the modal gain, leading to earlier gain saturation. In addition to the increase in spreading current at high temperature, the device heating due to the large injection current in the laser with a ridge height of $0.90\mu\text{m}$ may also contribute to the gain saturation. At 120°C , the modal gain profile of the laser with a ridge height of $1.75\mu\text{m}$ shows saturation behaviour, which again proves that the laser with a ridge height of $1.36\mu\text{m}$ has the best temperature stability among the three devices. Hence, the optimum ridge height in our QD lasers should be within the range of $1.36\mu\text{m}$ to $1.7\mu\text{m}$.

Figure 4.27 Peak net modal gain vs. injection current density at 20°C (squares), 80°C (circles), and 120°C (triangles) for InAs/GaAs QD lasers with different ridge heights of $0.90\mu\text{m}$ (cross-open symbols), $1.36\mu\text{m}$ (solid symbols), and $1.75\mu\text{m}$ (open symbols), respectively.

4.3.4 Summary

In summary, we studied the temperature dependent threshold current density and the modal gain of QD lasers with different ridge heights. The results show that QD lasers with a ridge height of $1.36\mu\text{m}$ have a lower threshold current density and a larger characteristic temperature due to the suppression of lateral carrier spreading and relatively small sidewall surface recombination. The comparison of the net modal gain profiles of the three lasers further proves that the laser with a ridge height of $1.36\mu\text{m}$ has the best temperature stability. Overall, the results suggest that the optimum ridge height corresponds to the etched surface located just above the active region, thus minimizing the spreading current without increasing surface recombination, resulting in reduction of threshold current and improvement of temperature sensitivity, which are both important for achieving high performance QD lasers.

4.4 The Self-Heating Effect in QD Lasers

4.4.1 Background

A laser operating under CW mode is well-known to encounter self-heating effects that degrade the laser performance, especially at high injection currents and high temperatures. Within the various investigations on QD lasers, only a little effort has been put into studying the self-heating effect on laser performance. As stated in Section 2.2.5, researchers have shown that the thermal conductivity of QD materials is about one order lower than that of the QW materials and it is two orders lower than that of the bulk materials due to the incoherent phonon scattering by the QDs [35, 65], which suggests that a more serious self-heating effect would

be present in QD devices. However, only a few investigations on the self-heating effect in QD lasers have been reported [36-38]. None of these has studied the self-heating effect on modal gain of QD lasers and the role that the p -type modulation doping plays in device heating.

4.4.2 Objectives and Main Results

In this section, we investigate the self-heating effect in 1.3 μ m InAs/GaAs QD lasers by comparing how the device performance changes between continuous wave (CW) and pulsed modes. Three types of QD lasers with different doping concentrations were measured in CW and pulsed modes with the heat sink temperature adjusted from 20°C to 120°C. We measured the thermal resistances (R_{th}) of the three devices and demonstrated significant reductions in the self-heating effect on threshold current density (J_{th}) and modal gain of the p -doped lasers compared to the undoped laser, which could provide guidance to reduce the self-heating effect in QD lasers.

4.4.3 Experiments, Results, and Analysis

In order to study the self heating effect in QD lasers, we first determined the thermal resistances of the undoped, p -doped (8 acceptors/QD), and p -doped (16 acceptors/QD) lasers. Assuming that the emission wavelength (λ) is a function only of temperature in the active region, we derived the thermal resistances (R_{th}) of the devices from the following equation [99]:

$$R_{th} = \frac{\Delta T}{\Delta P_{heat}} = \frac{\Delta \lambda}{\Delta P_{heat}} \times \left(\frac{\Delta \lambda}{\Delta T} \right)^{-1} \quad (4.33)$$

where P_{heat} is the total heating power, which is the difference between the total injected electrical power and the light output power, and T is the temperature of the heat sink. To calculate the two terms $\Delta\lambda/\Delta P_{heat}$ and $\Delta\lambda/\Delta T$ in Equation (4.33), the emission spectra of the three types of lasers were measured under different injection currents and heat sink temperatures. Figure 4.28 shows the emission spectra of the p -doped (16 acceptors/QD) laser obtained by varying the injection current from 40mA to 150mA in CW mode at 20°C. Figure 4.29 shows the emission spectra of the same device measured at heat sink temperatures from 20°C to 120°C at a constant injection current of 100mA. The spectra in the figures are normalized to the strongest one and plotted on a linear scale.

Figure 4.28 A graph of the CW spectra of the p -doped (16 acceptors/QD) laser as a function of injection current from 40mA to 150mA at 20°C.

Figure 4.29 The CW spectra of the *p*-doped (16 acceptors/QD) laser as a function of heat sink temperatures from 20°C to 100°C under constant injection current of 100mA.

Figure 4.30 shows the plots of the emitted peak wavelength as a function of total heating power (P_{heat} in Equation (4.33)) for the undoped (squares), *p*-doped (8 acceptors/QD) (circles), and *p*-doped (16 acceptors/QD) (triangles) lasers, which are extracted from the emission spectra (as shown in Figure 4.28) of the three types of devices obtained by varying the injection current in CW mode at 20°C. The peak wavelength changed linearly with P_{heat} and the rates of $\Delta\lambda/\Delta P_{heat}$ for the undoped, *p*-doped (8 acceptors/QD), and *p*-doped (16 acceptors/QD) lasers are 0.063nm/mW, 0.047nm/mW, and 0.059nm/mW, respectively. At a constant

injection current, the emission spectra (as shown in Figure 4.29) of the three devices were measured at heat sink temperatures from 20°C to 120°C. The emission peaks were well fitted by linear functions with slope coefficients ($\Delta\lambda/\Delta T$) of 0.30nm/°C, 0.34nm/°C, and 0.23nm/°C for the undoped, *p*-doped (8 acceptors/QD), and *p*-doped (16 acceptors/QD) lasers, respectively (see Figure 4.31). Substituting the values of $\Delta\lambda/\Delta P_{heat}$ and $\Delta\lambda/\Delta T$ in Equation (4.33), we can estimate the R_{th} of the undoped, *p*-doped (8 acceptors/QD), and *p*-doped (16 acceptors/QD) lasers. These thermal resistances are 210°C/W, 138°C/W, and 257°C/W, respectively.

Figure 4.30 A graph of the emitted peak wavelength vs. the total heating power (P_{heat} in Equation (4.33)) for the undoped (squares), *p*-doped (8 acceptors/QD) (circles), and *p*-doped (16 acceptors/QD) (triangles) InAs/GaAs QD lasers.

Figure 4.31 A graph of the emitted peak wavelength vs. the heat sink temperature for the undoped (squares), *p*-doped (8 acceptors/QD) (circles), and *p*-doped (16 acceptors/QD) (triangles) InAs/GaAs QD lasers.

Figure 4.32 shows the threshold current density as a function of heat sink temperatures ranging from 20°C to 120°C measured in CW (solid symbols) and pulsed (open symbols) modes. In pulsed mode measurements, the duty cycle and pulse width of the current pulses are set to 1% and 1μs, respectively.

Figure 4.32 The threshold current density (J_{th}) vs. temperature (from 20°C to 120°C) for the undoped (squares), p -doped (8 acceptors/QD) (circles), and p -doped (16 acceptors/QD) (triangles) InAs/GaAs QD lasers measured in CW (solid symbols) and pulsed (open symbols) modes.

Compared to the undoped laser, the p -doped (8 acceptors/QD) laser showed a smaller divergence between the curves obtained in CW and pulsed modes as temperature increased. This was due to the smaller R_{th} in the device, which implied a faster heat dissipation rate. In addition, less heat is accumulated in the p -doped (8 acceptors/QD) laser due to the lower J_{th} compared to the undoped laser. Therefore, the difference between the operations of CW and pulsed modes in the p -doped (8 acceptors/QD) laser was less than that in the undoped laser, implying a weak self-heating effect in the p -doped (8 acceptors/QD) laser. For the p -doped (16

acceptors/QD) laser, although it had a relatively larger R_{th} , its characteristic temperature was slightly negative from 20°C to 100°C in pulsed mode. This slightly negative characteristic temperature implies that, even though the temperature in the active region was much higher than the heat sink temperature, the J_{th} of this laser was unchanged or even reduced due to the negative characteristic temperature. Therefore, the difference between the J_{th} of the p -doped (16 acceptors/QD) laser measured in CW and pulsed modes becomes significant only in a higher temperature range.

The peak net modal gain characteristics of the three lasers measured using the Hakki-Paoli method [84] at heat sink temperatures of 20°C, 80°C, and 120°C in CW and pulsed modes are compared in Figure 4.33. At 20°C, the modal gain of the p -doped (16 acceptors/QD) laser in CW and pulsed modes was almost the same due to its good temperature stability. The difference of modal gain in CW and pulsed modes in the other two lasers was similar to each other at low temperatures. When the heat sink temperature increased to 80°C, the self-heating effect in the undoped and the p -doped (8 acceptors/QD) lasers became significant. The gain characteristics of both lasers in CW mode shifted to higher injection levels compared to those measured in pulsed mode. The shift in the undoped laser was larger than that in the p -doped (8 acceptors/QD) laser due to the larger R_{th} in the undoped device (note that the horizontal axes in Figure 4.33(a) and (b) are in the same scale).

Figure 4.33 Graphs of peak net modal gain vs. injection current density at 20°C (squares), 80°C (circles), and 120°C (triangles) for (a) undoped, (b) *p*-doped (8 acceptors/QD), and (c) *p*-doped (16 acceptors/QD) InAs/GaAs QD lasers measured in CW (solid symbols) and pulsed (open symbols) modes.

For the p -doped (16 acceptors/QD) laser, the gain characteristic in pulsed mode at 80°C performed better than the gain characteristic at 20°C due to the negative characteristic temperature. As the heat sink temperature further increased to 120°C, the gain characteristic of the undoped laser in CW mode showed a thermal saturation due to the large accumulated heat. Compared to the p -doped lasers, the difference in the gain profiles measured in the two operating modes in the undoped laser is more significant, which implies that p -doping largely suppresses the self-heating effect in laser diodes.

4.4.4 Summary

In summary, we studied the self-heating effect on threshold current density and modal gain of QD lasers with different doping densities. The results show that QD lasers with doping density of 8 acceptors/QD exhibit a weaker self-heating effect compared to the undoped laser due to their lower threshold current density and thermal resistance. Further increasing the doping density to 16 acceptors/QD leads to an infinite or even negative characteristic temperature, which significantly reduces the self-heating effect. However, the drawback in this device is its large threshold current. The results indicate that a light p -doping density of around 8 acceptors/QD in the QD laser suppresses the self-heating effect while achieving the same modal gain as the undoped laser with low injection current. This may provide guidance to future studies on arresting the self-heating effect in QD lasers.

Chapter 5 Conclusions and Recommendations

5.1 Conclusions

In this thesis, I described the study of the 1.3 μm ten-layer InAs/InGaAs/GaAs QD lasers with different doping concentrations. The lasers were characterized to investigate various factors affecting laser modal gain and, hence, to suggest better conditions of QD laser growth and fabrication to improve the device performance. The research conducted over the past four years was wide in its range and it primarily consisted of the theory, fabrication, experimental testing, and characterization of QD lasers.

First, the p -type modulation doping effect on the threshold current density, modal gain, and differential gain of QD lasers was investigated in the temperature range of 20°C to 120°C. The results show that a QD laser with a doping density of 8 acceptors/QD had a lower threshold current density and larger characteristic temperature, which is attributed to a competition between increased internal loss and improved carrier confinement induced by the p -doping. In addition to the threshold current and the characteristic temperature, the p -doped QD laser with a doping density of 8 acceptors/QD also showed larger modal gain and differential gain compared to the undoped device. This is consistent with the theoretical results calculated by Shchekin and Deppe [20], who suggested that p -doping can enhance the modal gain and high speed modulation performance in QD lasers. As the p -doping concentration increased to 16 acceptors/QD, an almost infinite T_0 value was obtained. However, the threshold current of this device increased significantly

and the improvement in differential gain was quite limited due to the parasitic effects of p -doping. The overall results indicated that an optimum condition could be achieved in QD lasers by carefully choosing the p -doping density. In this study, compared to the undoped QD laser, the device with about 8 acceptors/QD provides greater modal gain and differential gain coupled with low threshold current and relatively high characteristic temperature.

In addition to the p -doping effect on the GS gain of QD lasers, we also studied the competition of the GS and the ES gain in QD lasers with different doping concentrations. The simultaneous two-state lasing in InAs/GaAs QD lasers was demonstrated. The observation of two-state lasing could be explained by the ES and GS modal gain behaviours of the three laser devices where the carrier relaxation from the ES to GS was slower than the carrier relaxation from the barrier to ES. This resulted in the accumulation of carriers in the ES and, hence, increased ES gain. Eventually, the ES lasing threshold condition was reached and simultaneous two-state lasing was achieved. After ES lasing, the GS gain decreased due to a decrease in the number of carriers relaxing from ES to GS. By comparing the threshold current densities of the ES and GS lasing in QD lasers with different doping densities, we found that the ES lasing could be suppressed by modest p -type modulation doping. In this study, compared to the undoped QD laser, the device with the doping density of 8 acceptors/QD largely suppressed the ES lasing.

Next, we studied the temperature dependent threshold current density and the modal gain of QD lasers with different ridge heights. Devices with ridge heights of

0.90 μm , 1.36 μm , and 1.75 μm (corresponding to the etched surface located at the middle of the top cladding layer, close to the active region, and in the active region) were prepared. The results show that QD lasers with a ridge height of 1.36 μm had lowest threshold current density and high characteristic temperature due to suppression of lateral carrier spreading and minimization of surface recombination. The net modal gain profiles of lasers with ridge heights of 0.90 μm and 1.75 μm showed a modal gain saturation earlier than the net modal gain profile of the laser with a ridge height of 1.36 μm . This finding further proved that the latter device has the best temperature stability. Overall, the results suggested that an optimum ridge height corresponding to locating the etched surface just above the active region reduces the threshold current and improves laser modal gain and temperature sensitivity, both of which are important for achieving high performance QD lasers.

Finally, we studied the self-heating effect on the threshold current density and modal gain of QD lasers. Three devices with doping densities of 0, 8, and 16 acceptors/QD were investigated in both continuous wave and pulsed operating modes. The results show that a QD laser with a doping density of 8 acceptors/QD exhibited weaker self-heating effect compared to the undoped laser due to the lower threshold current and thermal resistance. For the device with a doping density of 16 acceptors/QD, a negative characteristic temperature from 20°C to 100°C was observed, which significantly reduced the self-heating effect in this device. However, the drawback is that the large doping concentration induced a large threshold current in the device due to increased non-radiative recombination. The overall results suggest that light *p*-doping of around 8 acceptors/QD in a QD

laser could suppress the self-heating effect to achieve the same modal gain as the undoped laser with a low injection current. This provides good guidance to future studies on arresting the self-heating effect in QD lasers.

5.2 Recommendations for Future Research

In our study, we clearly demonstrated the improvement in modal gain and differential gain in p -doped QD lasers. However, the direct modulation frequency of our devices is about 7GHz [100], which is not high enough to fulfil the requirements of fibre-optic communication applications. Therefore, future studies should focus on improving high speed performance in QD lasers.

Besides p -type modulation doping, there are several ways to improve the laser modal gain, differential gain and, hence, improve the high speed modulation performance in QD lasers. Tunnelling injection is a promising technique to improve the modulation bandwidth of QD lasers [101, 102]. As shown in Figure 5.1, carriers injected from the cladding layer are first thermalized in a wide injector layer to cool down. The thermalized carriers then tunnel through the thin barriers into the QDs without heating other carriers or phonons, which results in reduced carrier leakage from the active region and radiative recombination in the cladding layers. As a result, both the characteristic temperature and differential gain of a tunnelling injection QD laser will be enhanced, leading to an enhanced modulation bandwidth. A recent report has demonstrated a tunnelling injection QD laser with a modulation bandwidth of ~25GHz [103]. However, the characteristic temperature of the tunnelling injection QD lasers is lower than that of the p -doped QD lasers.

Therefore, combining the advantages of the *p*-type modulation doping technique and the tunnelling injection technique should be a good direction for future research on QD lasers.

Figure 5.1 Diagram of the energy band of a tunnelling injection QD laser [104].

In addition to the tunnelling injection technique, mode-locked QD lasers also attract intensive investigations [105-107]. The basic working principle of the mode-locking technique is to lock the phases of the longitudinal modes in a QD laser, which results in very short pulses with a repetition rate that is determined by the device cavity length. A typical structure of the mode-locked QD laser is shown in Figure 5.2. The device contains two sections: a short absorber and a long gain section. The absorber saturates faster than the gain section and, hence, only a short window opens for the pulse amplification, which shortens the laser pulses and

leads to laser mode locking.

Compared to QW devices, QD structures have significant advantages since they exhibit larger material gain in the gain section and faster recovery time in the absorber, which further shortens the laser pulses and lead to a high frequency of 40GHz in the mode-locked QD laser [51]. However, the performance of mode-locked QD lasers at higher temperatures is limited by the early gain saturation in the ground-state lasing. Since p -type modulation doping can improve the device characteristic temperature to infinity and suppress the excited-state lasing, we recommend investigating mode-locked p -doped QD lasers in future studies, which may realize temperature-insensitive mode-locked laser diodes.

Figure 5.2 Schematic drawing of the layout and electrical connection of a mode-locked QD laser [108].

In literature, most investigations of QD lasers focus on the InGaAs/GaAs material system, which has an emission wavelength around $1.3\mu\text{m}$. However, it is important to stress that lasers with emission wavelength of $1.5\mu\text{m}$ is suitable for long-haul

optical applications due to its low transmission loss. In order to realize 1.5 μm QD lasers, InAs QDs grown on InP substrate have been developed. More particularly QD structures with very small size (4nm high) and high density (10^{11}cm^{-2}) have been grown on the specific InP(113)B substrate orientation with optimized growth techniques [109]. A QD laser based on the InP substrate with emission wavelength of 1.55 μm has been demonstrated by Grillot *et al.* [110], the spectra are shown in Figure 5.3. It provides a possible direction to realize 1.5 μm QD lasers.

Figure 5.3 Emission spectra of 1.5 μm InAs–InP(113)B QD laser [110].

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