Characterization of quantum dot lasers with post-growth thermal annealing

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CHARACTERIZATION OF QUANTUM DOT LASERS WITH POST-GROWTH THERMAL ANNEALING

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in fulfillment of the requirement for the degree of
Doctor of Philosophy

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Statement of Originality

I hereby certify that the work embodied in this thesis is the result of original research and has not been submitted for a higher degree to any other University or Institution.

Date

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SUMMARY

Self-assembled InAs quantum dot (QD) lasers operating at 1.3 μm emission have attracted considerable attention due to their expected performance improvement over quantum well (QW) lasers. The goal of this research work is to characterize and to suggest a method to improve the QD laser performance by using post-growth annealing technique. A systematic study has been performed on p-doped ten-layer InAs/InGaAs QD lasers to investigate the characteristic parameters related to lasing behavior. High power and low transparency current density have been achieved in the broad area QD laser structure, which demonstrates high temperature performance up to 100 $^{\circ}\text{C}$. With the scaling down of the ridge width to 2 μm , the laser exhibits single lateral mode high output power and near ideal external differential quantum efficiency of 96% under pulsed mode operation.

The approach of post-growth annealing is initially performed on the passive dots-in-a-well (DWELL) structure in this thesis. Interdiffusion of In and Ga atoms caused by thermal annealing has been proven from the photoluminescence (PL) measurements, where blueshifts of the energy peaks were observed. The results show that p-doped quantum dot structures are more resistant to intermixing with higher thermal energy onset, which is attributed to the suppressed Ga diffusion resulting from the Be dopant.

The post-growth thermal annealing technique is further applied to the active QD laser structure. Significant improvements in the performance of p-doped ten-layer InAs/InGaAs QD laser are demonstrated after annealing at 600 $^{\circ}\text{C}$ for 15 s. The annealed laser shows increase in the saturated output power and external differential

quantum efficiency without obvious wavelength shift. Decrease in internal loss and improvement in the threshold current are achieved. Defect reduction is thought to be the most likely mechanism contributing to the improved performance according to the electroluminescence and improved characteristic temperature behavior.

Further investigations are carried out to study the annealing effects on the device performance of the QD lasers. The competition between the ground state (GS) and excited state (ES) lasing is investigated from the as-grown and thermally annealed samples. The modal gain competition between GS and ES are measured and analyzed around the ES threshold characteristics. Our results show that two-state competition is more significant in devices with short cavity length operating at high temperature. Most importantly, the results show that by adjusting the rapid thermal annealing (RTA) temperature, the competition between the GS and ES lasing can be modified.

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1. INTRODUCTION

1.1 MOTIVATION

Rapid development in optical communications and optoelectronics technology is crucial for expediting the transition from the industrial age to the information age. Higher performance photonic components, e.g. laser diodes, are required to assist the transition technology from point-to-point optical communications systems to networks. At the present time, semiconductor double heterostructure lasers, the key components in fiber communication system, have the advantages of low power requirements, small size and cost-effectiveness. In order to realize these advances successfully, there has been intensive research in the last two decades aimed at understanding the physics and improving the performance of the semiconductor lasers.

InAs-based quantum dot (QD) lasers, using GaAs substrate, are the subject of research effort due to their potential for application in the 1.3 μm fiber optical communication system. With the three-dimensional (3D) confinement of carriers, the InAs QD lasers offer potential improved performance in terms of low threshold current density, high material and differential gain and improved thermal stability, whilst exploiting the lower cost GaAs technology. However, in reality not all the advantages have been realized and this may explain why the QD devices have not yet become commercially available compared to quantum well (QW) devices. Currently, the most promising method for fabricating QDs is based on the effect of spontaneous nanoislanding during heteroepitaxial growth by either molecular beam epitaxy (MBE) or metal-organic chemical vapor deposition (MOCVD). Though the above mentioned self-organization methods for the production of nanostructures have been successfully used in the fabrication of small and defect-free quantum dots, their potential in

optoelectronics and nanoelectronics are severely hampered by a rather large spread in size distribution through thermal fluctuations and the complexity of the growth process involved. This process limitation imposes a great challenge to the development of robust and viable optoelectronic devices based on the QD structure.

In order to overcome the growth difficulties and improve the material qualities, the approach of post-growth thermal annealing has been proposed to offer simple and more practical schemes for the modification of the potential profile and thus the optical properties of the quantum-confined heterostructures. Quantum well intermixing (QWI) [1]-[2], a post-growth bandgap tuning technique, has been successfully employed to tune the wavelength of QW lasers and QW infrared photodetectors (QWIPs). Moreover, the post-growth annealing brings numerous benefits to the QW laser performance in terms of threshold current [3], power efficiency [4] and lateral electrical and optical confinement [5]. Unlike the QW heterostructures, the bandgap of the QD is intrinsically sensitive to thermal treatment [6]. Intermixing effect is expected to play a more important role in the QDs due to the large surface area and strain effect enclosing the QD materials as compared to the QW. In addition, the typically small dimension of QDs makes the intermixing effects more significant in changing the band structure and the optical properties of the material. Therefore, it is crucial that the three-dimensional confinement in QDs should be retained after high temperature annealing for the current research on QD intermixing. There have been many reports [6]-[9] showing that post-growth annealing affects both the height and shape of the QD confining potential without destroying its zero-dimensional density-of-states, hence changing the transition energies and the intersublevel spacing. This suggests the post-growth control of the bandgap and hence the emission wavelength could be achieved if such a technique is

utilized in the QD laser devices. Additionally, the photoluminescence (PL) linewidth of the ground state (GS) transitions significantly decreases as the intermixing increases. This indicates that the QD size and strain inhomogeneities, which are considered the main drawback of current self-assembled QDs, can be effectively reduced after the thermal annealing. The reduction in QD size distribution, suggesting the improved QD material quality resulting from the thermal annealing, is of prime importance for the development of practical QD devices. Although there have been numerous studies of post-growth annealing on the passive GaAs-based QD materials, few of them investigated the active QD devices, e.g. QD lasers. So far, apart from Djie *et al.*'s works [10]-[11], which are based on InAs/InAlGaAs quantum dash lasers on InP substrate, few investigations [12] have focused on the effects of rapid thermal annealing on the GaAs-based QD laser performance prior to this work. Therefore, this opens the research gaps for us to answer the question of how the post-growth annealing process affects the device properties of the QD lasers. Following the success of thermal annealing performed on the QW lasers and the advancement in the QD material systems, there are strong advantages and necessities to investigate the annealing effects on the QD laser devices. It is also expected that some improvements in the characteristic parameters related to the lasing operation can be achieved in this project. All these research gaps strongly motivate us to fill the unanswered blanks and seek innovative solutions for the current limitations of the QD laser systems. The successful development of this technique will open up new research windows for QD lasers, modifying the device performance with an attractive means of simple and cost-effective post-growth control.

1.2 OBJECTIVES

In view of the promising potential of the multiple-layer InAs/InGaAs QD laser structure operating at 1.3 μm fiber optical communication system, this research aims to:

- (a) Understand the working principle of the ten-layer p-doped InAs/InGaAs QD lasers.

The broad area QD laser structure with stripe width of 50 μm was used in this study.

- (b) Investigate the characteristics of QD lasers based on the narrow ridge waveguide (RWG) structure. The ten-layer p-doped InAs/InGaAs QD lasers with stripe width of 2 μm were studied under both the continuous wave (CW) and pulsed mode operation.

- (c) Examine the role of p-type doping in the QD material subjected to the post-growth thermal annealing process. Both the undoped and p-doped InAs/InGaAs dots-in-a-well (DWELL) structures were utilized for investigations.

- (d) Study the performance of annealed QD laser devices based on the optimized annealing condition. In this study, a ten-layer p-doped InAs/InGaAs QD laser structure was used for comparing the characteristic parameters of the as-grown and annealed lasers.

- (e) Suggest and develop a method to further improve the performance of the narrow RWG QD lasers.

1.3 MAJOR CONTRIBUTION OF THE THESIS

Semiconductor QD lasers are the key components for the development of future fiber optical networks. The promising structure of the ten-layer p-doped InAs/InGaAs

QD lasers emitting at $\sim 1.3 \mu\text{m}$ grown on GaAs substrate have been investigated in this project. Following the successful demonstration of high device performance in the broad area QD laser structures, the work is extended to the investigations of lasers with narrow ridge waveguide (RWG) structure to reach the design requirements for practical device applications. Based on the understanding of the role p-type doping plays in the QD material, the post-growth thermal annealing technique is introduced to the QD laser structure. Most significantly, this research demonstrates that the laser characteristic parameters and hence the lasing performance could be improved by utilizing the thermal annealing process under the optimized condition. The ability to control the device performance without regrowth of the QD material structure, suggests that thermal annealing is a promising approach to improve the performance of the QD-based systems, thus to realize their potential applications in optoelectronics and nanoelectronics. A list of the significant contributions of this work is provided below:

The broad area ten-layer p-doped $\text{InAs/In}_{0.15}\text{Ga}_{0.85}\text{As}$ QD lasers with stripe width of $50 \mu\text{m}$ have been characterized. High temperature photoluminescence (PL) up to 100°C has been demonstrated from this structure. High output power of 882 mW and low transparency current density of $5.9 \text{ A/cm}^2/\text{QD layer}$ have been measured from the $1.3 \mu\text{m}$ QD lasers fabricated using an optimized pulsed anodic oxidation (PAO) process. Due to the high ground state gain, ground state lasing can be achieved from a QD laser with short cavity length of $611 \mu\text{m}$, which corresponds to the maximum available modal gain of 23.1 cm^{-1} in this laser system. The QD lasers also demonstrate CW ground state lasing operation up to 100°C .

To reach the design requirements for practical device applications, narrow RWG lasers with stripe width of $2 \mu\text{m}$ based on a ten-layer p-doped InAs/InGaAs QD active

region have been fabricated and investigated. Under CW operation, this device ($2 \times 2000 \mu\text{m}^2$) delivered a total output power of up to 272.6 mW at 10 °C at 1.3 μm . Under pulsed operation, where the device heating is greatly minimized, the InAs QD laser ($2 \times 2000 \mu\text{m}^2$) exhibited extremely high output power (both facets) of up to 1.22 W at 20 °C, at high external differential quantum efficiency of 96%. Far field pattern measurement of the 2 μm RWG InAs QD lasers showed single lateral mode operation.

Post-growth rapid thermal annealing (RTA) has been used to investigate the intermixing and structural changes in the p-doped and undoped InAs/In_{0.1}Ga_{0.9}As dots-in-a-well (DWELL) structures. Interdiffusion of In and Ga atoms caused by thermal annealing has been proven from the PL measurements, where blueshifts of the energy peaks were observed. The results show that p-doped quantum dot structures are more resistant to intermixing with higher thermal energy onset, and the reason is explained as the suppressed Ga diffusion resulting from the Be dopant. Rapid quenching of the integrated PL intensity at high temperature has been observed in both undoped and p-doped DWELL QDs. Good agreement was obtained by fitting the integrated PL profile using two nonradiative recombination mechanisms, resulting in two activation energies that correspond to loss of carriers to nonradiative centers.

Following the success of the thermal annealing process performed on the QW structure, this approach has been extended to the investigation of the p-doped ten-layer InAs/InGaAs QD laser systems. Significant improvements in the device performance are demonstrated using RTA at 600 °C for 15 s. The annealed laser shows about 2.7 times increase in the saturated output power and external differential quantum efficiency without obvious wavelength shift. Decrease in internal loss of 2.9 cm^{-1} and improvement in the threshold current by 23% were achieved. Defect reduction is thought to be the

most likely mechanism contributing to the improved performance according to the electroluminescence and improved characteristic temperature behavior.

Finally, the competition between the ground state (GS) and excited state (ES) lasing has been investigated from the as-grown and thermally annealed ten-layer p-doped InAs/GaAs QD lasers. The modal gain competition between GS and ES are measured and analyzed around the ES threshold characteristics. Our results show that two-state competition is more significant in devices with short cavity length operating at high temperature. By comparing the as-grown and annealed devices, we demonstrate enhanced GS and suppressed ES lasing from the QD laser annealed at 600 °C for 15 s. The encouraging results suggest that thermal annealing is an attractive approach to modify the device performance if its condition is carefully designed.

1.4 ORGANIZATION OF THE THESIS

This thesis is organised into seven chapters. Chapter 1 gives an introduction of the thesis, where the motivation, objectives, and major contributions of the thesis are documented.

Chapter 2 describes the background information of QD lasers and the development of GaAs-based material, review the existing post-growth thermal annealing techniques and the details of experimental and characterisation techniques in this work.

The objectives of this project are presented in Chapters 3, 4, 5 and 6 (see Figure 1-1 for the research methodology). In Chapter 3, both the broad area and narrow RWG InAs QD lasers are described. The characteristic parameters related to the lasing

performance are reported. Chapter 4 outlines a study of the intermixing mechanism and comparison of the material property before and after the RTA process using PL measurements. Based on the investigations of the p-doped and undoped InAs/InGaAs DWELL structures subjected to the thermal annealing process, the role of p-type doping is discussed. Chapter 5 demonstrates the device performance improvement in the QD lasers based on the thermal annealing technique. Several devices with different cavity lengths are fabricated and characterized for the as-grown and annealed structures. Further studies on the annealing effects are documented in Chapter 6, where the competition between the GS and ES lasing behavior in the as-grown and thermally annealed QD lasers are presented.

Finally, Chapter 7 summarizes the major achievements in this work and puts forth some recommendations for future work.

Fig. 1-1 Diagram of overall research methodology.

1.5 AUTHOR'S PUBLICATIONS

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2. BACKGROUND INFORMATION

In this chapter, the background information on the QD lasers and the techniques used to improve such devices are presented. The annealing techniques performed on the QW and QD systems are also discussed. A brief introduction of the main experimental tools and characterisation techniques of the QD laser is documented.

2.1 QUANTUM DOT LASERS

The idea of using a double heterostructure as the active region of the semiconductor diode lasers to achieve room-temperature continuous-wave operation was originally introduced by Alferov *et al.* in 1970 [1]. The breakthrough occurred when the quantum-sized heterostructures were established in the laser system to improve the device performance. Since the first invention of quantum well lasers (van der Ziel *et al.* 1975) [2] with the carrier confinement occurring only in one direction, there have been intensive research all over the world to further increase the degrees of carrier confinement. The quantum dot laser structure with the carriers confined in three-dimensions was proposed by Dingle and Henry [3] as early as 1976. However, the real breakthrough occurred when the self-organized quantum dots based on spontaneous formation of three-dimensional islands were fabricated by Goldstein *et al.* in 1985 [4]. Since the first realization of lasing in self-organized QDs [5] in 1994, these devices have demonstrated on-going improvements in their performance.

2.1.1 Optical and electrical properties of quantum dots

The principle advantage of using size-quantized heterostructures in lasers originates from the increase in the density of states (DOS) for charge carriers near the

band edges (Fig. 2-1) [6]. As illustrated in Fig. 2-1, in contrast to QWs where the carriers are localized in the direction perpendicular to the layer but move freely in the layer plane, carriers in a quantum wire are localized in two directions. With carriers being confined in all three directions, a QD is realized with a totally discrete energy spectrum (Fig. 2-2). When the bulk structures are used as the active region of a laser device, the injected electrons fill all the available states from the band edge. As the temperature increases, the carriers begin to spread to higher energy states according to the Fermi-Dirac distribution. In order to fulfill the lasing condition, a number of states must be occupied before achieving population inversion. High threshold currents therefore characterize bulk semiconductor lasers and an increase in temperature requires a higher carrier injection rate to maintain a constant Fermi level, thus making these lasers very temperature dependent. For a QW with step-like DOS at each subband edge and a high concentration of injected carriers having the same energy, population inversion can be achieved at an earlier stage with lower threshold currents. However, because of the nature of two-dimensional quantization in a QW, it makes the QW lasers still somewhat temperature sensitive and in some applications this requires complicated and expensive circuitry to overcome these effects and maintain a constant output power. The situation is more favorable in the case of QDs where the DOS in the ideal case consists of a series of δ functions and therefore, population inversion can, in principle, be achieved with the injection of only one electron-hole pair per dot. This is the origin of low threshold advantage claimed for the QD lasers. The situation of concentration of most of the injected non-equilibrium carriers in an increasingly narrow energy range (δ function) near the bottom of the conduction band and top of the valence band, also enhances the maximum material gain and differential gain. Such large differential gain allows higher modulation frequency for high speed operation, and leads to low linewidth

enhancement factor α and low dynamic chirp. The discrete energy spectrum reduces the phonon coupling for high temperature stability. If in addition the separation of the states in the dot is greater than $\sim 3kT$ then carriers are not thermally excited into the higher energy levels and the laser threshold should be temperature insensitive [7].

Fig. 2-1 Density of states for carriers in structures with different dimensionalities [6].

Fig. 2-2 Schematic representation of energy diagrams for a single atom (left), bulk (center) and quantum dot (right) [6].

2.1.2 Growth of self-organized QDs

Though several methods were proposed to fabricate the QD structure, the real application of QD lasers became possible only when the approach of self-organized growth [8] was developed. By using the self-organized growth epitaxy, the macroscopic order of nanostructures is formed spontaneously from their initially random distributions. The driving forces for those self-organized arrays are elastic strain relaxation on facet edges, minimization of the surface energy of facets and the interaction between neighbouring islands through the strained substrate [9]. Depending on the lattice mismatch between the epitaxial layer and substrate, the formation of three-dimensional islands occurs in three modes: Frank-van der Merwe (FM) [10], Stranski-Krastanow (SK) [11] and Volmer-Weber (VM) [12], as shown in Fig. 2-3. FM mode is realized in lattice-matched system with two-dimensional layer-by-layer growth. In the case of large lattice mismatch ($>12\%$), VM mode occurs by three-dimensional islands growth. SK growth mode occurs in the case of moderate lattice mismatch ($>1.8\%$) starting with a planar growth mode (wetting layer) followed by the formation of three-dimensional islands (QDs).

Fig. 2-3 Schematic illustration of three epitaxial-growth modes: (a) Frank-van der Merve, (b) Volmer-Weber and (c) Stranski-Krastanow.

The most important features of self-organized growth are: 1) nanostructures are formed in one simple deposition step; 2) the nanostructures are ordered in size, shape and composition; 3) the nanostructures can be covered epitaxially without any crystal or interface defects. These capabilities make it a promising technique to fabricate QD lasers for the future development of cost-effective nanotechnology.

Typically, the temperature for molecular beam epitaxial (MBE) growth of In(Ga)As/GaAs QDs using SK mode is around 460-520 °C. The formation of InAs QDs is initiated at 1.5-1.7 monolayers (ML) and ends at ~2.5-3 ML (~50% overgrowth). The QD shape, size and density can be tailored through engineering the growth rate, time, temperature, material composition and substrate orientation. A rule of thumb is that faster rate, lower temperature, and shorter time lead to smaller and higher density QDs.

2.1.3 Development of self-organized quantum dot lasers

The first self-organized InGaAs QD laser was realized with threshold current density of 120 A/cm² at 77 K [13] in 1994. Soon after, room temperature operation was demonstrated for similar InGaAs/GaAs QD structures [14]. However, at room temperature, the device parameters remained worse than those of the QW devices. The reason for this is attributed to the temperature induced escape of carriers from the QDs. The approach of using stacked multiple QD layers was initially introduced to increase the density of QDs [15]. By using the stacked vertically coupled QD structure, the lasers demonstrate room temperature ground state (GS) lasing with a reduced threshold current density of 90 A/cm² [15]. Further improvements were found in the lasers with triple stacks of QDs, exhibiting the record lowest threshold current density of 13 A/cm²

[16]. It is well known that the most important novelty of using the multiple-stack technique is to improve the maximum achievable modal gain by preventing the gain saturation problem. The achievable modal gain, which is limited by the saturated gain (G^{sat}), in a single-layer QD is proportional to the surface density, i.e., $G^{\text{sat}} \propto N_{\text{QD}}$. The finite N_{QD} of the order of 10^{10} cm^{-2} in a self-assembled single-layer QD structure directly limits the available optical gain in the GS [17]. This leads to undesirable excited state (ES) lasing at high current and/or high temperature [18]. Due to the low optical confinement factor, the GS modal gain for a single QD sheet is typically 4 cm^{-1} . Use of triple stacks of QDs increases the GS modal gain to 12 cm^{-1} [19]. Using ten-fold stacks of QDs, lasers with modal gain exceeding 58 cm^{-1} have been demonstrated [20]. The general rule of thumb is the higher the number of QD layers, the less pronounced is the effect of gain saturation. However, further increase in the number of QD layers will bring growth difficulties, resulting in threading dislocations due to the accumulated strain in the layers. Non-vertically coupled QD structures, which are realized when the GaAs spacer layer between the QD planes are thick enough ($>10 \text{ nm}$), are implemented to avoid the formation of defects. So far, the optimum value of the stack number is ten for high performance QD lasers, which demonstrate high output power and reasonably low threshold current density [21].

In the early days, InAs and InGaAs QD lasers failed to achieve speed performance over planar QW laser, which was attributed to the closely-spaced energy levels of the confined holes. Using a simplified model of infinite barriers at the QD-matrix interface, and for a three-dimensional rectangular QD structure, the quantization energy is estimated as $E \sim (\pi\hbar n/L)^2/2m^*$, where n is the quantum number, m^* is the effective mass, and L is the rectangular length. In the case of GaAs-based QD ($m \sim$

$0.063m_e$ for electrons and $m \sim 0.51m_e$ for heavy holes), an energy ΔE of ~ 100 meV for electrons and ~ 10 meV for holes are obtained if $L \sim 10$ nm is used. The former is much smaller than the room temperature thermal energy of ~ 26 meV. Such closely-spaced hole levels result in thermal broadening of the hole states, which decreases the GS gain and makes the maximum gain quite temperature sensitive [22]. As illustrated in the p-doped case of Fig. 2-4, building in excess holes [23] can improve the gain characteristics of the QD layer dramatically at high temperature. While injected electrons have a high probability of residing only in the QDs' ground states, the large built-in hole concentration ensures that the injected electrons always find GS holes with which to recombine. In this manner, the gain and differential gain for GS lasing can be enhanced, and deleterious effects such as gain saturation due to hot carriers and carrier leakage associated with the thermal broadening of holes are reduced. P-doped QD lasers with remarkably improved performance such as large modulation frequency and high characteristic temperature (T_0) have been reported [24]-[26]. It is found the improvement in T_0 is mainly due to the enhanced Auger recombination [22], which increases the threshold current. Recent studies [27]-[28] show that another possible mechanism contributing to the improved T_0 , could be explained by a delayed carrier thermalization, resulting from a deeper confinement potential of electrons. Furthermore, the excess holes provided by p-doping can occupy the wetting layer states, which may severely limit the potential benefits of this technique [29].

Fig. 2-4 Schematic illustration of the QD energy levels with undoped and p-doped structure.

In summary, compared to conventional QD lasers, multiple-stacking and p-doping enable QD lasers with significantly improved performance in terms of low threshold current density J_{th} , reduced linewidth, enhanced linewidth enhancement factor α (α -factor), and high 3dB frequency f_{-3dB} for high speed operation. The current status of the self-organized QD lasers with associated figures of merit is listed in Table 2-1.

Table 2-1. Current status of self-organized QD lasers.

Figure of merit	Representative Value	References
J_{th}	7 A/cm ² (1.21 μ m broad area) 1.4 mA (1.3 μ m, single mode)	Shimizu <i>et al.</i> , 2005 [30] Libshits <i>et al.</i> , 2004 [31]
T_0	532 K (10-60 $^{\circ}$ C, p-doped) $\sim\infty$ (5-65 $^{\circ}$ C, p-doped)	Ji <i>et al.</i> , 2010 [32] Mi <i>et al.</i> , 2005 [26]
f_{-3dB}	25 GHz (1.1 μ m p-doped) 60 GHz (upper limit)	Fathpour <i>et al.</i> , 2005 [33] Asryan <i>et al.</i> , 2010 [34]
α -factor	~ 0 (p-doped) ~ 0 (p-doped)	Alexander <i>et al.</i> , 2007 [35] Kim <i>et al.</i> , 2008 [36]
Chirp	<0.2 $\text{\AA}$ (p-doped, 1.3 μ m, 2-10 GHz modulation) 0.1 $\text{\AA}$ (1.6 μ m, 2.5 GHz modulation)	Fathpour <i>et al.</i> , 2005 [33] Saito <i>et al.</i> , 2001 [34]

2.2 POST-GROWTH ANNEALING TECHNIQUE

The post-growth annealing technique is a simple and effective method used in semiconductor material processing to modify the structural and optical properties of the structure to avoid the regrowth process. Normally, atomic interdiffusion or intermixing will occur during the high temperature annealing treatment. In this section, both the quantum well and quantum dot intermixing technique will be reviewed.

2.2.1 QW intermixing

In literature, QW intermixing (QWI) is referred to interdiffusion or disordering. Heterostructure intermixing is a promising postgrowth technique used widely in QW devices and structures to modify the electrical and optical properties within the same epitaxial layer structure. During high temperature annealing, the impurities or created point defects alter the Fermi level and enhance the solubility of certain point defects [36], which result in an increase in atomic interdiffusion rate and promote QWI. The annealing process also recovers the crystal damage due to point defect creation for minimising optical and electrical degradation. This process causes graded QW bandgap profiles and, in general, results in an increase of the bandgap energy (as shown in Fig. 2-5). QW intermixing (QWI) technique [39-46] has been found to be a very useful method to achieve photonic integration due to its ability to selectively fine tune the energy bandgap in different regions within the same epitaxial layer structure, through the interdiffusion between QW and adjacent barrier material. QWI is a post-growth technique to tailor the energy bandgap across a single chip, which generates considerable interest due to its simplicity, compatibility, and effectiveness for many photonic applications. It enables various benefits such as excellent alignments, negligible

reflection losses and intrinsic mode matching. QWI has provided a very enticing vision for the future of optoelectronics.

Fig. 2-5 Postgrowth bandgap engineering process using QWI technique with its QW energy band (a) unintermixed section (b) intermixed section.

Depending on the processing schemes utilized, a number of QWI techniques have been developed, including impurity-induced disordering (IID) [40] and impurity-free vacancy disordering (IFVD) [41]. The first demonstration of IID in the AlAs/GaAs superlattice was reported by Laidig *et al.* in 1981 [40]. Among all of the QWI methods, IID is the only process, which requires the introduction of impurities into the QW materials in order to realize the intermixing process. Using IFVD technique, no penetration of impurities is required and the degree of intermixing is controlled by the diffusion of vacancies at high annealing temperature.

There are several IFVD techniques, namely dielectric cap induced intermixing [42], laser induced disordering (LID) [43] and plasma induced/suppressed intermixing [44]. The dielectric cap induced intermixing involves the formation of a dielectric capping material on the QW materials and subsequent high temperature annealing to promote the injection of vacancies from the dielectric cap to materials and hence enhance the intermixing at selected area. For instance, in GaAs/AlGaAs QW materials, SiO₂ is known to induce out-diffusion of Ga atoms during annealing, hence generating

group III vacancies in the QW material. The thermal stress at the interface between the GaAs and the SiO₂ layer plays a major role. The thermal expansion coefficient of GaAs is ten times larger than that of SiO₂. During high temperature annealing, the bonding in the highly porous SiO₂ layer deposited using PECVD may be broken due to the stress gradient between the GaAs and SiO₂ film. Thus, the out-diffusion of Ga would help to relieve the tensile stress in the GaAs. Nevertheless, As atoms may diffuse into SiO₂ during high temperature annealing. However the diffusion coefficient of As in SiO₂ is extremely low as compared to Ga. These Ga vacancies then propagate downward into the QW and enhance the interdiffusion rate of Ga and Al hence result in QWI [38]. The LID technique is first demonstrated by Epler *et al.* [45], by using a continuous wave (cw) Ar⁺ laser with a power density of ~320 kWmm⁻² to introduce encapsulated Si into the epitaxial layers as a source for IID, which takes place during thermal annealing. Laser induced disordering (LID) is a promising QWI process to achieve disordering in InGaAs-InGaAsP QW technique due to the poor thermal stability in InGaAsP material system. QWI technique based on plasma damage generated in plasma etching machine has been developed since the initial work using H₂ plasma glow discharge in a reactive ion-etching (RIE) system on GaAs/AlGaAs structures [44]. It is known that the plasma etch machine can cause damage to the substrate, which is undesirable as it can cause degradation in the electrical properties of the substrate. However, these properties can be recovered by annealing the substrate after the plasma exposure.

In summary, the QWI technique offers an effective post-growth method for the lateral integration of different bandgaps, refractive index and optical absorption within the same epitaxial layers. Additionally, high performance QW lasers based on the QWI technique have already been demonstrated [46], [47].

2.2.2 QD intermixing

The intermixing effect is expected to play an important role in QDs, because of the large surface area to volume ratio compared to the bulk or QW structure. In current In(Ga)As/GaAs QD systems, as the dimension of the QDs is typically in the order of nanometers, small interdiffusion between the dots and the surrounding materials as illustrated in Fig. 2-6, is expected to produce a significant change in the band structure and the optical properties of the materials [48], [49].

Fig. 2-6 Interdiffusion smears the alloy distribution resulting in band gap disordering in 3-dimension. Band gap profiles for the noninterdiffused (left) and interdiffused (right) QD along the x direction are shown [48].

The QD intermixing (QDI) technique is believed to be capable of both improving the performance of the active QD media and integrating the active QD sections with passive waveguide [50]. Since the late 1990s, there has been intense research [51]-[53] on the effect of QDI. In order to better investigate the interdiffusion behavior in the QD structure, several methods have been performed both experimentally and theoretically. In the initial studies, the non-destructive photoluminescence (PL) method was applied with promising results [54]-[56]. Narrowing and blueshift in the PL spectra indicates an improvement in optical property and tunability of band gap that is

necessary for device applications. A theoretical three-dimensional QD diffusion model combined with experimental PL measurements and transmission electron microscopy (TEM) was proposed to determine the effect of annealing induced interdiffusion on the electronic energy levels and energy variation in the dot ensemble [48]. Other techniques including x-ray diffraction (XRD) [57] and cross-section scanning-tunneling spectroscopy (XSTM) [58] have also been applied for investigating the atomic intermixing in QD systems. Ion channelling measurements offer evidence for mass transport of group III element (In) along or perpendicular to the growth direction (100) as a result of atomic intermixing between the QDs and their surroundings [59]. Recently, the effect of thermal annealing on the intersubband energy levels has been studied with far-infrared absorption spectroscopy [60].

Amongst those numerous studies of intermixing effects, there are few studies to investigate the intermixing effects on the QD laser device [61], [62]. This opens the research gaps for us to answer the question of how the post-growth annealing process affects the device properties of the QD lasers, which is also the motivation of this research work.

2.3 EXPERIMENTAL TECHNIQUES

The aim of this section is to present the experiments conducted in this research. The main elements comprising the experimental setup will be described in the order in which they are encountered by the samples. The topics presented will be 1) the sample design and growth, 2) device fabrication process, and 3) thermal processing using the rapid thermal processor (RTP).

2.3.1 Quantum dot laser structure

The main QD laser structure for the device characterization is a ten-layer p-doped InAs/In_{0.15}Ga_{0.85}As QD laser structure (as shown in Fig. 2-7) grown by Innolume GmbH. The structure is particularly designed for the emission wavelength at $\sim 1.3 \mu\text{m}$ of the optical communication system. The same laser structure is also used for the post-growth annealing study. Both p-doped and undoped InAs/InGaAs dots-in-a-well (DWELL) structures (as shown in Fig. 4-1 of Chapter 4) are employed to investigate the QD intermixing effect. These DWELL structures are designed and grown in our laboratory using the molecular beam epitaxy (MBE) process.

Fig. 2-7 Schematic illustration of the InAs/InGaAs ten-layer p-doped QD laser structure.

2.3.2 Laser fabrication process

The fabrication process of the edge emitting ridge waveguide QD laser is illustrated in Fig. 2-8. The QD laser wafer is firstly cleaned by acetone, isopropyl

alcohol (IPA) and de-ionized water (DI) water. The laser stripe (Fig. 2-9) is formed by standard photolithography and wet etching. After coating with positive photoresist (AZ 1518), the wafer is exposed under UV light and developed to form the laser stripe pattern. The width of the stripe is dependent on the mask used during the photolithography step. In this project, stripe widths of 2-4 μm are established to realize a narrow RWG laser structure, and stripe width of 50 μm is also included for the broad area laser characterization. A wet etching ($\text{H}_3\text{PO}_4\text{:H}_2\text{O}_2\text{:DI water} = 1\text{:}1\text{:}5$) process follows, and good control of the etch depth is necessary to achieve the narrow RWG structure, since the refractive index step between the ridge and trench region is determined by the etch depth. Through optimization of the ridge height [63]-[64], the entire p-doped layers above the QD active region outside the ridge is etched before the pulsed anodic oxidation (PAO) process. The novelty of the fabrication process is the utilization of pulsed anodic oxidation (PAO) to form a native oxide layer at room temperature for both electrical and optical confinement, which will be discussed in the following sections. Before removal of the photoresist, the wafer is subjected to a dielectric oxidation process for better electrical and optical confinement. Subsequently, p-type ohmic contact layers (Ti/Au, 50/300 nm) are deposited by electron beam evaporation, while n-type ohmic contact layers (Ni/Ge/Au/Ni/Au, 5/20/100/25/300 nm) are deposited on the backside of the substrate following lapping down to $\sim 100\text{ }\mu\text{m}$. The wafers are annealed at 410 $^\circ\text{C}$ for 3 min in N_2 ambient after metallization. Finally, the wafers are cleaved into laser bars of various cavity lengths for further testing and characterization. To minimize the device heating, the devices are bonded p-side down (the active region is close to the heat sink).

Fig. 2-8 Edge emitting QD laser fabrication process.

Fig. 2-9 Top-view of the stripe pattern on the laser wafer. The stripe width is $2\mu\text{m}$ as shown.

The PAO technique is adopted in our fabrication process to form the current blocking layer of the ridge waveguide QD lasers, since it is simple and reliable

compared to the conventional deposited oxide technique [65, 66]. The pulsed anodization is carried out at room temperature to produce the native oxide. Figure 2-9 schematically shows the PAO setup, consisting of a pulse generator, a power amplifier, an oscilloscope and a vacuum pump. The pulsed signal is generated from the pulse generator, with pulse frequency of 144 Hz, pulse width of 700 μ s and amplitude of 2 V. After getting through the power amplifier, the amplitude of the pulsed signal is amplified to 80 V, which is the dominant factor determining the final thickness of the oxide formed by PAO. A vacuum tweezer is used to hold the sample and conduct current. Once the sample surface is placed inside the electrolyte containing ethylene, de-ionized water and phosphoric acid (40:20:1 by volume), the pulse anodization process starts. As seen from Fig. 2-10, a palladium pad connected to the negative terminal is put into the electrolyte, and the sample is placed underneath the vacuum tube, which is connected to the positive terminal of the pulsed signal. The total anodization time is around 260 s. Under such conditions, the final anodic oxide thickness is about 100 nm. It is known that thicker oxide can be obtained if higher voltage from the pulse system or higher pulse duty cycle is used. The working principle of the anodization process is described by the chemical formulae below.

At the initial step,

The reactions for gallium are:

The reactions for arsenic are:

The overall reactions are:

Fig. 2-10 Experimental setup for pulsed anodic oxidation.

The output voltage across the small resistor (10Ω) is observed on an oscilloscope to monitor the time dependence of the current in the circuit. Typical waveforms displayed on the oscilloscope are shown in Fig. 2-11, in which channel 1 and channel 2 represent the input and output voltages, respectively. As expected, the current flow (hence the output voltage) in the circuit decreases as the oxide layer becomes

thicker. However, the magnitude of the leading edge of the voltage pulse doesn't change, as the reading is taken across the small resistor.

Fig. 2-11 Typical waveforms displayed on the oscilloscope. Channel 1 (upper) is the input pulsed signal, and channel 2 (lower) is the output voltage across the small impedance.

Figure 2-12 shows a representative oscilloscope trace for the time dependent output voltage waveforms. In Fig. 2-12, T_0 , T_f represent the initial and final pulses, and T_1 , T_2 are the pulses in between. As observed, the leading edge of the pulses remains constant for all the waveforms, whereas, the trailing edge of the pulses decreases with time corresponding to the growth of the oxide layer. 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 (MOS) capacitor as the oxide layer thickens [65]. At the beginning of the each voltage pulse, the capacitance of the oxide

acts to short out the oxide resistance. Once the capacitor charges, the current decreases to a steady-state value within the pulse, resulting in a decreasing trailing edge. As the oxide thickens, the resistance increases, therefore, the steady-state current decreases from pulse to pulse, i.e. T_0 , T_1 , T_2 etc. As long as the voltage pulse is long enough for the capacitor to achieve a quasi-steady state, this performance is invariantly repeated. The oxide growth terminates when the oxide resistance is large enough to render the available voltage pulse insufficient to drive the anodic reactions, reaching the T_f pulse in Fig 2-12. The pulsed nature of the process allows the formation of a uniform oxide layer with high growth rate at room temperature. This is because the pulse process is a combination of oxidation and etching steps. When the pulse is off, the solution acts as a mild etchant for the oxide. When the pulse is stabilized (T_f in Fig. 2-12), a quasi-steady state is achieved in which the oxide dissolution rate at the oxide/solution interface equals the oxide formation rate at the oxide/semiconductor interface. In this manner, an oxide film is grown, and a ridge is defined simultaneously.

Fig. 2-12 Plot of oscilloscope trace for the time dependent output voltage waveforms.

2.3.3 Annealing process in Rapid Thermal Processor

Rapid thermal processing in the time regime of 1-5 minutes has received great attention in recent years compared to conventional furnace processing due to some advantages, such as minimisation of dopant redistribution and out-diffusion. The rapid thermal processor (RTP) system is a single-wafer reactor in which the thermal process is carried out. The RTP system consists of four major components: (1) energy source, (2) process chamber, (3) temperature measurement apparatus, and (4) temperature controller.

A schematic diagram of a typical RTP system using tungsten halogen lamps is shown in Fig. 2-13. The process chamber is usually made of quartz, silicon carbide or stainless steel, and has quartz windows for the optical radiation to illuminate the wafer. A measurement system is placed in a control loop to set the wafer temperature. The wafer temperature in the RTP system can be measured with a non-contact optical pyrometer or a thermocouple.

Fig. 2-13 The rapid thermal processor for annealing process.

Before the laser fabrication process, the samples were annealed in a Jipelec/Jetstar RTP in N₂ atmosphere to prevent contamination. The temperature was controlled by a thermocouple with high accuracy of ± 1 °C. Two fresh pieces of GaAs proximity caps were used to provide the As over-pressure environment during the annealing process and to further prevent the sample surface from As out-diffusion. The annealing condition is summarized in Table 2-2.

Table 2-2. Annealing condition for investigated samples.

Samples	Annealing temperature	Annealing time
InAs/InGaAs dots-in-a-well (DWELL)	600-900 °C	30 s
InAs/InGaAs QD laser	600-650 °C	15 s

2. 4 CHARACTERIZATION TECHNIQUES

In this section, the two main characterisation systems used in this project are described. Photoluminescence (PL) and electroluminescence (EL) measurements are widely used for the material and laser performance characterizations.

2.4.1 Photoluminescence spectroscopy

PL is used to study the fundamental carrier recombination process in semiconductors, to characterise the optical quality of the material, and to study bulk or epitaxial films for inter- and intra-wafer variation.

PL measurement is usually performed below room temperature as it produces a sharper and smoother profile. At lower temperature, the linewidth or the full-width at half-maximum (FWHM) of the profile is generally smaller. This is due to lesser phonon vibration in the crystal at lower temperature, less phonon scattering, and thus less

sideband intensity is obtained. At room temperature, the large concentration of phonons and exciton levels merge into a continuum absorption spectrum. Therefore, the absorption spectrum from excitons can hardly be separated from the continuum absorption spectrum and this broadens the linewidth. Also, at lower temperature, the charge carrier density decreases and reduces the sideband intensity. The decrease in the charge carrier density is due to the change in the Fermi level to a more abrupt profile at lower temperatures. Besides, the intensity of the PL spectrum is higher at lower temperature owing to lower phonon scattering, which leads to a higher recombination efficiency. The effect of temperature on the PL properties of QDs is of great importance for their use in devices. It has been found that at low temperature, carriers are frozen randomly into the dot states and the PL spectrum reflects the absorption of QD ensemble [66]. With increasing temperature, carriers could be thermally activated outside the dot into the wetting layer and/or the GaAs barrier and then relax into a different dot. Carrier hopping [67] between dots favors a drift of carriers toward the dots having a higher binding energy, and hence a lower energy emission, resulting in a narrowing of the PL spectrum followed by a luminescence peak redshift larger than that expected for the thermal shrinkage of the InAs bandgap with increasing temperature.

At lower temperature, the PL peak wavelength obtained is shifted to lower wavelength. This can be explained by the increase in the bulk energy bandgap at lower temperature, which is formulated as:

$$E_g = E_{go} - \frac{\alpha T^2}{(\beta + T)} \quad (2.10)$$

where E_g is the bandgap energy at temperature T , E_{go} is bandgap energy at 0 K, T is the temperature in Kelvin, and α and β are empirical constants [68]. This equation governs

the temperature and bandgap difference for ternary compounds. Quaternary compounds are also roughly governed by this equation with a certain degree of error.

In this project, the PL measurements were performed at room temperature and low temperature for the as-grown and thermally annealed samples. The excitation source is the Ar-ion laser source with a peak wavelength of 514.5 nm. The output signal is collected by a liquid nitrogen cooled Ge detector. The system has scan steps of 2 nm due to the limitation of the stage controller.

2.4.2 Electroluminescence spectroscopy (EL)

Instead of using an optical excitation source as in the PL measurement, the samples are electrically biased to produce the electroluminescence spectra. The input electrical signal was injected into the laser chip by the current source. The output light was collected using a 100- μm -diameter core multimode silica-based fiber connected to an optical spectrum analyzer (OSA) through an optical fiber. The temperature was varied with a Peltier thermoelectric heater/cooler from 0 to 100 °C. Using this simple experimental setup, the gain spectra could be extracted from the amplified spontaneous emission (ASE) spectra using the Hakki-Paoli method [69]. By measuring the modulation depth of the Fabry-Perot (FP) resonances in the emission spectra, the output will be sent to the computer for data processing. A MATLAB program has been constructed to reject all data input except the maxima and minima of the FP resonances. The maxima and minima are stored sequentially in separate matrix arrays until the whole spectrum is scanned. The program then computes the net modal gain using the equation [69]:

$$G_{net} = \Gamma g - \alpha_i = \frac{1}{L} \ln \frac{\sqrt{S} - 1}{\sqrt{S} + 1} + \frac{1}{2L} \ln \left(\frac{1}{R_1 R_2} \right) \quad (2.11)$$

where G_{net} is the modal gain, Γ is confinement factor, g is the material gain, α_i is the internal loss, S is the ratio of intensity maximum and minimum in the FP resonances, L is the cavity length, and R_1 and R_2 are the facet reflectivities.

3. PERFORMANCE OF QUANTUM DOT LASERS

In this chapter, the basic characteristics of InAs/InGaAs QD lasers are presented. Both the broad area and narrow ridge waveguide (RWG) structures are included in this study. Further optimisation of the laser structural design is conducted based on the understanding of the laser characterizations.

3.1 BROAD AREA LASER STRUCTURE

A ten-layer InAs/InGaAs QD laser structure is used in this study. The transmission electron microscopy (TEM) image of the active QD region is shown in Fig. 3-1.

Fig. 3-1 TEM image of InAs QD active region.

Fig. 3-2 PL spectrum at 293 K of InAs QD laser structure.

Figure 3-2 shows the PL spectrum from InAs QD laser structure. The PL measurement was carried out at 293 K under 514.5 nm Ar^+ laser excitation, with the excitation power density of 305 mW. The emission peaks at 1.293 μm and 1.207 μm are attributed to the QD ground state (GS) and the first excited state (ES) transitions, respectively. The full-width at half-maximum (FWHM) of the GS emission peak is about 40 meV. This is comparable to that from a high-quality single-layer QD structure, which is 34 meV [1]-[2]. GS photoluminescence up to 100 $^{\circ}\text{C}$ is demonstrated from this QD laser structure under constant excitation power of 305 mW, which is shown in Fig. 3-3(a). To better illustrate the PL properties, we plot the temperature dependencies of the peak position of GS and first ES emission in Fig. 3-3(b). The peak GS emission wavelength shifts monotonically from 1292 nm to 1330 nm with the temperature increasing from 293 K to 373 K. Similar observation is obtained from the peak ES emission wavelength, which redshifts from 1211 nm to 1254 nm with increasing

temperature from 293 K to 373 K. The PL peak position redshifts together with a narrowing of the PL spectrum (as shown in Fig. 3-3(a)), could be attribute to carrier hopping [3]. It is found that as the temperature increases, carriers may be thermally activated outside the dot into the wetting layer and/or the GaAs barrier and then relax into a different dot having a higher banding energy (a lower energy emission). Though both GS and first ES transitions are observed in Fig. 3-3(a), GS emissions remained dominant even at high temperature. This suggests that the QD laser structure exhibits strong luminescent efficiency without degradation in material quality even with ten QD layers [1]. Normally, QD lasers switch to the ES lasing at high temperature due to the reduction of the GS gain as a result of thermally activated carrier loss and increase in band-filling in the ES as the GS gain becomes saturated [2]. Since GS emission is maintained in the InAs QD laser structure up to 100 °C under high excitation level, this indicates the availability of high GS gain from the p-doped ten-layer InAs QD active region.

Fig. 3-3 Temperature dependent PL spectra of InAs QD laser structure from 293 K to 373 K with an excitation power of 305mW (a) Relative intensity (b) Peak position.

The laser performance study is carried out with the device bonded p-side down (the active region is close to the heat sink), in order to minimize the device heating. The continuous wave (CW) power-current-voltage (P - I - V) characteristic of a p-doped InAs QD laser ($50 \times 2750 \mu\text{m}^2$) is shown in Fig. 3-4. High output power (both facets) of 882 mW at 10°C is achieved, which is limited by the thermal roll-over. High slope efficiency of 0.426 W/A in the linear region and reasonable low threshold current density J_{th} of 106 A/cm^2 have been obtained from this laser device.

Fig. 3-4 CW *P-I-V* characteristics of a p-side down bonded InAs/InGaAs QD laser ($50 \times 2500 \mu\text{m}^2$) at 10°C .

Temperature-dependent *P-I* characterization is further carried out on an InAs QD laser with similar structure ($50 \times 2500 \mu\text{m}^2$), which is shown in Fig. 3-5. It indicates the high performance of this laser, which is able to exhibit CW lasing as high as 100°C . The inset of Fig. 3-5 shows the GS lasing spectra from the same laser centered at 1302.4 and 1331.2 nm measured at 25 and 100°C , respectively. This is good evidence of CW GS lasing in the $1.3 \mu\text{m}$ range from room temperature (RT) to 100°C in this laser structure. We attribute this high temperature GS lasing to the high available GS gain from the ten-layer structure.

Fig. 3-5 CW P - I (10-100 °C) characteristics of an InAs QD laser (50×2500 μm^2). Inset shows the GS lasing spectra centred at 1302.4 nm (25 °C) and 1331.2 nm (100 °C).

In most application, the ability of the laser diode to perform well at elevated temperature is of great interest. It is of utmost importance for the QD lasers to be robust enough so as not to suffer from device deterioration at high temperature. The characteristic temperature (T_0), is a measure of the temperature sensitivity of the laser device, which is calculated by the formula below:

$$I = I_0 \exp(T/T_0) \quad (3.1)$$

where I is the threshold current observed at temperature T . Higher values of T_0 imply that the threshold current of the device increases less rapidly with increasing

temperatures. This translates into the laser being more thermally stable, which is desirable for the device application. Characteristic temperature of 84.9 and 47.3 K are observed in the temperature range of 10~40 °C and 50~100 °C, respectively (see Fig. 3-6). Though p-type doping is adopted in this laser structure, the values of characteristic temperature are not as high as reported in Ref 3, due to the low doping concentration ($\sim 2 \times 10^{17} \text{ cm}^{-3}$) in this laser structure. To date, the optimum value for the doping level is $\sim 5 \times 10^{17} \text{ cm}^{-3}$ [4] in devices with high T_0 and reasonably low threshold current density.

Fig. 3-6 Plot of $\ln(I_{th})$ against T for an InAs laser ($50 \times 2500 \text{ } \mu\text{m}^2$). T_0 is 84.9 K (10 ~ 40 °C), and 47.3 K (50 ~ 100 °C), respectively.

Based on the basic P - I characteristics, the cavity-length dependent studies on the QD lasers are performed using Eq. (3.2) and Eq. (3.3) [5].

$$\eta_d^{-1} = \eta_i^{-1} \left(\frac{\alpha_i + \frac{1}{L} \ln \frac{1}{R}}{\frac{1}{L} \ln \frac{1}{R}} \right) \quad (3.2)$$

where η_d is the differential quantum efficiency, η_i is the internal quantum efficiency, α_i is the internal optical loss, L is the cavity length and $R=0.32$ is the optical power reflectivity of the two cleaved facets.

$$\ln J_{th} = \ln \left(\frac{eJ_{tr}}{\eta_i} \right) + \frac{\alpha_i}{\Gamma g_0} + \frac{1}{\Gamma g_0 L} \ln \left(\frac{1}{R} \right) - 1 \quad (3.3)$$

where J_{th} is threshold current density, J_{tr} is transparency current density, Γ is the optical confinement factor and g_0 is the material gain. Figure 3-7 shows the differential quantum efficiency (η_d) and threshold current density (J_{th}) as function of cavity length L . The bottom-left axis gives the relationship of η_d^{-1} vs. L , and the top-right axis describes the $\ln(J_{th})$ vs. $1/L$ behavior. Various cavity length QD lasers ($L=1.875\sim 5$ mm) are used to determine the internal efficiency (η_i) and internal optical loss (α_i). The values of α_i and η_i derived from the relationship between η_d^{-1} and L are 4.5 cm^{-1} and 93.5%, respectively. The transparency current density (J_{tr}) of the QD laser is calculated to be 58.6 A/cm^2 , which is equivalent to $5.9 \text{ A/cm}^2/\text{layer}$.

Fig. 3-7 Plot of η_d^{-1} vs. L and $\ln(J_{th})$ vs. $1/L$ from a batch of InAs/InGaAs QD lasers.

In this broad area laser structure, the shortest L of the QD laser, which can maintain GS lasing, is 611 μm . Figures 3-8(a)-(c) show the lasing spectra from this InAs QD laser under different injection current at 25 °C. In Fig. 3-8(a), at lower I of 150 mA ($\sim 1.1 I_{th}$), GS lasing at 1298 nm is clearly observed. When $I=285$ mA ($\sim 2.1 I_{th}$), ES lasing starts as shown in Fig. 3-8(b). The ES lasing becomes dominant when the injection current I is further increased to 300 mA ($\sim 2.2 I_{th}$), as shown in Fig. 3-8(c).

Fig. 3-8 Plot of lasing spectra from an InAs QD laser ($50 \times 611 \mu\text{m}^2$) under different injection current I . (a) $I=150 \text{ mA}=1.1 I_{th}$, (b) $I=285 \text{ mA}=2.1 I_{th}$, (c) $I=300 \text{ mA}=2.2 I_{th}$.

Two-state lasing behavior has previously been observed [6], which was attributed to the finite intraband relaxation time combined with a limited density of GS. In shorter cavities, such effect becomes significant as the number of available states for the relaxation is reduced [6]. This can also explain why the gain switching behavior occurred in the QD laser studied in this work, when it is under higher current injection. Though ES lasing starts at higher I , this is the shortest L in our QD laser that can show GS lasing, corresponding to the maximum modal gain ($\Gamma \cdot g_{th} = \alpha_i + \frac{1}{L} \ln(\frac{1}{R})$) of 23.1 cm^{-1} from the GS in this laser system. Very recently, Salhi *et al.* [7] reported GS $\Gamma \cdot g_{th}$ of 41 cm^{-1} from a 7-layer QD laser ($120 \times 360 \mu\text{m}^2$), which is the highest value ever reported. Figure 3-9 also shows the P - I characteristics from the longest QD laser

($50 \times 5000 \text{ } \mu\text{m}^2$) studied in this work, the inset of which shows the GS lasing spectrum, centered at 1308 nm.

Fig. 3-9 P - I characteristics from an InAs QD laser ($50 \times 5000 \text{ } \mu\text{m}^2$). Inset shows the lasing spectrum from this laser.

3.2 NARROW RIDGE WAVEGUIDE LASER STRUCTURE

Narrow ridge waveguide (RWG) structure [8-15] is an approach utilized in a laser device to achieve single mode operation, which is desirable for better device to fiber coupling efficiency in optical fiber communication system. So far, there are few works reported on single mode operation in high performance In(Ga)As/GaAs QD lasers [8]-[10]. It is commonly known that as the ridge width narrows, the sidewall condition plays an important role in the laser performance, where sidewall scattering/recombination [11] tends to degrade the laser performance. Undesirable lateral current spreading resulting from sidewall effects have been investigated for improving the laser structure design [16-18]. Moreover, the small lasing volume in

narrow RWG lasers may increase the optical losses as a result of processes related to scattering. Such effects may increase the threshold current density and limit the high temperature operation [19]. A key factor to achieve single mode emission is narrow ridge width of the QD laser structure. To obtain strong index guiding and to suppress current spreading, careful balance between the etch depth and ridge width should be accomplished [16]. Our previous works [20]-[21] have shown that by optimizing the PAO process after sidewall etching, high-performance RWG lasers with reduced lateral current spreading could be achieved.

Figure 3-10 shows the plot of CW output power and biasing voltage (V) as function of injection current, I , measured from devices of dimension $2 \times 2000 \mu\text{m}^2$ at 10°C . High output power (both facets) of around 272.6 mW is obtained. The output power eventually saturates at 800 mA due to thermal rollover. However, distinct kinks are observed under high current injection, which we attribute to mode hopping caused by device heating [22], rather than current-induced ground-to-excited-state lasing transition [23]. The latter mechanism, caused by finite intraband relaxation time combined with limited density of GS in quantum dot structures, is only significant for short-cavity devices, in which the number of available ground states for carrier relaxation is reduced [6]. Furthermore, a report by Markus *et al.* [6] indicated that the ES threshold current is more than 10 times higher than GS threshold current for cavity length of $2000 \mu\text{m}$, which is not true in our case. The lasing spectrum from an InAs QD laser ($50 \times 5000 \mu\text{m}^2$) is presented in Fig. 3-11 for verification. The lasing wavelengths of 1308 nm and 1351.1 nm are obtained under injection current of 354 mA at 25°C and 1 A at 100°C , respectively. This proves GS lasing from such a laser structure under high injection current level even at high temperature up to 100°C . Based on the above

analysis, it is reasonable to conclude that the kink in power output is most likely caused by longitudinal mode hopping, which arises primarily due to temperature fluctuation in the laser. The heating of the laser active region by the injection current under CW operation, may cause nonlinearity in gain, which consequently changes the oscillation wavelength as well as output power.

Fig. 3-10 P - I - V characteristics of a $2 \times 2000 \mu\text{m}^2$ RWG InAs QD laser in CW operation.

The output power is obtained from the front as-cleaved facet.

Fig. 3-11 Plot of lasing spectrum from an InAs QD laser ($50 \times 5000 \mu\text{m}^2$). The laser showed ground state lasing from 25 °C up to 100 °C with injection current up to 1 A.

The unstable switching between modes causes intensity noise, resulting in degradation in the laser performance [22]. Furthermore, mode hopping is expected to be more pronounced in narrow ridge structures where the cross-sectional area is relatively small. More detailed investigation on the mode hopping behavior is warranted to further study this effect. Nevertheless, our observations from operating the device in CW mode suggest the presence of a significant heating effect.

To alleviate the effects of device heating in CW operation, the InAs QD lasers were measured under pulsed operation ($1\mu\text{s}$, duty cycle = 1%) at 20 °C. Figure 3-12 shows the output power-current characteristics for a $2 \times 2000 \mu\text{m}^2$ device with uncoated facets. Extremely high output power of 610 mW (per facet) was recorded at injection current of 1.6 A. To the best of our knowledge, this is among the highest value of output power in the literature ever reported for narrow RWG InAs QD lasers.

Compared with CW operation, power saturation and kinks in the output power characteristics are greatly reduced in pulsed mode, which is attributed to reduction in device heating. High slope efficiency η of 0.46 W/A per facet was obtained from the P - I curve, and near ideal external differential quantum efficiency η_d of 96% was calculated from Eq. (3.4) [5]:

$$\eta_d = 2 \times \frac{\Delta P / \Delta(h\nu)}{\Delta I / \Delta q} = 2 \times \frac{\Delta P}{\Delta I} \times \frac{\lambda(\mu m)}{1.24 eV} \quad (3.4)$$

where η_d is the external differential quantum efficiency of the InAs QD laser, and $\Delta P / \Delta I$ is the slope efficiency obtained from the measured P - I characteristics. h is the Planck's constant, q the electronic charge, c is the speed of light in vacuum, λ is the emission wavelength, and $\nu = c / \lambda$ is the emission frequency of the InAs QD laser.

Fig. 3-12 P - I characteristics of a $2 \times 2000 \mu m^2$ RWG InAs QD laser in pulsed operation (1 μs , duty cycle = 1%) at 20 °C.

The far-field patterns (FFP) shown in Fig. 3-13 indicate the InAs RWG QD laser emitted at single lateral mode under different injection current levels from 450 to 600 mA. The laser beam divergence in the lateral direction is around 4° at the injection current levels investigated, indicating excellent beam quality in these devices.

Fig. 3-13 Plot of far-field pattern at different injection current levels in pulsed mode (1 μ s, duty cycle = 1%) at 20 $^\circ$ C.

Ouyang *et al.* has reported narrow RWG InAs QD lasers with ridge width of 8 μ m [11], and observed that lasers with deep-mesa geometry exhibited superior characteristics compared with shallow-mesa devices. Under pulsed operation (500 ns, 5

kHz), the high reflection/uncoated InAs QD laser of dimension $8 \times 1500 \mu\text{m}^2$ showed high external differential efficiency of 50% and low threshold current density of $\sim 130 \text{ A/cm}^2$ at moderate output power $\sim 6 \text{ mW}$. Compared with our results, the ten-layer InAs QD lasers fabricated using PAO were able to deliver comparable, and in some cases better performance with near ideal external differential efficiency of 96% and extremely high output power of 610 mW/facet under pulsed operation. Furthermore, the devices also exhibit single lateral mode emission.

The output power P and external differential quantum efficiency η_d of our ten-layer InAs narrow RWG QD lasers are among the highest values in the $1.29 \sim 1.30 \mu\text{m}$ wavelength range ever reported. The high device performance is attributed to the high quality QD laser structure and optimized self-aligned PAO method compared with the conventional SiO_2 confinement. The better passivation of the sidewalls by the native oxide formed by the PAO process could contribute to the reduction in nonradiative centers between the sidewall and oxide layer. This is particularly critical in narrow RWG devices such as the ones investigated in this study. These factors are believed to have contributed significantly to the high performance observed in our narrow RWG devices.

3.3 SUMMARY

High temperature PL up to 100°C has been demonstrated from p-doped ten-layer InAs QD structures. The basic characteristics of QD lasers are investigated from both the broad area and narrow RWG structures.

In the broad area structure, high output power of 882 mW and low transparency current density of $5.9 \text{ A/cm}^2/\text{QD layer}$ have been obtained using the optimized PAO

process. With the high available GS gain, GS lasing can be achieved from a QD laser with short cavity length of 611 μm , which corresponds to the maximum available modal gain of 23.1 cm^{-1} . The QD laser also demonstrated CW GS lasing operation up to 100 $^{\circ}\text{C}$.

Using the narrow RWG structure, devices exhibit GS lasing at high total output power of 272.6 mW at $\sim 1.3 \mu\text{m}$ under CW operation. Extremely high single lateral mode output power of 610 mW/facet has been achieved in pulsed operation with minimal power saturation under high current injection. High slope efficiency of 0.46 W/A per facet, near ideal external differential quantum efficiency of 96% and low lateral beam divergence of 4° is also demonstrated from this device.

4. QUANTUM DOT INTERMIXING: MATERIAL STUDY

Before starting the rapid thermal annealing (RTA) study on the active QD laser structure for device application, a systematic study to understand the mechanism of intermixing effects on the passive QD material structure is presented. This study is carried out using both p-doped and undoped InAs/InGaAs dots-in-a-well (DWELL) structures emitting at 1.3 μm . Having the understanding of the material growth and design, a systematic study of the intermixing effect and its impact on the DWELL material quality is discussed in the third part of this chapter using low temperature and room temperature PL measurements. Temperature dependent PL measurements are further performed to provide insights into the effect of RTA and intermixing mechanisms on the p-doped and undoped QD structures.

4.1 INTRODUCTION

Current advances in III-V QD heterostructures place this material system on a potential path to succeed quantum well (QW) heterostructures for high performance lasers and other active and passive photonic components. In particular, the adoption of the dots-in-a-well (DWELL) structure [1]-[2] and modulation doped QDs [3], [4] have resulted in significant performance improvements in the QD lasers. Low room-temperature threshold current density [4]-[6] was reported from the DWELL structure with self-organized InAs QDs covered by a strain-reducing cap layer to increase the QD surface density and carrier capture efficiency. P-type modulation doping in QDs was proposed to improve the QD laser performance by achieving temperature stability in both threshold current and differential quantum efficiency [3], [7]. The lower characteristic temperature (T_0) of the undoped QD lasers at room temperature is

attributed to thermal broadening of the holes in the QDs due to its closely spaced energy levels [8]. To realize high performance QD lasers, it is critical to achieve high dot density with small size distribution [9]-[13], which currently is relatively low and somewhat difficult to achieve in self-assembled QDs.

Thermally induced intermixing is attracting considerable attention as a way of tuning and controlling the emission properties of the QD assemblies [10]-[20]. The intermixing effect is expected to play an important role in the QD structures because of the large surface area to volume ratio compared to bulk or QW structures [14]. Typically, in the QD structures, blueshift of the photoluminescence (PL) peak energy coupled with narrowing of the peak linewidth is observed after rapid thermal annealing (RTA). The sharper PL linewidth caused by intermixing indicates improvement in optical quality, which is desirable for optoelectronics applications [14]. Moreover, it has been shown that intermixing can be enhanced by using a silicon-dioxide (SiO_2) cap rather than GaAs proximity cap or Si_xN_y cap during rapid thermal annealing (RTA) [10], [11], [14]-[17]. However, most results were reported based on studies of the QDs with large inhomogeneous size distribution and emission wavelength typically below $1.2\ \mu\text{m}$ [10]-[14]. There are few reports on QDs of high uniformity and emission wavelength of $\sim 1.3\ \mu\text{m}$. Furthermore, current published literature carries limited intermixing studies based on the p-type modulation doped QD structures, and therefore the role of p-type doping in the QD intermixing mechanism remains unclear.

4.2 MATERIAL DESIGN AND GROWTH

The DWELL samples were grown on n^+ -GaAs (100) substrate using molecular beam epitaxy (MBE). Figure 4-1 shows a schematic illustration of the p-doped DWELL

sample [21]. The As_4 pressure was maintained at 1.0×10^{-6} torr during the growth of QDs. Each DWELL layer consists of 2.5 monolayers (MLs) of InAs grown on 1 nm of $\text{In}_{0.1}\text{Ga}_{0.9}\text{As}$ and covered by 5 nm of $\text{In}_{0.1}\text{Ga}_{0.9}\text{As}$ cap layer. The growth rate of the InAs QDs is 0.1 ML/s. Three InAs/InGaAs DWELL periodic structures are separated by a 30 nm GaAs spacer layer. The growth temperature is 480 °C for the indium-containing layers. Following the deposition of each DWELL layer, the initial 10 nm GaAs spacer layer was deposited at 480 °C. For the p-doped structure, the second 10 nm GaAs spacer, deposited at 580 °C, was doped with beryllium (Be) at $1 \times 10^{18} \text{ cm}^{-3}$ (equivalent to 20 acceptors per QD). In contrast to the p-doped sample, there was no Be doping in the second GaAs spacer layer in the undoped structure. Next, the growth temperature was kept at 580 °C for the last 10 nm GaAs spacer layer. The growth temperature was then decreased to 480 °C for the growth of the next DWELL periodic structure. The entire growth process ends with a final 20 nm GaAs cap layer.

Fig. 4-1 Schematic diagram of the p-doped InAs/InGaAs DWELL structure [21].

Samples prepared for the RTA process were capped with 200 nm SiO₂ deposited by plasma enhanced chemical vapor deposition (PECVD). The samples were cleaved into 3×3 mm² squares. The intermixing experiments were carried out in a RTA process chamber with GaAs proximity cap under continuous flow nitrogen ambient. The annealing temperature was varied from 600 to 900 °C, and the annealing time was fixed at 30 s. PL measurements were performed on the p-doped and undoped samples at low and room temperature (RT) using 514.5 nm Ar⁺ laser excitation. Temperature dependent PL measurements were further carried out from 5 K to 295 K under constant laser excitation density of 2.5 W/cm².

4.3 OPTICAL PROPERTIES OF INTERMIXED P-DOPED AND UNDOPED QD STRUCTURE

4.3.1 Low temperature photoluminescence results

Figures 4-2(a) and 4-2(b) show the PL spectra of the undoped and p-doped DWELL samples, respectively, annealed from 600 °C to 900 °C at constant annealing time of 30 s. The annealing temperatures were set higher than the growth temperature of 580 °C for the as-grown samples in both structures.

Fig. 4-2 PL spectra of QD DWELL samples after annealing at different temperatures for 30 s from: (a) undoped and (b) p-doped InAs QD structures.

In the undoped samples, shown in Fig. 4-2(a), one energy peak corresponding to the ground state (GS) emission is observed from the samples annealed at low temperature (600 °C~650 °C), as well as the as-grown sample. However, for the p-doped samples in Fig. 4-2(b), two energy peaks are observed from the as-grown sample and those annealed at low temperature (600 °C~700 °C) regime. To verify the PL peak at high energy level, excitation power dependent measurements are performed on the as-grown sample, as shown in Fig. 4-3. It is found that the high energy peak signal becomes more pronounced as the excitation power is increased. This suggests the high energy signal comes from the excited state (ES) emission rather than the GS emission from the QDs of different sizes. By comparing Fig. 4-2(a) and Fig. 4-2(b), the spectra of both undoped and p-doped samples show similar trends as they gradually blueshift in the emission energy following increase in the annealing temperature. In the case of the undoped samples as shown in Fig. 4-2(a), the PL results in terms of linewidth and peak energy position show no significant change at annealing temperature from 600 °C to 650 °C, indicating insignificant group III atom intermixing effects in this low temperature range. There are two intermixing mechanisms involved: one is the exchange of In and Ga atoms between the InAs QD and its surrounding InGaAs QW, and the other is the In-Ga interdiffusion through the InGaAs/GaAs interface. Both mechanisms arise from the large Ga atom concentration gradient with sufficient thermal energy provided by the RTA treatment [17]. The group III atom intermixing mechanism modifies the composition profile from an abrupt interface to a graded one, leading to a shallower confining profile. Enhanced PL intensity can be observed from the undoped samples annealed at 600 °C, which can be attributed to the efficient removal of nonradiative recombination centers due to the low-temperature growth (480 °C) required for the QD region. A slight decrease in PL intensity is observed from the 650

°C annealing, which could be due to the carrier leakage from the shallower interdiffused QD potential [18]. After annealing at 700 °C, significant intermixing effect with large blueshift and spectral broadening is observed from the undoped sample. This indicates a drastic change in the dot structure after the thermal annealing. The large blueshift of the main PL peak, possibly caused by the increase in the QD lateral sizes, has been reported in the literature [19], [20]. It shows that the large strain in and around the QDs, which increases the group III atom vacancy concentration [20], is likely to enhance the lateral In/Ga interdiffusion. Such laterally enhanced interdiffusion could cause relatively fast dissolution of the QDs at high annealing temperatures [20], which can be realized from our undoped samples annealed at 750 °C and above. At extremely high annealing temperature of 900 °C, the undoped sample exhibits very weak PL intensity centered at 1.41 eV, suggesting the relaxation of the entire DWELL structure and overall degradation of the material crystallinity.

Fig. 4-3 Excitation power dependent PL measurements for the as-grown p-doped sample at 5 K. The excitation power was varied from 20 to 42 W/cm².

Similar evolution of the PL spectra can be observed from the p-doped samples as shown in Fig. 4-2(b). However, the intermixing effect becomes obvious with decrease in PL intensity and spectral broadening from the p-doped sample annealed at a higher temperature of 750 °C (compared to 700 °C in the undoped sample). This 50 °C difference in the annealing temperature, seems to indicate the p-doped sample is more resistant to thermal annealing, with a higher thermal energy onset (high annealing temperature) before the intermixing effect becomes obvious. This could be due to the presence of Be dopants in the p-doped sample. It is well known that the intermixing process strongly depends on the density of defects such as vacancies, interstitials and dislocations [19]. In the SiO₂-capped undoped samples (as shown in Fig. 4-4(a)), the rate of intermixing mechanism is mainly determined by the number of Ga vacancies available for In/Ga interdiffusion. As reported in the literature [12], [19], a large number of Ga vacancies can form at the SiO₂/GaAs interface during RTA, which is due to fast Ga out-diffusion into the SiO₂ layer. These Ga vacancies subsequently diffuse into the QD region, enhancing the In/Ga interdiffusion through the dot/cap interface [12], [19]. On the contrary, the Ga vacancies diffusion is not supported in our p-doped sample which has a higher Ga interstitial concentration. This leads to the suppressed intermixing in the p-doped samples. The suppressed intermixing behavior in QWs caused by the inhibited diffusion of group III vacancy has been demonstrated in a previous study [22], in which the p-doped AlGaAs/GaAs structure shows lower degrees of bandgap shifts compared to the undoped and n-doped AlGaAs under the same RTA conditions. The same explanation could possibly be adopted in our p-doped InAs/InGaAs structure. The Ga vacancy generated by the SiO₂ cap is suppressed in the p-doped sample (as shown in Fig. 4-4(b)), which has a high concentration of Ga atom interstitials I_{Ga} due to the presence of Be dopants. Moreover, the out-diffusion of Be

induced by the thermal annealing, leads to under saturation of the interstitials I_{Ga} which retards the Ga self-diffusion [23]-[25]. This retarded Ga diffusion can further suppress the degree of intermixing effect in the p-doped samples. An interesting result is observed from the p-doped sample annealed at 850 °C. It reveals negligible blueshift of the main PL peak position compared to the sample annealed at 800 °C. This observation is in contrast to most reported results [10]-[19] at such a high annealing temperature regime. For comparison, in the case of the undoped sample as shown in Fig. 4-2(a), a significant blueshift with the peak energy shifting from 1.27 eV (800 °C) to 1.38 eV (850 °C), is obtained. Thus, we further confirm the diffusion of Be atoms induced by RTA, which can greatly retard Ga self-diffusion and hence the intermixing rate.

Fig. 4-4 Schematic of In/Ga interdiffusion mechanism in the (a) undoped structure and (b) p-doped structure.

4.3.2 Room temperature photoluminescence results

To understand the effects of thermal annealing described above, further analyses on the RT PL data of the p-doped and undoped samples have been carried out as shown in Fig. 4-5. The integrated PL (IPL) intensity profile (Fig. 4-5(a)), energy peak shift profile (Fig. 4-5(b)) and full-width at half-maximum (FWHM) (Fig. 4-5(c)) are plotted as function of annealing temperature. The analyses are only focused at the low to medium annealing temperature range (from 600 °C to 750 °C), where the intermixing effect is not so significant. This is because at high annealing temperature (e.g. >800 °C), degradation in the material crystallinity coupled with significant decrease in PL intensity and energy peak broadening will render the material useless for device applications. In both p-doped and undoped DWELL structures, the PL spectra of the as-grown samples and those annealed from 600 °C to 750 °C can be well fitted by two Gaussian line shape functions (not shown here) corresponding to the GS and ES. Figure 4-5(a) shows the IPL intensity drops drastically for the p-doped and undoped samples at high annealing temperature range (e.g. >700 °C), compared to the as-grown samples. However, at low annealing temperatures (600 °C), enhanced IPL intensity is observed in the GS and ES emission from both structures. At these annealing temperature points, the p-doped sample reveals greater PL intensity enhancement compared to the as-grown sample, indicating a higher degree of improvement in the p-doped structure. It is well known that the intensity improvement is due to the efficient removal of nonradiative recombination centers in the QD region, which is applicable to both structures. However, in the case of the p-doped structure, in addition to the defects removal mechanism, the diffusion of Be atoms into the QD region also takes place during RTA, subsequently creating excessive holes in the QD region. These excessive holes, with

which the electrons are able to recombine, result in enhanced optical emission process. This could explain our observations of a higher degree of intensity improvement at the same annealing temperature (e.g. 600 °C for the p-doped sample). From the energy peak shift profile shown in Fig. 4-5(b), negligible energy shifts in the GS emission are observed from the p-doped samples annealed from 600 °C to 750 °C. Only a small blueshift of 23.2 meV is exhibited by the ES emission at annealing temperature of 750 °C, indicating the onset of significant intermixing behavior at this point, which is consistent with its low temperature PL data in Fig. 4-2(b). Similar trends can be observed from the undoped sample, where negligible energy shifts in both GS and ES emissions are seen at annealing temperature from 600 °C to 650 °C. Relatively large blueshifts of 111 and 120.3 meV for GS and ES, respectively, are observed after annealing at 700 °C, coupled with significant FWHM broadening as shown in Fig. 4-5(c). This trend is also consistent with its low temperature PL data (Fig. 4-2(a)), confirming the larger degree of intermixing effect in the undoped structure.

Fig. 4-5 PL data of: (a) integrated PL intensity, (b) energy peak shift profile and (c) FWHM for the p-doped [■: GS □: ES] and undoped [●: GS ○: ES] samples measured at RT.

4.3.3 Temperature dependent analysis

Temperature-dependent PL measurements were carried out to further study the effects caused by RTA. The IPL intensities were studied from 5 K to RT for the as-grown and annealed samples, for both p-doped and undoped DWELL samples. Figure 4-6 shows the Arrhenius plots of the IPL intensities for the p-doped samples annealed at 600 and 750 °C together with the as-grown sample. For comparison, Figure 4-7 shows the Arrhenius plots of the IPL intensities for the undoped samples annealed at 600 and 700 °C together with the as-grown sample. In both undoped and p-doped structures, the integrated PL intensity remains constant at the low temperature regime, but drops

significantly as the temperature increases for the as-grown and annealed samples. This characterizes a strong thermal quenching at high temperature for the all samples investigated. The experimental data is fitted using the equation [26]-[27]:

$$I = \frac{I_0}{1 + C_1 \exp(-E_1 / kT) + C_2 \exp(-E_2 / kT)} \quad (4.1)$$

where I is the IPL intensity, I_0 the IPL intensity at the low temperature limit, C_1 , C_2 the fitting constants, E_1 , E_2 the activation energies at two temperature regions, and k the Boltzmann's constant. The solid lines in Fig. 4-6 and Fig. 4-7 are the best fits for the experimental data throughout the entire temperature range. The results suggest the presence of two nonradiative recombination mechanisms, corresponding to two different activation energies E_1 and E_2 at low and high temperature regions, respectively. The lower activation energy E_1 is related to energy loss of carriers to the nonradiative recombination centers such as defect states or due to QD size fluctuation. Tables 4-1 and 4-2 summarize the values of E_1 and E_2 for the p-doped and undoped samples, respectively. Both GS and ES emissions are included.

Fig. 4-6 Arrhenius plots of the integrated PL intensity from the p-doped samples for (a) GS emission (b) ES emission. Symbols represent experimental data and lines are best fits to the data.

Fig. 4-7 Arrhenius plots of the integrated PL intensity from the undoped samples for (a) GS emission (b) ES emission. Symbols represent experimental data and lines are best fits to the data.

Table 4-1. Summary of E_1 and E_2 values for the p-doped as-grown and annealed samples.

Samples	GS		ES	
	E_1 (meV)	E_2 (meV)	E_1 (meV)	E_2 (meV)
As-grown	16.5	200	38	135
600 °C	18	223	32	170
650 °C	17	173	27	126
700 °C	17	103	23	71
750 °C	15	85	19	55

Table 4-2. Summary of E_1 and E_2 values for the undoped as-grown and annealed samples.

Samples	GS		ES	
	E_1 (meV)	E_2 (meV)	E_1 (meV)	E_2 (meV)
As-grown	10.6	225	37	150
600 °C	10	235	35	140
650 °C	9	151	37	112
700 °C	8.5	105	28	90

Figure 4-8 plots the values of E_2 as function of annealing temperature. The data points for the p-doped as-grown sample are indicated. To understand the physical origin of these activation energies, we firstly examine the p-doped as-grown sample, from which the value of $E_2 = 200$ meV for the GS emission is derived. The activation energy E_2 (obtained at the high temperature region) is thought to be the energy required for the thermal escape of carriers from the InAs QDs to the GaAs barrier [28]-[29]. Based on our rate equation model [30], the energy difference between the confined QD GS to the GaAs barrier is calculated to be 206 meV, which is comparable to the fitted activation energy E_2 of 200 meV in this work. By comparing the data in Fig. 4-8, after the thermal annealing, the activation energy E_2 has increased to 223 meV for the samples annealed at 600 °C for the GS transitions. This higher activation energy seems

to imply stronger carrier confinement property after the thermal annealing. This improvement is possibly due to the efficient removal of nonradiative recombination centers during RTA, and also to the presence and diffusion of Be atoms into the QDs in the p-doped structure. Further increase in the annealing temperature induces In/Ga atomic interdiffusion, resulting in shallower confinement energy for the QDs. Therefore, the value of E_2 reduces from annealing temperature of 650 °C onwards. Activation energy of $E_2 = 135$ meV is derived from the ES emission from the p-doped as-grown sample. In this case, E_2 is the energy loss from the first ES of the confined QD to the barrier. Compared to the GS emission from the as-grown sample (E_2 of 200 meV deduced above), the activation energy E_2 of the ES emission is ~65 meV smaller. This energy discrepancy, which corresponds to the intrasubband energy spacing between the GS and the first ES, is in agreement with the value of 64 meV from theoretical calculation [30]. As the annealing temperature increases, the intrasubband energy spacing decreases. Similar behavior has been reported in the literature [17], [31]. Compared to the GS emission, similar results are observed from the ES emission for the annealed p-doped samples, whereby E_2 increases in the sample annealed at 600 °C, and then decreases as the annealing temperature increases. This effect indicates a modification of the confinement energy potential caused by the thermal annealing.

Fig. 4-8 Activation energies of as-grown and annealed samples as function of annealing temperature for the p-doped sample [$\bullet$: E_2 GS $\circ$: E_2 ES].

The data points for the as-grown sample are indicated.

Figure 4-9 shows the variation of the activation energies with annealing temperature for the undoped DWELL sample. The data points for the as-grown sample are indicated. The activation energy E_2 derived from the as-grown sample is slightly higher than that of the p-doped sample for both GS and ES emissions (e.g. $(E_2)_{GS} = 225$ meV, $(E_2)_{ES} = 140$ meV for the undoped and $(E_2)_{GS} = 200$ meV, $(E_2)_{ES} = 135$ meV for the p-doped sample). The higher E_2 value in the undoped sample is possibly due to the effect of holes escaping from the QDs to the barrier region. Besides electrons escaping from the QDs to the barrier, the closely spaced hole levels result in thermal smearing of the carrier population amongst many hole states [3], and therefore the holes escape

mechanism has to be taken into account in the undoped sample. Similar to the p-doped DWELL sample, the activation energy E_2 increases to 235 meV for the confined GS at low annealing temperature of 600 °C, which may suggest better carrier confinement after the thermal annealing. However, for the samples annealed at 650 °C and above, the shallower confinement energy caused by the intermixing effect leads to decrease in the value of E_2 . The intrasubband energy spacing between the GS and ES is calculated to be 75 meV for the as-grown undoped sample, and it increases to 95 meV after annealing at 600 °C. Further increase in the annealing temperature reduces the intrasubband energy spacing, and a significant decrease in the value of E_2 to 15 meV is observed from the sample annealed at 700 °C. The broad intrasubband gap tuning range (95~15 meV) obtained here, suggests that the undoped structure is likely to be more advantageous for performing wavelength tuning as compared to the p-doped structure. It is worth to mention that unlike the p-doped sample (Fig. 4-8), the undoped sample exhibits an increase in the intrasubband energy spacing at low annealing temperature of 600 °C. So far, the reason for the increase in this value observed from the undoped sample is unclear. This aspect requires further investigation to better understand the role of p-doping in the QD intermixing mechanism.

Fig. 4-9 Activation energies of as-grown and annealed samples as function of annealing temperature for the undoped sample [$\bullet$: E_2 GS $\circ$: E_2 ES].

4.4 SUMMARY

The effects of rapid thermal annealing have been investigated in InAs/InGaAs dots-in-a-well structures grown by MBE. Both low temperature and room temperature PL measurements were carried out to characterize the material quality after the thermal annealing. Structural changes caused by atomic interdiffusion giving rise to PL peak energy blueshift are observed from the undoped and p-doped samples. Our investigations show improvement in the PL intensity for the p-doped and undoped samples annealed at 600 °C. Furthermore, the p-doped sample exhibits a higher thermal energy onset for the occurrence of significant intermixing, which is due to the presence and diffusion of Be atoms, resulting in suppressed Ga diffusion in the p-doped structure.

Further investigations were carried out using temperature dependent PL measurements. Rapid quenching of the integrated PL intensity at high temperature was observed from the undoped and p-doped samples. Good agreement was obtained by fitting the integrated PL profile using two nonradiative recombination mechanisms, resulting in two activation energies that correspond to loss of carriers to nonradiative centers. Our study shows that a larger degree of wavelength tuning is possible in the undoped structure compared to the p-doped structure for device applications. This is possibly due to a larger degree of intermixing effect in the undoped structure.

5. PERFORMANCE OF ANNEALED QUANTUM DOT LASERS

5.1 INTRODUCTION

In chapter 4, we have investigated the annealing effects on the InAs/InGaAs dots-in-well structure, showing improvement in photoluminescence (PL) intensity in the p-doped structure at relatively low annealing temperature, *e.g.* 600 °C. This suggests that post-growth thermal annealing is a promising method to improve the device performance. Although Djie *et al.* [1]-[2] have demonstrated performance improvements in InAs/InAlGaAs quantum dash lasers based on the post-growth annealing technique, few investigations [3] focus on the effects of rapid thermal annealing (RTA) on the GaAs-based QD laser performance.

When the QD material is used in the laser structure, the QD energy levels, especially the hole levels, become much closer. The closely spaced hole levels result in significant hole thermalization and gain saturation, and hence degrade the device performance. P-type modulation doping [4]-[7] and multilayer stack techniques [4]-[8] have been proposed to improve the hole thermalization and gain saturation. Infinite characteristic temperature (T_0) from 5 to 75 °C has been demonstrated for a 1.3 μm InAs/GaAs QD laser using p-type modulation doping [4]. Extremely low room temperature (RT) threshold current density of 17 A/cm² is achieved by multilayer stacked QDs [8]. However, p-type modulation doping in the QDs has undesired effects, such as increasing the internal loss [9] due to inter-valence band absorption (IVBA) and reduction in carrier lifetime [10]. Moreover, it is reported that multilayer stacks (>6 layers) will generate “volcano-like” defects in the QD layers due to the high strain accumulation [11].

In this chapter, the p-doped (doping concentration of 16 acceptors per QD) ten-layer InAs/InGaAs/GaAs QD laser structure is used to investigate the material characteristics subjected to RTA. To understand the annealing effect on the p-doped QD lasers, a comparison is made between the as-grown and annealed laser diodes. The comparison reveals significant improvements in device performance in the annealed laser, including the external differential efficiency, threshold current and characteristic temperature.

5.2 EXPERIMENTS AND RESULTS

Before the device fabrication process, two QD laser samples were annealed at 600 and 650 °C, respectively for 15 s with GaAs proximity caps under continuous nitrogen flow. The photoluminescence (PL) spectrum is measured at room temperature (RT) using the 514.5 nm line of an Ar⁺ laser. Subsequent to the PL measurement, the ridge waveguide (4 μm ridge width) lasers are fabricated by standard n- and p-contact metallization, photolithography and pulsed anodic oxidation (PAO). The detailed description of the material design, growth, characterization and device fabrication are found in chapter 2. Individual InAs/InGaAs QD lasers (without facet coating) are then cleaved into different cavity length L for further characterizations.

5.2.1 Photoluminescence measurements

The material quality before and after RTA was examined using PL measurements. Figure 5-1 shows the RT PL spectrum of the as-grown sample and samples annealed at 600 °C and 650 °C (hollow squares). A ground state (GS) emission

peak centered at 1.295 μm with full-width at half-maximum (FWHM) of 36.3 meV is observed from the as-grown sample. After RTA at 600 $^{\circ}\text{C}$ for 15 s, the PL intensity increases by ~ 2.6 times and no obvious wavelength shift is observed. The FWHM remains at about 36.3 meV. Increase in the annealing temperature to 650 $^{\circ}\text{C}$ results in 7 nm blueshift in the emission wavelength and slight decrease in the PL intensity. By considering the effect of annealing temperature on the wavelength and PL intensity, the as-grown sample and the sample annealed at 600 $^{\circ}\text{C}$ were processed into laser devices.

Fig. 5-1 RT PL spectrum of the as-grown and QD laser structure annealed at 600 $^{\circ}\text{C}$ and 650 $^{\circ}\text{C}$ for 15 s.

5.2.2 Light-current measurements

The CW power-current-voltage (P - I - V) characteristics of the as-grown and the QD laser annealed at 600 °C are shown in Fig. 5-2. Both devices have the same dimension of $4 \times 2500 \text{ } \mu\text{m}^2$. Significant improvement in the device performance is observed in the annealed laser. Compared with the as-grown laser, the annealed laser exhibits 2.3 times increase in the saturated output power (P_0) and the maximum conversion efficiency ($\eta_c = P/(IV)$). Using Eq. (5.1), the external differential efficiency η_d is found to have increased from 17% to 29% in the annealed laser [12].

$$\eta_d = 2 \times \frac{\Delta P / \Delta(h\nu)}{\Delta I / \Delta q} = 2 \times \frac{\Delta P}{\Delta I} \times \frac{\lambda \text{ (}\mu\text{m)}}{1.24 \text{ (eV)}} \quad (5.1)$$

where $\Delta P / \Delta I$ is the slope efficiency obtained from the measured P - I characteristics. h is the Planck's constant, q the electronic charge, frequency $\nu = c/\lambda$, where c is the speed of light in vacuum, and λ the emission wavelength of the InAs QD laser. Significant improvement in the threshold current I_{th} of 23% is also achieved in the annealed device. Figure 5-3 compares the laser emission at current pumping of $1.1 \times I_{th}$ for both devices. The lasing peak emission for the annealed laser is centered at 1315 nm, corresponding to only ~2 nm shorter, compared to that of the as-grown laser. The negligible change in the lasing wavelength after annealing is in agreement with the PL spectrum shown in Fig. 5-1.

Fig. 5-2 CW P - I - V characteristics of the as-grown and annealed (600 °C for 15 s) QD laser at 25 °C. Both devices have cavity length of 2.5 mm.

Fig. 5-3 Plot of the lasing spectra of both devices under current injection of $1.1 \times I_{th}$.

5.2.3 Cavity length dependent measurements

Based on the RT P - I characteristics of the InAs QD lasers with different L , Figs. 5-4(a) and 5-4(b) plot the relationship between reciprocal of external quantum efficiency (η_d^{-1}) vs. L (left-bottom axes) and logarithmic value of threshold current density ($\ln(J_{th})$) vs. $1/L$ (right-top axes) for the as-grown and annealed laser, respectively. By comparing Figs. 5-4(a) and 5-4(b), reduced internal loss (α_i) from 11.2 cm^{-1} to 8.5 cm^{-1} and increased internal quantum efficiency (η_i) from 63% to 79% have been demonstrated from the annealed laser. α_i and η_i are derived from the relationship between η_d^{-1} and L using Eq. (5.2) [12]:

$$\eta_d^{-1} = \eta_i^{-1} \left\{ \frac{\alpha_i + \frac{1}{L} \ln \frac{1}{R}}{\frac{1}{L} \ln \frac{1}{R}} \right\} \quad (3.2)$$

where $R=0.32$, is the optical power reflectivity of the two cleaved facets. The transparency current density (J_{tr}) of the QD lasers are calculated to be 332 A/cm^2 and 336 A/cm^2 for the as-grown and annealed laser, respectively, using Eq. (5.3) [12]:

$$\ln J_{th} = \ln \left(\frac{eJ_{tr}}{\eta_i} \right) + \frac{\alpha_i}{\Gamma g_o} + \frac{1}{\Gamma g_o L} \ln \left(\frac{1}{R} \right) - 1 \quad (3.3)$$

where Γ is the optical confinement factor and g_o is the material gain. From the above equation, we note that the value of J_{tr} depends on J_{th} , α_i and η_i . Based on our calculated result, it seems that J_{tr} is insensitive to the annealing process at RT. The detailed characteristic parameters of the as-grown and annealed laser are summarized in Table 5-1. Measurements of several laser chips of each type exhibit nearly identical performance. Figure 5-2 also shows the almost identical I - V curves of the as-grown and annealed laser, which proves the improvement in device performance is due to the annealing, not the fabrication.

Fig. 5-4 Plot of η_d^{-1} vs. L (left-bottom axes) and $\ln(J_{th})$ vs. $1/L$ (right-top axes) for (a) as-grown QD lasers and (b) annealed (600°C for 15 s) QD lasers.

Table 5-1. Characteristics of the as-grown and annealed QD lasers with $L=2.5$ mm.

Parameters	As-grown	Annealed
Threshold current I_{th} (mA)	224	173
Maximum output power (mW)	64	144
Internal loss α_i (cm^{-1})	11.2	8.5
External differential efficiency η_d (%)	17	29
Internal quantum efficiency η_i (%)	63	79
Maximum conversion efficiency η_c (%)	6	12
Transparency current density J_{tr} (A/cm^2)	332	336

5.2.4 Temperature dependent measurements

The temperature stability of the laser is found to improve with annealing. Figure 5-5(a) shows the threshold current density (J_{th}) as function of temperature for the as-grown and annealed (600 °C for 15 s) laser under CW operation. Both devices have the same dimension of $4 \times 2000 \mu\text{m}^2$. Within the temperature range investigated, both the as-grown and annealed device demonstrate ground state (GS) lasing. The emission wavelengths increase as the temperature increases, as shown in Fig. 5-5(b).

Fig. 5-5 (a) Plot of threshold current density as function of temperature for the as-grown and annealed (600 °C for 15 s) QD laser.

(b) Plot of emission wavelength as function of temperature for the as-grown and annealed (600 °C for 15 s) QD laser.

By fitting the experimental data using Eq. (5.4), high characteristic temperature (T_0) of 1080 K is obtained from the as-grown laser in the temperature range of 10-35 °C.

$$J_{th} = J_0 \exp\left(\frac{T}{T_0}\right) \quad (5.4)$$

This extremely high T_0 is consistent with the value reported by Fathpour [4], where $T_0 = \infty$ has been demonstrated in the temperature range of 5-75 °C for the p-doped InGaAs/GaAs QD lasers. In our case, a possible reason for such a high value of T_0 obtained could be due to Auger recombination in the p-doped structure. As the temperature increases, the decrease in Auger recombination is compensated by the

increase of recombination in the barrier/waveguide regions. This mechanism is originated from the p-doping effects on the QD laser structure [4]. Above 40 °C, the as-grown laser shows significant increase in J_{th} , with T_0 of 133 K in the 40-55 °C range, suggesting serious thermal broadening of holes [4] at this temperature interval. This as-grown device could only be operated up to 55 °C, whereas the annealed laser can successfully lased up to 70 °C, indicating improved high temperature performance of the QD lasers subjected to the annealing process. Furthermore, T_0 of the annealed laser increases to 2100 K and 172 K for the low (10-40 °C) and high (45-70 °C) temperature range, respectively. It is noted that the turning point above which J_{th} increases significantly, is shifted to higher temperature in the annealed laser (45 °C) compared to the as-grown device (40 °C). Fathpour *et al.* [4] have reported this turning point is related to the carrier recombination in the barrier/waveguide regions. The higher the temperature of the turning point, the lower is the carrier recombination in the barrier/waveguide regions.

Similar to T_0 , temperature characteristic coefficient of external quantum efficiency (T_I) is another important physical parameter to analyze the temperature sensitivity of semiconductor laser. Figure 5-6 depicts η_d as function of temperature for the as-grown and annealed laser. From this figure, temperature characteristic coefficient T_I is calculated following the equation:

$$\eta_d = \eta_{d0} \exp\left(-\frac{T}{T_I}\right) \quad (5.5)$$

Fig. 5-6 Plot of external differential quantum efficiency as function of temperature for the as grown and annealed (600 °C for 15 s) QD laser. Both devices have cavity length of 2 mm.

By comparing Fig. 5-6 and Fig. 5-5(a), one observes that the regions of decrease in η_d correspond to the regions of increase in J_{th} . In other words, η_d behaves opposite to J_{th} over the temperature range measured. This observation indicates that the temperature dependence of lasing threshold current is determined by a decrease in efficiency [13]. Compared to Eq. (5.4), with the minus sign presented in the exponential term of Eq. (5.5), one can generally conclude that T_0 should increase (decrease) as T_l increases (decreases). As shown in Fig. 5-6, the as-grown laser exhibits T_l of 238 K and 50 K corresponding to the low (10-35 °C) and high (40-55 °C) temperature region,

respectively. By comparing with the as-grown device, the improved T_0 demonstrated from the annealed laser could be confirmed by the improved T_I , with T_I of 394 K and 91 K obtained for the low (10-40 °C) and high temperature (45-70 °C) region, respectively. The above observation further suggests the temperature stability is improved in the annealed laser. It is worth to mention that in the annealed laser, there is a shift of turning point of T_I (from 40 to 45 °C), which coincides with the observation of T_0 . This result indicates that T_I could be modified in the same manner as T_0 during the RTA process.

The main mechanisms which can improve QD emission using RTA include reduction in the defect-related nonradiative recombination centers [2], improved QD uniformity [14], increase in confinement barrier [15], and diffusion of dopant due to annealing [16]. Figure 5-1 shows that after annealing at 600 °C for 15 s, the peak wavelength and FWHM of the QD PL spectrum are not changed, indicating that annealing at 600 °C does not change the QD uniformity and confinement barrier. This is reasonable given that 600 °C is merely 20 °C higher than the highest growth temperature (580 °C) of the p-doped QD laser. Dopant diffusion due to annealing is not considered the main reason contributing to the improved performance in the QD laser. This is because unlike our previous finding in Be-doped InAs QDs in chapter 4, the dopant in the modulation doped layer of the QD laser investigated in this study is carbon, which has low diffusion length of ~1 nm at annealing temperature of 600 °C [17]. Therefore, it is reasonable to ignore dopant diffusion induced by RTA in this laser device. The most likely mechanism responsible for the improved performance in the QD laser due to annealing is reduction in the defect-related nonradiative centers, which is evident from the reduction in internal loss (as shown in Table 5-1) and increase in the

turning point of the characteristic temperature (as shown in Fig. 5-5(a)). These grown-in defects could have originated from the high strain accumulated in the multi-layer stacked QDs [11], the low-temperature grown GaAs spacer layer [18] or the modulation doped layer [19].

In this study, the doping concentration of the p-doped QD laser structure is 16 acceptors per QD, which is higher than the one (8 acceptors per QD) studied previously in chapter 3. By comparing the data extracted, in terms of characteristic temperature, the as-grown p-doped (16 acceptors/QD) laser exhibits T_0 of 1080 K from 10 °C to 35 °C and 133 K from 40 °C to 55 °C, which is much higher than the characteristic temperatures of the p-doped (8 acceptors/QD) laser (84.9 K from 10 °C to 40 °C and 47.3 K from 50 °C to 100 °C). The improvement in the T_0 of the p-doped laser is in agreement with previous reports [20]-[21], showing the increase in both Auger recombination and carrier thermalization between dots with increasing temperature. Although p-doping improves T_0 , higher doping concentration seems to degrade the device performance in terms of the internal loss, the transparency current density and the internal quantum efficiency. Compared to the lasers doped with 8 acceptors/QD ($\alpha_i=4.46 \text{ cm}^{-1}$, $J_{tr}=58.6 \text{ A/cm}^2$, $\eta_i=93.5\%$) studied in chapter 3, the p-doped (16 acceptors/QD) lasers reveal higher α_i of 11.2 cm^{-1} , higher J_{tr} of 336 A/cm^2 and lower η_i of 63%. Such undesired effects introduced by p-doping may be due to inter-valence band absorption [9] and nonradiative recombination [10], which increases threshold current of the device. Our results suggest that in order to achieve temperature insensitivity, a larger doping density is required. However, at higher doping density, the devices exhibit undesired performance degradation. Therefore, we propose that RTA

could be an effective method to enhance the device performance of the p-doped structure with high doping concentration.

5.2.5 Current dependent measurements

To elucidate the effect of thermal annealing on the laser performance, measurement of the spontaneous electroluminescence is further carried out. The electroluminescence is collected by an optical fiber and optical spectrum analyzer (OSA) at RT. To minimize the influence of self-heating on the electroluminescence, the lasers are tested under pulsed operation with pulse width of 10 μ s and duty cycle of 1%. The total current injected into a QD laser can be written as [22]:

$$I = eV(An + Bn^2 + Cn^3) \quad (5.6)$$

where e is the electron charge, V the pumped volume of the active region and n the carrier density. A is the monomolecular recombination coefficient, which describes the nonradiative recombination through defect states. B is the interband radiative recombination coefficient. C is the nonradiative Auger coefficient. Z is larger than 2 in InAs/GaAs QDs due to the strong Auger recombination [23]-[24]. Over a limited range of I , where $I \leq I_{th}$, Eq. (5.6) can be rewritten as:

$$I \propto n^Z \quad (5.7)$$

where $1 \leq Z \leq 3$ depending on the relative importance of monomolecular, radiative and Auger recombination processes. The measured integrated spontaneous emission rate L_{sp} is proportional to the radiative current, which is shown in Eq. (5.8):

$$L_{sp} \propto Bn^2 \quad (5.8)$$

Therefore, we have

$$n \propto L^{1/2} \quad (5.9)$$

Based on Eq. (5.7) and Eq. (5.9), Eq. (5.10) is derived as:

$$\ln(I) \propto Z \ln(L_{sp}^{1/2}) \quad (5.10)$$

In Fig. 5-7, where $\ln(I)$ is plotted vs. $\ln(L_{sp}^{1/2})$ at RT, the value of Z reduces from 2.58 to 2.21 for the as-grown and annealed laser, respectively. As the Z value approaches 2 after annealing for the range of currents investigated, we might expect that the radiative recombination becomes more dominant rather than the monomolecular recombination or Auger process [25]. This result is well-supported by our experimental data, which demonstrate improved external quantum efficiency and internal efficiency as well as reduced internal loss in the annealed laser. As a result of RTA, the radiative recombination process might be enhanced by reducing the nonradiative recombination through the defect-related nonradiative centers. Moreover, the reduction in Auger-assisted carrier capture in the annealed sample could also contribute to the decrease in Z . This is actually in agreement with the temperature-dependent performance illustrated in Fig. 5-6. The literature [13], [26] show that the severe nonradiative Auger recombination in InAs/GaAs QD lasers could be considered as the main loss process responsible for the strong temperature sensitivity of the QD lasers around RT. The improvement in T_0 and T_I , especially at high temperature region ($T > 40^\circ\text{C}$) for the annealed laser, implies the strong Auger recombination is possibly reduced as a consequence of thermal annealing by reducing the defect densities, and hence improving the temperature dependence of threshold current and external differential quantum efficiency in the annealed device. The defect-enhanced Auger recombination process has been reported to be due to the low temperature growth of GaAs [27]. In our InAs QD

lasers, as a result of the annealing process, it is possible that Auger recombination is reduced accompanied by the lower defect density in the laser structure. To understand this, further investigations are on the way to better understand the behavior of Auger recombination subject to the thermal annealing in the QD laser system.

Fig. 5-7 Plot of $\ln(I)$ vs. $\ln(L_{sp}^{1/2})$ for the as-grown and annealed (600 °C for 15 s) QD laser with cavity length of 3 mm, in pulsed operation (10 μ s, duty cycle=1%) at 25 °C.

5.3 SUMMARY

Significantly improved performance in 1.3 μ m p-doped ten-layer InAs/InGaAs/GaAs QD laser resulting from RTA at 600 °C for 15 s has been demonstrated. The annealed lasers exhibit notable increase in output power, differential

quantum efficiency, internal efficiency and characteristic temperature. The reduction in internal loss and threshold current has also been demonstrated from the annealed laser devices. The mechanism responsible for the improved performance has been discussed and studied by electroluminescence measurements. Defect reduction is thought to be the most likely mechanism contributing to the improved performance according to the electroluminescence and improved characteristic temperature behavior.

6. TWO-STATE LASING COMPETITION IN QUANTUM DOT LASERS

6.1 INTRODUCTION

Self-assembled InAs quantum dot (QD) lasers operating at 1.3 μm emission have attracted considerable attention due to their expected performance improvement over quantum well (QW) lasers in terms of low threshold current density, low temperature sensitivity, and high modulation bandwidth [1]-[2]. To achieve these characteristics, QD lasers should be operated at low injection current levels to avoid ground state (GS) lasing saturation [3], [4]. On the other hand, with increase in current injection, a second lasing peak attributed to the excited state (ES) is observed at shorter wavelength. Both experimental [3], [5] and theoretical [6] studies have shown that ES lasing will eventually surpass that of GS, and become the dominant lasing peak if the injection current were to be further increased. Such ES lasing, which originates from the slow intraband relaxation combined with the limited density of states, can significantly affect GS lasing efficiency and hence degrade the device performance [3]. While an understanding of the competing behavior between GS and ES lasing for QD lasers is very much desired, there are only limited experimental reports [7] on the gain comparison between these two states, especially around the second lasing threshold. The competing mechanism between GS and ES lasing at high injection current and temperature remains a question for current research.

Post-growth rapid thermal annealing (RTA) is an effective approach to study the effects of QD intermixing [8]-[13]. By changing the electronic structure of the QD system, RTA can affect the intrasubband spacing between the GS and ES, and similarly, the competition between GS and ES lasing [12]. In chapter 5, we have demonstrated

performance improvements from the lasers annealed at 600 °C for 15 s by using the post-growth annealing method. More investigations are presented in this chapter by varying the annealing temperature from 600 °C to 650 °C. It will be shown that the laser performance could be modified by adjusting the RTA temperature. Most importantly, the competition behavior between the ground state (GS) and excited state (ES) lasing in the as-grown and annealed InAs/InGaAs QD lasers are investigated under various conditions. This study focuses on the devices with different cavity lengths measured at different temperatures. Eventually, the gain spectra of the as-grown and annealed devices are measured around the ES threshold condition, demonstrating enhanced GS and suppressed ES lasing from the QD laser annealed at 600 °C for 15 s.

6.2 RESULTS AND DISCUSSIONS

6.2.1 Basic characteristics

The ten-layer p-doped InAs/InGaAs QD lasers are used in this study. Before the fabrication, the QD laser samples were annealed in nitrogen ambient for 15 s at 600 and 650 °C using a rapid thermal processor, with GaAs proximity capping. Subsequently, the as-grown and annealed samples were processed into ridge waveguide (RWG) lasers with 4 μm wide oxide stripes using wet etching, pulsed anodic oxidation (PAO) and metallization. After cleaving the samples into laser bars of different cavity lengths from 1-3 mm, the as-cleaved lasers were characterized under continuous wave (CW) operation.

Figure 6-1 shows the typical room-temperature (RT) power-current (P - I) curves for the as-grown samples and those annealed at 600 °C and 650 °C for 15 s. All the laser chips have cavity length (L) of 1 mm. As shown in Fig. 6-1, the threshold current (I_{th}) of the as-grown laser for GS lasing is ~37.5 mA, and the devices annealed at 600 °C and

650 °C exhibit I_{th} of ~31.6 mA and ~41.8 mA, respectively. Both the as-grown and 650 °C annealed laser saturate at high injection current, revealing maximum output power (P_o) of 81 mW and 52 mW, respectively. P_o of the 600 °C annealed laser exceeds 106 mW, without obvious thermal rollover up to 350 mA. The differential efficiency (η_d) behaves in a similar manner, with η_d increasing from ~26.8% in the as-grown laser to ~37.3% in the 600 °C annealed laser, but it drops to ~16.4% in the 650 °C annealed device. To verify the repeatability of the P - I characteristics, measurements of several laser chips are depicted in Fig. 6-2, which demonstrates similar performance for the same type of laser device.

Fig. 6-1 CW P - I characteristics of the as-grown, 600 °C and 650 °C annealed QD lasers with the corresponding laser spectra under injection current level around the ES threshold condition.

Fig. 6-2 Plot of threshold current (solid circle symbols) and external differential efficiency (solid square symbols) measured from three sets of devices with cavity length of 1 mm for the as-grown lasers and the lasers annealed at 600 °C and 650 °C.

The device improvements in terms of P_o and η_d obtained in the 600 °C annealed laser are consistent with the findings reported in chapter 5. This could be attributed to reduction in nonradiative recombination resulting from the thermal annealing [10]. However, the device annealed at 650 °C suffered degradation in performance with reduction in η_d by ~38.8% as compared to the as-grown device. This could be due to the occurrence of a small degree of In-Ga interdiffusion between the QDs and its surrounding barrier layer. The inset in Fig. 6-1 shows the EL spectra of all devices ($L=1$

mm) captured under ES threshold condition. Compared to the GS lasing peak of the as-grown sample, a 5 nm blueshift was observed in the 650 °C annealed sample, suggesting the onset of In-Ga intermixing at this anneal temperature. The reduction in intrasubband spacing between GS and ES from 98 nm (for the as-grown sample) to 94 nm (for the 650 °C annealed sample) further suggests the occurrence of the intermixing effect. The I_{th} of ES lasing in the as-grown, 600 °C and 650 °C annealed lasers are 129, 128, and 133 mA, respectively. This corresponds to the ratio of ES threshold current to GS threshold current $(I_{th})_{ES}/(I_{th})_{GS}$ of 3.4, 4.0 and 3.2, respectively. Compared to the as-grown device, the increase (decrease) in this ratio in the 600 °C (650 °C) annealed device suggests the competition between GS and ES behavior is enhanced/suppressed depending on the anneal temperature.

Fig. 6-3 Plot of threshold current as function of temperature for the (a) as-grown laser and the lasers annealed at (b) 600 °C and (c) 650 °C for both GS (solid square symbols) and ES (solid circle symbols) lasing.

Figure 6-3 shows the threshold current (I_{th}) as function of temperature for the as-grown and the lasers annealed at 600 °C and 650 °C under CW operation. All devices have the same dimension of $4 \times 1000 \mu\text{m}^2$. Within the temperature range investigated, both the GS and ES lasing are demonstrated from the as-grown and annealed devices, where the ES lasing is observed at high injection current levels. By fitting the experimental data using Eq. (6.1) and Eq. (6.2), the characteristic temperature (T_0) could be determined for both GS and ES lasing emissions.

$$(I_{th})_{GS} = I_0 \exp\left(\frac{T}{T_0}\right) \quad (6.1)$$

$$(I_{th})_{ES} = I_0 \exp\left(-\frac{T}{T_0}\right) \quad (6.2)$$

Extremely high T_0 for the GS lasing are obtained for the as-grown (815 K) and the lasers annealed at 600 °C (855 K) and 650 °C (800 K) at the low temperature region. These results are consistent with our findings reported in chapter 5. The reason for such a high value of T_0 obtained could be explained by the decrease in Auger recombination, which is compensated by the increase in recombination in the barrier/waveguide regions. Similar results have been reported by Fathpour *et al.*, demonstrating the p-doping effects on the temperature performance in the QD laser structure [14]. As shown in Fig. 6-3(a), above 40 °C, the as-grown laser shows significant increase in I_{th} , with T_0 of 102 K in the 45-70 °C range, suggesting serious thermal broadening of holes [14] at this temperature interval. The as-grown device could be operated up to 55 °C, whereas the 600 °C annealed laser (see Fig. 6-3(b)) can successfully lased up to 80 °C, indicating significantly improved high temperature performance of the QD lasers subjected to the annealing process. For the device annealed at 650 °C shown in Fig. 6-3(c), the highest

operating temperature drops to 60 °C, which is worse than that in the as-grown sample, suggesting the degraded device performance at this annealing condition. Furthermore, the value of T_0 for GS lasing is increased to 122 K and decreased to 96 K for the 600 °C (see Fig. 6-3(b)) and 650 °C (see Fig. 6-3(c)) annealed laser, respectively, compared to the as-grown sample (see Fig. 6-3(a)) at the high temperature region. In the case of GS lasing, the turning point above which I_{th} increases significantly, is shifted to a higher temperature of 60 °C in the 600 °C annealed laser (see Fig. 6-3(b)), but it drops to 40 °C in the 650 °C annealed laser (see Fig. 6-3(c)). As far as we know, the turning point is related to the carrier recombination process in the barrier/waveguide regions [14]. The higher the temperature of the turning point, the lower is the carrier recombination in the barrier/waveguide regions. From all the observations above, it indicates the device temperature performance could be modified by changing the annealing temperatures.

In the case of ES lasing, the value of T_0 increases upon annealing, showing 107 K and 137 K for the 600 °C (see Fig. 6-3(b)) and 650 °C (see Fig. 6-3(c)) annealed laser, respectively, at the low temperature region. In both as-grown (see Fig. 6-3(a)) and 650 °C annealed (see Fig. 6-3(c)) lasers, we note that the turning point at which I_{th} decreases significantly for ES lasing coincides with the turning point for GS lasing. This strongly proves the competition behavior between the two states under the same current injection level. At the temperature region above 40 °C, a significant decrease in T_0 is observed from the 650 °C annealed laser (see Fig. 6-3(c)) (16 K) compared to the as-grown laser (see Fig. 6-3(a)) (28 K). However, there are no obvious changes in T_0 for the laser annealed at 600 °C, as shown in Fig. 6-3(b). It is known that the smaller the value of T_0 , the lower is the ES threshold current required for the ES lasing threshold condition. In other words, the ES lasing is enhanced in the 650 °C annealed device with

a lower value of T_0 . The findings again suggest the fact that the competition between GS and ES lasing behavior could be enhanced/suppressed by adjusting the anneal temperature.

6.2.2 Threshold current analysis

Further measurements were carried out to study the threshold current characteristic of both the GS and ES lasing. The investigations in this section are based on the CW EL spectra measured at various temperatures. Figure 6-4 depicts the ratio of ES and GS threshold currents ($(I_{th})_{ES}/(I_{th})_{GS}$) as function of the test temperature. In general, one observes the value of $(I_{th})_{ES}/(I_{th})_{GS}$ reduces as temperature increases, suggesting that ES lasing is favored over GS lasing at high temperature. In other words, GS lasing is more sensitive to temperature variation compared to ES lasing. However, note that the device annealed at 600 °C demonstrates the highest working temperature (CW) of up to 80 °C. Furthermore, within the temperature range investigated, the 600 °C annealed laser shows a higher value of $(I_{th})_{ES}/(I_{th})_{GS}$ compared to the as-grown device. The difference between the $(I_{th})_{ES}/(I_{th})_{GS}$ value of the 600 °C annealed laser and that of the as-grown device is larger at high temperature (e.g. 60 °C), confirming that optimized annealing enhances GS lasing and suppresses ES lasing. The trend of the curve for the 650 °C annealed device is similar to that of the as-grown device. However in this case, a lower value of $(I_{th})_{ES}/(I_{th})_{GS}$ was observed, indicating that GS lasing is suppressed and ES lasing enhanced.

Fig. 6-4 Ratio of ES and GS threshold current as function of temperature for as-grown (solid square), 600 °C annealed (solid circle) and 650 °C annealed (solid triangle) devices. All devices have cavity lengths of 1 mm.

Figure 6-5 plots the values of $(I_{th})_{ES}/(I_{th})_{GS}$ of the as-grown and annealed lasers of different L measured at RT. All devices show strong dependence of the $(I_{th})_{ES}/(I_{th})_{GS}$ value on L , with smaller values at short L . This indicates stronger competition between GS lasing and ES lasing in devices with short L due to the higher GS threshold gain, which is consistent with the work of Markus *et al.* [4]. For a fixed L , the data shows higher (lower) $(I_{th})_{ES}/(I_{th})_{GS}$ value for the 600 °C (650 °C) annealed laser compared to the as-grown laser. However, in devices with long L (e.g. $L=2$ mm), the $(I_{th})_{ES}/(I_{th})_{GS}$ values are almost identical for all devices, indicating that annealing has insignificant effect on the device [12]. Based on the above observations, we can draw the conclusion

that the GS and ES competition can be observed under a number of different conditions, including low and high temperature, at cavity lengths ranging from 1 to 2 mm.

Fig. 6-5 Plot of ratio of ES and GS threshold current for as-grown and annealed devices of different cavity lengths measured at 25 °C.

6.2.3 Modal gain measurements

The modal gain measurements were performed with an optical spectrum analyzer (OSA) at room temperature. Details of the experimental setup can be found in chapter 2. The net modal gain (G_{net}) was extracted from the amplified spontaneous emission (ASE) spectra using the Hakki-Paoli method [15]. By measuring the modulation depth of the Fabry-Perot (FP) resonances in the ASE spectra, G_{net} was determined from the equation:

$$G_{net} = \Gamma g - \alpha_i = \frac{1}{L} \ln \frac{\sqrt{S} - 1}{\sqrt{S} + 1} + \frac{1}{2L} \ln \left(\frac{1}{R_1 R_2} \right) \quad (2.11)$$

where α_i is the internal loss, S is the ratio of intensity maximum and minimum in the FP resonances, L is the cavity length, and R_1 and R_2 are the facet reflectivities. Figures 6-6(a) to 6-6(d) depict the net modal gain spectra of the as-grown laser device at a series of injection current levels. The measurements were performed above the GS lasing threshold but around the ES lasing threshold condition. This device has a cavity length of 1 mm. When the injection current is low, as shown in Fig. 6-6(a), only the GS lasing is observable with the maximum GS net modal gain pinned at its threshold value ($\sim 11 \text{ cm}^{-1}$). The ES modal gain, on the other hand, reveals a negative value for the whole wavelength range investigated. As shown in Fig. 6-6(b) to Fig. 6-6(c), the ES modal gain increases following increase in the injection current. Once the injection current is above the ES lasing level, the value of maximum ES net modal gain (as shown in Figs. 6-6(c)-(d)) is pinned at its threshold value ($\sim 10 \text{ cm}^{-1}$). By comparison, from Fig. 6-6(b) to Fig. 6-6(d), the GS modal gain decreases as the injection current increases. In the case of high injection current (shown in Fig. 6-6(d)), the GS transition does not provide enough modal gain for lasing operation, leaving the ES as the only surviving lasing peak. The observations from the modal gain spectra clearly show the competition between GS and ES lasing in the as-grown laser device.

Fig. 6-6 Net modal gain spectra as function of wavelength for the as-grown laser device at various injection currents at (a) $I=3.1(I_{th})_{GS}$, (b) $I=3.3(I_{th})_{GS}$, (c) $I=3.5(I_{th})_{GS}$, and (d) $I=3.7(I_{th})_{GS}$.

Further investigations were carried out on the as-grown and the lasers annealed at 600 °C and 650 °C. Figures 6-7(a) and 6-7(b) compare the measured maximum net modal gain of the GS and ES lasing, respectively, as function of normalized injection current for devices with $L=1$ mm at RT. As shown in Fig. 6-7, before the onset of the ES lasing threshold, the maximum modal gain of the GS lasing (~ 11 cm⁻¹) for all samples is almost unchanged, while the gain of ES lasing increases rapidly with injection current. The former phenomenon indicates the GS gain is clamped at the threshold value by the laser oscillation condition. Possible reasons for the latter phenomenon include: (i) the slow carrier relaxation from the ES to GS compared to that from barrier to ES [16] or (ii) the almost full carrier occupation in the GS. One also observes that before the onset of the ES lasing threshold, the differential gain (dG_{net}/dI) for the ES in the 600 °C annealed device is the smallest (see Fig. 6-7(b)), *e.g.* the slope of G_{net}

increment is the lowest. This indicates there are more injected carriers relaxing to the GS level, thus leading to fewer carriers occupying the ES level for the 600 °C annealed laser as illustrated in Fig. 6-8. As shown in all samples (see Fig. 6-7(b)), upon ES lasing, the ES gain still increases (but at much slower rate) compared to the pre-lasing stage, probably due to incomplete carrier occupation of the ES levels. The unsaturated ES gain observed from all devices also suggests the carrier relaxation time from barrier to ES level is shorter than the ES radiative lifetime. On the other hand, as shown in Fig. 6-7(a), the GS gain decreases upon ES lasing since the number of injected carriers relaxing from the ES level is now smaller. The rate of decrease of the GS gain (dG_{net}/dI) was found to be lower in both the 600 °C and 650 °C annealed devices compared to the as-grown device. Again, the reduction in dG_{net}/dI , coupled with the increased transparency current (where $G_{net}=0$) of the 600 °C annealed device well supports the fact that GS (ES) lasing is enhanced (suppressed) after optimized annealing. Such observation can be explained by a faster carrier relaxation mechanism induced by annealing. The shorter carrier relaxation time in the 600 °C annealed device is believed to be due to reduction of nonradiative recombination centers (see Fig. 6-8(b)) as result of the annealing, leading to more efficient carrier relaxation [17]. However in the 650 °C annealed laser, although dG_{net}/dI is reduced, the lower transparency current results in more favorable ES (rather than GS) transition. To better understand this behavior, more investigations are in progress to study the annealing effect on the two-state lasing behavior.

Fig. 6-7 Maximum net modal gain of (a) GS and (b) ES emission vs. normalized injection current for as-grown (solid square), 600 °C (solid circle) and 650 °C (solid triangle) annealed QD lasers at 25 °C.

Fig. 6-8 Schematic diagram of QD energy levels for (a) as-grown, (b) 600°C and (c) 650°C annealed lasers. E_{e1} and E_{e2} are the electron energy levels for the first ES and GS, respectively. E_{h1} and E_{h2} are the hole energy levels for the first ES and GS. E_d is the carrier energy level for the nonradiative defect state.

6.3 SUMMARY

The competition of GS and ES lasing is investigated from the as-grown and thermally annealed QD lasers using post-growth RTA technique. Various laser devices with different cavity lengths were measured at different temperatures. Our investigations on the threshold characteristics show that two-state competition is more significant in devices with short cavity length operating at high temperature. The gain spectra of the as-grown and annealed devices are measured around the ES threshold condition, showing the two-state lasing competition amongst all types of devices. Most importantly, by adjusting the RTA temperature, the competition between the GS and ES lasing can be modified. By comparing the as-grown and annealed devices, we demonstrate enhanced GS and suppressed ES lasing from the QD laser annealed at 600 °C for 15 s.

7. CONCLUSIONS AND SUGGESTIONS FOR FUTURE WORK

In this chapter, a summary of the thesis is given with some recommendations for future work.

7.1 CONCLUSIONS

In this thesis, the characteristics of InAs/InGaAs QD laser emitting at 1.3 μm have been investigated. Most importantly, the post-growth annealing technique is established to enhance the device performance with negligible shift in the emission wavelength. In chapter 3, both the broad area and narrow ridge waveguide (RWG) QD laser structures are investigated. High output power with low transparency current density has been obtained in the broad area laser structure. The QD laser also demonstrates CW ground state (GS) lasing operation up to 100 $^{\circ}\text{C}$. By using the narrow RWG structure, devices exhibit GS lasing with high output power. Near ideal external differential quantum efficiency of 96% is achieved in pulsed operation with minimal device heating. Such a device also demonstrates single lateral mode emission.

Post-growth annealing technique is utilized to study its effects on the device performance. In chapter 4, various thermal annealing conditions at different annealing temperatures have been explored in the dots-in-a-well (DWELL) structure. A systematic study of the material properties after annealing has been carried out using low and room temperature photoluminescence (PL) measurement to check the optical property of the undoped and p-doped DWELL structure. At the high annealing temperature region (*e.g.* $>750^{\circ}\text{C}$), structural changes caused by atomic interdiffusion giving rise to PL peak energy blueshift are observed from the undoped and p-doped

samples. Our investigations show improvement in the PL intensity for the p-doped and undoped samples annealed at 600 °C. Furthermore, the p-doped sample exhibits a higher thermal energy onset for the occurrence of significant intermixing, which is due to the presence and diffusion of Be atoms, resulting in suppressed Ga diffusion in the p-doped structure. Further investigations have been carried out using the temperature dependent PL measurements. Rapid quenching of the integrated PL intensity at high temperature is observed from the undoped and p-doped samples. The carrier loss mechanisms are studied by analyzing the activation energies corresponding to the different nonradiative recombination processes.

Based on the annealing condition obtained in chapter 4, a further study has been carried out on the ten-layer InAs/InGaAs QD laser structure in chapter 5. Significant improvements in the device performance of the p-doped QD laser have been demonstrated using rapid thermal annealing (RTA) at 600 °C for 15 s. The annealed lasers exhibit notable increase in output power, differential quantum efficiency without obvious emission wavelength shift. The reduction in internal loss and threshold current has also been achieved in the annealed laser devices. The mechanism responsible for the improved performance has been discussed and studied by electroluminescence measurements. Defect reduction is thought to be the most likely mechanism contributing to the improved performance according to the electroluminescence and improved characteristic temperature behavior.

With the successful demonstration of the improved device performance resulting from RTA, more investigations are carried out in chapter 6. The competition between the ground state (GS) and excited state (ES) lasing is demonstrated on the as-grown and thermally annealed QD lasers. The study is carried out by measuring various laser

devices of different cavity lengths under different temperatures. Our results show that two-state competition is more significant in devices with short cavity length operating at high temperature. The modal gain competition between the GS and ES are measured and analyzed around the ES threshold characteristics. Our investigations demonstrate the competition between the GS and ES lasing can be modified by adjusting the RTA temperature.

7.2 SUGGESTIONS FOR FUTURE WORK

1. This thesis only focuses on the characteristics of the p-doped QD lasers. It is widely known that p-type doping technique has been proposed to improve the laser characteristic temperature by improving the hole thermalization. However, this technique could potentially bring undesired effects, such as increasing the internal loss [1] due to inter-valence band absorption (IVBA) and reduction in the carrier lifetime [2]. Moreover, the improvement in the modal gain resulting from p-type doping, has not been clearly demonstrated. At low current injections, one generally observes that the p-doped QD laser showed either smaller or similar modal gain compared to the undoped laser. At high current injections, p-doped lasers showed higher modal gain than the undoped laser. These inconsistent results suggest further investigations could be carried out to fill the unanswered blanks. A comparison study can be performed between the undoped and p-doped structures to better understand the p-doping effects on the device performance.
2. For the study of thermal annealing effects on the QD laser performance, relatively low annealing temperature, i.e. 600 °C and fixed annealing time of 15 s have been applied, to realize device performance improvement after RTA. More annealing

conditions, such as higher annealing temperature and longer annealing time, could be tested on the laser structure. It will be interesting to perform systematic investigations on the changes in the laser characteristic parameters with respect to various annealing conditions. Another recommended topic is to study the device performance of the intermixed QD lasers after high temperature (>700 °C) RTA. Generally, a large blueshift in the emission wavelength and reduction in intersublevel energy spacing will be observed at high annealing temperature [3]-[4]. It is noted that the ability to tune the intersublevel spacing between the GS and ES of the QDs is of great interest for various device applications such as the realization of mid-infrared detectors and other devices based on intersubband transitions, broadband QD lasers and QD superluminescent light-emitting diodes.

3. It will be interesting to carry out the investigations of the QD lasers for the small signal modulation operation. Currently, the modulation bandwidth of the QD lasers is limited to around 10 GHz due to the following reasons: 1) The inhomogeneous linewidth broadening associated with the dot size distribution imposes a limit on the performance of the QD lasers. 2) The hot-carrier effects and gain compression [5] due to the large density of states in the wetting layer and barrier states further degrade the modulation bandwidth. It will be interesting to investigate the high speed modulation behavior of the QD laser under various injection current at different temperatures. With the successful demonstration of the improved device performance using the post-growth annealing technique, it is reasonable to extend such a study to the small signal modulation response. By comparing the modulation bandwidth of the devices before and after annealing, the effects on the high speed performance could be determined. The intermixing effects, induced by the high

temperature RTA, have been shown to improve the carrier lifetime and reduce the carrier capture and relaxation [6]. It is expected that potentially high modulation speed could be achieved as a result of the QD intermixing.

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CHAPTER 3

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CHAPTER 4

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