Thermal effects in 1.3- μ m InAs/GaAs quantum-dot vertical-cavity surface-emitting lasers

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**Thermal Effects in 1.3- μm InAs/GaAs
Quantum-Dot Vertical-Cavity Surface-Emitting
Lasers**

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in partial fulfillment of the requirement for the degree of
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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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Abstract

1.3- μm GaAs/InAs quantum-dot (QD) vertical-cavity surface-emitting lasers (VCSELs) are attracting great interest in the research of laser diodes due to the special merits of the QD structure. However, the performance of QD VCSELs is influenced negatively by their carrier confinement, which suffers a significant degradation due to a serious self-heating effect. The goal of this project is to analyze and characterize the influence of self-heating on the performance of output power in 1.3- μm GaAs/InAs QD VCSELs and to realize the improvement and optimization in device fabrication. This research work includes both theoretical (modeling) and experimental (device processing) approaches.

In theoretical study, a self-consistent model comprised of rate equations and the thermal conduction equation was established to analyze the influence of self-heating on the carrier occupation, the quantum efficiency and the output power of 1.3- μm GaAs/InAs QD VCSELs. The simulation results showed that the poor hole confinement in QDs is due to the thin wetting layer, and the increase in the surface density and the layer number of QDs can significantly decrease the self-heating generation and improve the quantum efficiency. The output power of QD VCSELs is mainly determined by the quantum efficiency. A higher output power can be achieved by increasing the number of QD layers and the surface density. However, there exists an optimized number of QD layers (~ 15) to achieve the highest roll-over output power.

The theoretical simulation revealed that the serious carrier thermalization in 1.3- μm GaAs/InAs QD VCSELs is mainly due to the poor hole confinement. As a result, we adopted the p -type modulation doping in the wafer structure for device fabrication. It was found that the p -type modulation doping effectively enhances the temperature stability of threshold current. For the device with oxide-aperture diameter of 10 μm , a high characteristic temperature (T_0) of ~ 510 K was achieved. However, the degradation of the QD emissions at high temperatures seriously influences the output power, which can be improved by enhancing the carrier confinement in the QD wetting layer.

The continuous-wave single-mode operation of 1.3- μm p -doped GaAs/InAs QD VCSELs was demonstrated. The temperature-dependent output characteristics were investigated from 20 to 50°C. The highest output power of 0.435 mW and the lowest threshold current of 1.2 mA were achieved. Single-mode emission with a side-mode suppression ratio (SMSR) of 34 dB was observed at room temperature. The critical size of oxide-aperture for single-mode operation was also discussed.

The theoretical and experimental investigations were combined together to characterize the influence of self-heating under pulsed operation with different duty cycles. A good agreement was obtained between our self-consistent model and the measurement results. The results showed that, in 1.3- μm p -doped GaAs/InAs QD VCSELs, about 60% of the output power is limited by self-heating in a device with single-mode operation (its oxide-aperture area is $5 \times 6 \mu\text{m}^2$). The temperature increase

in the active region and the QD injection efficiency were calculated and discussed based on different oxide-aperture areas and duty cycles.

To improve the thermal behavior and output performance (power and spectrum) of 1.3- μm GaAs/InAs QD VCSELs, we adopted a dielectric-free approach and the surface-relief technique in device fabrication. These are both realized in the QD VCSEL for the first time. Compared with the conventional dielectric-dependent approach, the lower differential resistance and improved output power were achieved by the dielectric-free approach: with the oxide-aperture diameter of 10 μm , the differential resistance (79.4 Ω) was reduced by 36.47% and the output power (1.28 mW) was improved by 78.32% under continuous-wave operation at room temperature. The output power is up to 3.42 mW under pulsed operation with the oxide-aperture diameter of 15 μm . The surface-relief technique helps to enhance the emission of the fundamental mode effectively. The characteristic of small signal modulation response was also analyzed.

The future recommendation of research in QD VCSELs focuses on the further improvement of the side-mode suppression ratio (SMSR) with the surface-relief technique and the optimization of small-signal modulation response by the dielectric-free approach.

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1. Introduction

1.1 Background and Motivation

1.1.1 VCSEL: Advantages and Applications

Vertical-cavity surface-emitting lasers (VCSELs; see Figure 1.1(a)) are a monolithic kind of semiconductor lasers. Their beam emissions are perpendicular to the wafer surface [1]. Therefore, the structure and operation of VCSELs are quite different from conventional edge-emitting distributed feedback lasers (DFB lasers; see Figure 1.1(b)), which leads to the inherent advantages of VCSELs. A comparison of several typical structural features between VCSELs and DFB lasers and the respective advantages of VCSELs are listed below [2-5].

(a)

(b)

Figure 1.1 The schematic structure of the different types of semiconductor lasers:

(a) VCSELs [4] and (b) DFB lasers [6].

VCSELS versus DFB Lasers

- The cavity length of VCSELS (one to three times emission wavelength (λ)) is much shorter than the cavity length of DFB lasers (100λ - 1000λ). Therefore, it is much easier to achieve single-longitudinal-mode operation, low threshold gain, and large relaxation frequency (high-speed modulation capacity) [3] with VCSELS.
- The area of the active region in VCSELS can be reduced by selective oxidation [4,5] (see Figure 1.1(a)). This leads to a better electrical and optical confinement and a relatively low threshold current (can be a factor of 10 lower than DFB lasers [7]).
- The typical emissions of VCSELS are circular, symmetric Gaussian beams (Figure 1.1(a)), while the emissions of DFB lasers are astigmatic beams (Figure 1.1(b)). Thus, the higher coupling efficiency into standard optical fibers can be achieved with VCSELS [2].
- The laser beam emission of VCSELS is perpendicular from the top surface (Figure 1.1(a)). DFB lasers, in contrast, emit from surfaces formed by cleaving the individual chip out of a wafer (Figure 1.1(b)). Therefore, VCSELS can densely pack and precisely arrange two-dimensional (2-D) laser arrays [4] more easily than DFB lasers.
- The cost of the modules and the packaging is much more economical for VCSELS and the devices are easy to bond and mount [4].

Drawing on these unique properties, VCSELs have attracted increasing interest and have gained a reputation as a superior technology in many areas. Relevant applications include optical fiber communication, optical signal processing, optical interconnects, etc. Gigabit Ethernet and fiber channels also represent current major markets for VCSELs. VCSEL-based 10-G Ethernet modules are now ready for practical systems [7]. For example, commercial 850-nm GaAs VCSELs have been well established and widely applied in local-area networks (LANs) with modulation frequencies well into the gigahertz range [8].

1.1.2 1.3- μ m VCSELs: Importance and Development

Although 850-nm VCSELs play an important role in optical fiber communication, the maximum fiber-transmission distance of 850-nm VCSEL modules is only up to 300 meters [9] (for example, on Gigabit Ethernet standard for 1000Base-SX link, the 850-nm modules can operate with a maximum fiber length of 220-meters [10,11]).

The reason behind this short reach by the 850-nm modules is shown in Figure 1.2. There are three wavelength windows for the light transmission with fibers: 850-nm, 1.3- μ m, and 1.55- μ m [12]. The attenuation at 1.3 μ m is around 0.3 dB/km, while the attenuation at 850 nm is 2 dB/km. Therefore, wavelengths in the 850-nm window are only useful for local-area networks (LANs), while the ones in the 1.3- μ m window are suitable for metropolitan and wide-area networks (WANs) as their

transmission distance is up to 10 km [13]. Therefore, VCSELs emitting around $1.3\ \mu\text{m}$ are currently attracting much research interest [14-19].

Figure 1.2 The spectral dependence of loss mechanisms and total attenuation in a standard fiber. Also shown are spectral ranges for three communication windows (based on data from assorted sources, from Liu [12]).

Various materials have been proposed and demonstrated for building 1.3- μm VCSELs [8]. As illustrated in Figure 1.3 [9], one approach is with InP-based materials in which a 1.3- μm emission is routinely achieved. However, these materials are much less suited to form distributed Bragg reflector (DBR) mirror stacks since they offer only a small change in the index of refraction. More importantly, they have a very poor heat conductivity [20]. An InGaAsP/InP Bragg mirror with 50 or more periods is required to achieve the reflectivity level ($R = 0.99$) required for lasing. To overcome this problem, InP-based active regions have been fused with separately grown, GaAs-based distributed-Bragg reflector (DBR) mirrors [21] or even with GaAs-based short-wavelength lasers [22] that optically pump the 1.3- μm active region. However, this process is not very amenable to large-scale production. An alternative method uses AlGaAsSb-based DBRs on InP substrates [22] but the problems of reliability and cost efficiency that arise from the use of these DBRs remain unsolved.

Figure 1.3 A 1.3- μm emission achieved with a conventional III-V semiconductor [9].

Another approach uses the well-established technology of GaAs-based VCSELs [9,20,21]. This approach allows the monolithic growth of the whole VCSEL structure and effectively reduces the cost and complexity of fabrication. The main problem might be the limited emission at long wavelengths. Figure 1.3 illustrates that, due to strain limitation, the emission of a GaAs-based VCSEL which has oxidized AlAs/GaAs DBR stacks and an InGaAs quantum-well (QW) active region is only 1.15 – 1.2 μm [9]. To overcome this wavelength limitation, one possibility is to introduce nitrogen doping in the InGaAs QW layers [9,20,23,24]. The introduction of nitrogen atoms changes the band structure of InGaAs, reduces the bandgap energy,

and, therefore, “shifts” the emission wavelength towards $1.3\ \mu\text{m}$. However, a specified nitrogen (N) plasma source is required in wafer processing. In addition, compared to GaInAs, the optical quality of the N-containing alloy degrades significantly with an increasing N-content [9]. This also negatively influences the device’s performance.

Another, more promising, alternative is using GaAs-based VCSELs with InAs/GaAs quantum dots (QD) in the active region. Researchers currently consider these VCSELs particularly advantageous and attractive in research in the $1.3\text{-}\mu\text{m}$ photonics module design [25-30]. The several inherent merits of the QD structure compared with the QW structure are listed below:

- As illustrated in Figure 1.4, the carrier confinement of the QD is three-dimensional (3-D) while the carrier confinement of the QW is only one-dimensional (1-D). Therefore, it is easier to limit the carriers of the QD lasers to fewer energy levels. In addition, the density of states (DOS) in the QD lasers concentrate in fully quantized, discrete, and more widely separated energy levels compared with the ones in the QW lasers (see Figure 1.5) [31].

Figure 1.4 Carrier confinements. (a) QD; (b) QW.

Figure 1.5 The density of states (DOS) of carriers in the structures of QD and QW lasers. (a) QD; (b) QW.

- Since the discrete and widely spread energy levels are present in the QD structure, more carriers are likely to be excited directly from the ground state to the excited states. Thus, it is much easier to achieve population inversion, leading to low threshold current in the QD lasers [31].
- In addition, the 3-D carrier confinement of QD lasers results in a high thermal stability of threshold current (high characteristic temperature (T_0)), which provides high material gain and differential gain. In addition, the emission wavelength is also less sensitive with temperature [32].

Besides the above inherent merits, the structure of InAs/GaAs QDs on GaAs substrates are likely to achieve AlGaAs/GaAs distributed Bragg Reflector mirrors (DBRs) with high performance (good thermal stability and high reflectivity) [32]. The respective fabrication process of the InAs/GaAs-QD structure on a GaAs-substrate has already been well established with low cost and good reliability [31,32]. Molecular beam epitaxy (MBE) is one mature technology and is widely applied. In

this approach, the optimization of growth parameters can ensure a very good control of the size, shape, and density of arrays, enabling the possibility of fine-tuning the growth temperature, deposition rate, and V/III flux ratio.

In summary, GaAs-based VCSELs with InAs/GaAs QDs in the active region are expected to exhibit low threshold current, high quantum efficiency, and high output power. Therefore, they are considered good potential candidates for 1.3- μm fiber communication. Current research is now focused on the oxide-confined structure [17,19,26,29]. Selective oxidation is formed in the AlGaAs layer, which provides better optical and electrical confinement and is an important factor in achieving single-mode lasing [19].

1.1.3 Research Gap and Motivation

Although 1.3- μm GaAs-based QD VCSELs are currently very attractive due to the superior inherent properties of their QD structures and the mature technology, their reported output performance still registers far from the expectation. Up to now, the highest reported continuous wave (CW) output power of 1.3- μm QD VCSELs is only 2 mW [27] at room temperature (RT), while for 1.3- μm QD EELs, even at 100°C, the highest output power is more than 20 mW [33]. In addition, the threshold current density (J_{th}) of 1.3- μm InAs/GaAs GaAs-based QD VCSELs is around 1.5 – 18 kA/cm² [16,26,34-37], which is much higher than the J_{th} of 1.3- μm QD EELs (less than 200 A/cm² reported in [32]).

The failure of the actual output performance of 1.3- μm InAs/GaAs GaAs-based QD VCSELs to measure up to expected their performance is mainly due to the self-heating effect. The deterioration of carrier confinement leads to a reduction in injection quantum efficiency. Therefore, the output power is further degraded. In addition, serious carrier thermalization results in gain saturation, which consequently affects the temperature sensitivity of the threshold characteristics [17,19,38-39].

In a semiconductor laser, the main heat contributor is the active region [40]. Heat is generated from the non-radiative recombination and the absorption of spontaneous emission. Another significant heat source is Joule heating due to the relative high series resistance of the p -doped DBR mirrors [41]. For VCSELs with oxidation confinement, a small oxide-aperture is necessary to achieve single-longitudinal-mode emission. However, the small oxide-aperture also results in a high self-heating effect and degradation in injection quantum efficiency [17,19,26,29]. The influence of the above heat sources on the output power of quantum well (QW) VCSELs has already been studied and demonstrated [42,43]. A lot of theoretical models have been developed and analyzed to investigate on the thermal behavior of QW or other types of VCSELs [44-48]. However, the self-heating effect and its corresponding influence on the carrier confinement and the output power in QD VCSELs have received little attention. Hence, the following issues that remain in the development of 1.3- μm InAs/GaAs GaAs-based QD VCSELs constitute the research gaps for this thesis:

1. Not much information is available on the principle of heat generation and distribution inside the VCSELs.
2. There is lack of studies on the limitation of self-heating on the carrier confinement, the injection quantum efficiency, and the output power.
3. It is necessary to make the following investigations from experimental characterization or theoretical analysis:
 - a) Investigate the single-longitudinal-mode lasing;
 - b) Characterize the influence of self-heating on the output power and other crucial parameters;
 - c) Optimize the structure design to improve the performance (threshold current, output power, spectrum, etc.).

All these research gaps strongly motivate us to resolve the scientific issues and to seek better answers. Both a theoretical and an experimental approach are employed during this research process.

1.2 Project Objectives

In view of the serious deterioration of the output performance caused by the self-heating effect in 1.3- μm InAs/GaAs GaAs-based QD VCSELs and in view of the research gap in respective theoretical analysis and experimental characterization, this project has the following objectives:

1. Theoretically study and analyze the self-heating effect in 1.3- μm InAs/GaAs GaAs-based QD VCSELs:
 - a) Conduct a literature review on the concepts of heat generation and distribution and on different thermal models (especially the previous developed models of QW VCSELs) in order to analyze the self-heating effect in VCSELs.
 - b) Based on the theoretical understanding, establish a self-consistent model in order to analyze the influence of self-heating over the carrier confinement and output power.
 - c) According to the model analysis, investigate the device structural optimization and eventually apply it in device fabrication.
2. Experimentally fabricate and characterize 1.3- μm InAs/GaAs GaAs-based QD VCSELs
 - a) Practice and familiarize the process of device fabrication and measurement and calibrate the experimental settings.
 - b) Fabricate 1.3- μm InAs/GaAs GaAs-based QD VCSELs and measure their output and threshold performance.
 - c) Achieve single-longitudinal-mode lasing and investigate the respective influence of the oxide-aperture size.
3. Combine the theoretical modeling and the experimental measurement to characterize the influence of the self-heating effect on the output power.

4. Investigate the optimization method to improve output power together with the enhancement of the fundamental mode emission in 1.3- μm InAs/GaAs GaAs-based QD VCSELs.

1.3 Major Contributions of this Thesis

According to the project objectives, the research work has three main parts. First, a theoretical model is established to analyze the influence of self-heating on the carrier dynamics and the output and threshold performance of 1.3- μm InAs/GaAs GaAs-based QD VCSELs. From the simulation and the analysis, the structural design optimization needs to be investigated. Secondly, a device fabrication and characterization is carried out, the requirement of single-mode emission is obtained, and respective performance is analyzed. Third, the influence of self-heating on output power is characterized by combining the theoretical and experimental investigations. An optimization method to improve output power and enhance fundamental-mode lasing is suggested and realized in fabrication. The respective recommendation in future development is also summarized.

Therefore, this research project involves both theoretical and experimental investigations that are equally important to the success of the project. A description of the significant contributions of this work follows.

For the theoretical investigation, a self-consistent model comprised of rate equations and the thermal conduction equation was established and used to analyze

the influence of self-heating on the carrier occupation, the injection quantum efficiency, and the output power of 1.3- μm InAs-GaAs GaAs-based QD VCSELs. The simulation results showed that the serious carrier thermalization in QD VCSELs is mainly attributed to the high rate of hole escape. The poor hole confinement in QDs is due to the thin wetting layer. Therefore, an increase in the QD surface density and the layer number can significantly improve the self-heating effect and the injection quantum efficiency. The output power of the QD VCSEL is mainly determined by the injection quantum efficiency. A high number of QD layers and QD surface density can achieve a high output power. However, an optimized number of QD layers exists (~ 15) to achieve the highest roll-over output power.

For the experimental investigation, the p -type modulation doping, which has been successfully applied in QD EELs [49-51], was applied in our device processing to improve hole confinement. There are 17 layers of p -doped InAs/GaAs QDs located within the 3λ intercavity of the active region of the QD-VCSEL and the lasing wavelength of the fabricated devices was around 1273 nm. Both multi- and single-mode operations were realized and we found that p -type modulation doping effectively enhanced the temperature stability of the threshold current. However, in p -doped lasers, the output power is still seriously influenced by self-heating due to the serious deterioration of the QD emissions at high temperatures. For multi-mode VCSELs with oxide-aperture diameters of 10 μm , high characteristic temperatures (T_0) of ~ 510 K and low threshold current densities of 65 A/cm^2 per QD layer were achieved. The highest output power from the devices registered over 0.74 mW and the

respective temperature characteristics of the devices were investigated. The photoluminescence test revealed that the deterioration in the performance of QD VCSELs caused by self-heating results from the temperature sensitivity of the QD emission instead of from a mismatch between the gain wavelength and cavity modes. The real temperature at the QD VCSEL active region above threshold is estimated from the shift in lasing wavelength, which is consistent with the calculations based on our self-consistent model.

Continuous-wave (CW) single-mode operation with a high output power of 0.435 mW was demonstrated in devices with oxide-aperture areas of $5 \times 6 \mu\text{m}^2$. The *p*-type modulation doping in the QD active region contributed to the high thermal stability in the threshold current. Single-mode operation with SMSR of 34 dB and 5.7 dB were achieved at room temperature (RT) and at 50°C, respectively. The device with a larger oxide-aperture of $7 \times 8 \mu\text{m}^2$ exhibited multimode operation with a higher output power and slope efficiency and a lower threshold current density.

The theoretical and experimental investigations of this research were combined together to characterize the influence of the self-heating effect on the output power. The measurement under pulsed current injection with different duty cycles was demonstrated. At room temperature and at a frequency of 500 Hz, the self-heating effect was reduced significantly and a higher output power was achieved when the current injection time was less than 0.2 ms. For devices with oxide-aperture areas of $5 \times 6 \mu\text{m}^2$ (single-mode QD VCSELs), the CW operation power was improved by nearly 60% if the self-heating effect was eliminated completely. We discovered

that the influence of self-heating on output power is less serious in devices with larger oxide-aperture areas (multi-mode QD VCSELs). A similar trend was also observed in the analysis of the temperature response at the active region and the QD injection quantum efficiency. The measurement results also showed a good agreement with the simulation results from our previously established, self-consistent model.

To improve the thermal behavior of 1.3- μm InAs-GaAs QD VCSELs, the dielectric-free (DF) approach [52] and the surface-relief technique [53] were adopted in device fabrication. Compared with the conventional dielectric-dependent approaches, lower differential resistance and improved output power were achieved by the DF approach in our device processing. With the same oxide-aperture area, the differential resistance was reduced by 36.47% and output power was improved by 78.32% under continuous-wave operation, which is up to 3.42 mW under pulsed operation with an oxide-aperture diameter of 15 μm . The surface-relief technique is also realized in 1.3- μm InAs-GaAs QD VCSELs for the first time in this research, which helps to enhance the emission of fundamental mode.

At the conclusion of this research, a future research plan is suggested to achieve single-mode operation in 1.3- μm InAs/GaAs QD VCSELs with surface-relief and to improve the small signal modulation response in the dielectric-free approach. A few techniques were previously recommended [54-57], such as electron beam lithography, reactive ion beam etching, inverted surface-relief, and proton implantation.

1.4 Organization of this Thesis

This thesis is organized into ten chapters. Chapter 1 introduces the thesis, the background and motivation, the objectives, and the major contributions of the thesis.

The realization of the objectives of this project are presented in Chapters 2 – 9 (see Figure 1.6), which contain both the theoretical and experimental investigations. Chapters 2 – 4 focus on the theoretical investigation of the self-heating effect. In Chapter 2, previous thermal models of VCSELs are reviewed and compared. The purpose of this comparison is to find a suitable way to establish a self-consistent model for 1.3- μm InAs/GaAs QD VCSELs. Our established model, comprised of rate equations and the thermal conduction equation, is demonstrated in Chapter 3. In Chapter 4, we illustrate the simulation results and the respective analysis on the influence of self-heating on the carrier dynamics and the output and threshold performance.

The experimental issues are documented in Chapters 5 – 8. In Chapter 5, the fabrication procedures of 1.3- μm InAs/GaAs QD VCSELs with *p*-type modulation doping are introduced as well as the wafer structure. The measurement and analysis of temperature characteristics in multi-mode QD VCSELs are demonstrated in Chapter 6. Chapter 7 presents the investigation of single-mode operation.

The influence of self-heating on output power is characterized and demonstrated in Chapter 8. This is also compared with and discussed together with theoretical simulation from our established self-consistent model. Chapter 9 presents

the improvement of thermal behavior, including the dielectric-free approach as well as the surface-relief technique.

Finally, Chapter 10 summarizes the major achievements of this work and contains some recommendations for future research work on QD VCSELs.

Figure 1.6 Diagram of the research methodology employed in this study.

2. Literature Review of Previous Thermal Models for VCSELs

Although many applications have been found for long-wavelength VCSELs, such as data communication and telecommunication, the design of the VCSELs in this range remains far from optimal. One of the most important problems is that their operation is seriously limited by their thermal behavior.

In order to understand this problem and remedy it, we built a thermal model for theoretical study. Next, computer simulation was applied to show the physical process taking place inside a VCSEL volume. From the simulation results, the relative influence of various factors (such as the structure design and the material of the device) on the output and the threshold performance of the VCSELs is further analyzed. Therefore, the crucial parameters for efficient performance were identified and analyzed to find the means of improving the device.

So far, the established thermal models of VCSELs can be divided into two categories: (1) the direct approach and (2) the self-consistent approach. The models are grouped in these categories according to their analysis and calculation methods. The direct approach models use direct calculations and the self-consistent approach models employ a “trial and error” or self-consistent analysis. Normally, the latter is considered more reasonable and more widely applied in recent research publications. However, a few earlier models based on the direct approach also provide some effective methods to simplify the calculation process. Therefore, in order to obtain the

strategy of a thermal model for 1.3- μm InAs/GaAs QD VCSELs, both direct and self-consistent approaches are reviewed.

In this chapter, the mechanisms of heat generation and conduction in VCSELs will be introduced first. The two categories of modeling methods will be reviewed and compared in Section 2.2. Our model and the corresponding analysis of this model will be summarized in Section 2.3.

2.1 Heat Generation and Conduction Mechanisms

Figure 2.1 contains a diagram of a typical QD VCSEL structure, including p -type contact, isolation layer, p -type distributed Bragg reflectors (P -DBRs), oxide-aperture, QD active region, n -type distributed Bragg reflectors (N -DBRs), substrate, n -type contact and heatsink. Several mechanisms of heat generation are contained inside the structure [1]:

1. Joule heating when current flows through the DBR stacks and contacts
2. A non-radiative recombination of electrons and holes in the active region
3. An absorptive heating of the lasing light due to high doping concentration
4. An absorptive heating of spontaneous emission

According to the analysis performed by Nakwaski and Osinski [2], there are two dominant heat sources in VCSELs: (1) Joule heating in the DBR stacks and (2) heating from the non-radiative recombination and the absorption of spontaneous emission in the active region. Most thermal models were established based on these

two main heating mechanisms to calculate the temperature profile and to analyze the corresponding influence of the output power.

Figure 2.1 Diagram of a typical VCSEL structure.

2.1.1 Joule Heating in DBR Stacks

The current flow in the DBR regions results in a voltage drop and generates Joule heating. The voltage drop is due to the band edge discontinuity at the interface of the different films in the DBR regions. Electrons and holes flowing in the vertical direction of the superlattice can pass through the energy barrier at the interface through thermionic emission or quantum tunneling [3]. Tai *et al.* [4] showed that, for graded interfaces, tunneling is the dominant process. Because holes have a much larger effective mass, the tunneling of holes through a barrier is more difficult than the tunneling of electrons. Another important factor is the oxide-aperture between the p -type DBR region and the QD active region. This oxide-aperture is required to be small in order to obtain the electrical and optical confinement. However, it also results in a high electrical resistance and serious Joule heating. Hence, most of the resistance (the majority of the Joule heating generation), occurs in the p -type DBR region. In addition, films inside the DBR region also contribute to the total Joule heating.

2.1.2 Heat Generation in the Active Region

When electrons and holes are injected into the active region, they recombine and release energy. There are two types of possible recombination processes [3]. The first is the radiative recombination, from which photons are generated. The second is the non-radiative recombination, from which phonons or heat is released. In addition, heat is also generated from the absorption of photons, including those which are emitted

during the spontaneous and stimulated emission process. In other words, heating in the active region is due to the absorption of spontaneous emission and the non-radiative recombination.

2.1.3 Thermal Conduction Equation

Heat conduction in semiconductor lasers is in the microscale regime since the phonon mean free path and wavelength are of a characteristic device dimension [5]. Strictly speaking, the classical Fourier heat conduction equation is no longer valid due to interface and boundary scattering. Two different methods to analyze heat conduction in the microscale regimes exist [5]. One starts from the Boltzmann transport equation. The other uses the Fourier heat conduction equation with a modified thermal conductivity. Because the former approach requires detailed information about the phonon scattering rate that is always hard to obtain in VCSEL operations, most models take the latter approach. Chen *et al.* [6] showed that the thermal diffusivity of VCSEL structures is much lower than that of their corresponding bulk media and suggested an anisotropic thermal diffusivity in their analysis on the thermal behavior of VCSELs.

Based on the above discussion, the three-dimensional thermal conduction equation that governs the temperature profile of VCSELs can be shown as [7]:

$$\frac{1}{k_i} \frac{\partial T(r,t)}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left[r \frac{\partial T(r,t)}{\partial r} \right] + \frac{1}{\lambda_i} Q(r, z, t) \quad (2.1)$$

where r , z and t denote the radius, height from bottom and time, respectively; k_i and λ_i are the thermal diffusion coefficient and effective thermal conductivity; $T(r, t)$ and $Q(r, z, t)$ represent the temperature and heat density at certain r , z and t . The boundary conditions for Equation (2.1) are constant temperature at the bottom contact and adiabatic boundaries for all other external surfaces. This is a reasonable assumption because calculations on similar structures indicate that heat loss due to natural convection and thermal radiation from the top surface is much smaller compared to heat conduction to the substrate [8]. At the interface between two different materials, the continuity of temperature and heat flux is applied.

2.2 Thermal Model Review

As mentioned earlier, according to the difference in temperature profile calculation, all established thermal models for VCSELs can be grouped into two categories: (1) the direct approach and (2) the self-consistent approach. The dominate heat sources considered in both approaches are the non-radiative recombination, the absorption of spontaneous emission, and Joule heating. For the direct approach, which was mainly applied in earlier research, the calculation is in a single direction. The temperature dependence of many physical parameters is not considered, such as the thermal conductivity, the internal quantum efficiency, and the voltage drop inside the VCSEL. That is, all parameters are treated as constants in the entire analysis. For the self-consistent approach, the problem solving is based on a “trial and error” process.

When a possible temperature profile is generated, the temperature-dependent parameters will be varied and tested. The evaluation process ends when all the temperature-dependent parameters and the temperature profile are matched or a “self-consistent” criterion is satisfied.

In most cases, the self-consistent approach is a methodical way of analyzing problems and the results it yields are believed to be very reliable. Under certain circumstances, the direct approach can be used to develop useful calculation methods and obtain important parameters in a simplified fashion. These methods are also quite helpful in simulations based on the self-consistent approach.

2.2.1 Direct Approach

The first analytical thermal model of VCSELs, in which the direct approach was applied, was developed by Kinoshita *et al.* in 1987 [9]. It was assumed that only a single flat-disk heat source was located in the centre of the active region. However, the influence of the multi-layer structure was considered in two-dimensional heat flux spreading and the boundary condition of all surfaces was analyzed. In addition to the lack of temperature dependency on physical parameters, the main limitation of this model was the negligence of all structural nonuniformity in the radial direction.

Another, very simple one-dimensional VCSEL thermal model was reported by Baets in 1988 [10]. Although similar limitations still existed, the model was

supplemented with some threshold analysis and interesting considerations concerning the role of amplified spontaneous emission in VCSELs.

Chen *et al.* [1,11] developed a model for the p -substrate VCSEL with short-period-superlattice DBRs. In this model, a very careful evaluation of heat generating mechanisms was carried out. This evaluation included almost all of the important heat sources mentioned in Section 2.1 (e.g. Joule heating in all barriers and volumes, the non-radiative recombination, and the absorption of spontaneous emission in the active region). A detailed analysis of the current flow was performed, including the thermionic and tunneling currents through heteroboundaries, the influence of the band-gap discontinuity on the heterointerface resistance, and the anisotropy in the electrical conductivities caused by quantum effects in the layered structures. However, all of the physical parameters of the device in this model were assumed to be temperature-independent.

A useful analytical method named the finite element method (FE) was applied in the models of Piprek, Yoo, and Baba *et al.* [12-14]. In this method, each DBR mirror was replaced with an equivalent, uniform, thermally anisotropic medium. In this way, the analysis of heat flux spreading inside the VCSEL structure could be further simplified. Therefore, the FE method is also frequently applied in self-consistent models.

Zhao and McNerney developed a model to analyze the transient temperature response of VCSELs based on the direct approach [7]. In this model, a new analytical method to solve the thermal conduction equation was reported. The Green's function

approach proposed by Osinski and Nakwaski [15] was applied in the calculation, by which the development of the temperature profile was effectively simplified. This model was also very helpful and widely applied in the self-consistent approach.

2.2.2 Self-Consistent Approach

Osinski and Nakwaski reported the first, complete, self-consistent thermal-electrical analytical simulation in 1991 [16]. This simulation was applied to the etched-well VCSELs. In a self-consistent iteration, the temperature dependence of many material and device parameters was considered, including the thermal conductivity, the electrical resistivity, the threshold current, the quantum efficiency, and the voltage drop at the p - n junction. In addition, the temperature dependence of all important heat generating mechanisms was taken into account, including the non-radiative recombination, the absorption of spontaneous emission, and Joule heating in all layers. Another contribution of this approach was the analytical discussion of the two-dimensional (2-D) current spreading and the temperature profile. The non-uniformity of the heat flux spreading in different layers was considered.

With a similar method, Nakwaski and Osinski incorporated another self-consistent model of proton-implanted VCSELs [17,18]. Besides the consideration of the parameters mentioned above, the temperature dependence of the free carrier absorption was considered in the iteration. In addition, in the simulation of proton-implanted VCSELs, the thermal profile of the entire structure was obtained

separately by each heat source. The cumulative temperature distribution in the entire volume of the device was determined by adding together the contributions of all heat sources. This approach simplified the analysis and calculation of the temperature profile and was applied or modified in many later simulations. Sarzala [19], for example, developed a full thermal-electrical self-consistent model on AlGaAs proton-implanted VCSELs by using the superposition principle and the finite-element (FE) method. The model was helpful to analyze the radial carrier diffusion within the layer contained in the active region. Another improvement in this approach was that the temperature dependence of the carrier diffusion coefficient was considered in the self-consistent iteration.

The above self-consistent models provided an analytical method to obtain the current spreading, the temperature profile, and the relationship between temperature and many important parameters in VCSELs. However, only a handful of the models mentioned the exact calculation of the emitted photon density, which is directly related to the output power and its thermal roll-over property. In addition, some important temperature-dependent parameters, such as the threshold current density and the internal quantum efficiency, were calculated without the consideration of carrier dynamics within different energy levels. In order to make models consistent with actual conditions, a comprehensive technique based on rate equations is widely adopted to describe the laser's characteristics [20-22].

Rate equations provide an accurate description of the static, spectral, and dynamic characteristics of semiconductor lasers with different structures in the active

region. They mainly focus on the carrier dynamics in the different energy levels to analyze important parameters of lasers, including the emitted photon density, the optical gain, the internal quantum efficiency, and the threshold current density. To analyze VCSEL characteristics under different thermal conditions, Mena *et al.* evaluated the temperature-dependent description of the optical gain and the offside current of QW VCSELs by rate equations [21]. Liu *et al.* [23] applied Mena's method to develop a thermal dependent model and to analyze the temperature dependency of the leakage current in VCSELs. Sukhoivanov and Samokhvalov [24] provided a method to calculate the temperature-dependent gain coefficient and the threshold current density from rate equations. Yu [20] also developed a model based on rate equations to show the dynamics of injection heating and hot carriers, which is further adopted to analyze the performance of small signal modulation in VCSELs.

Besides the models mentioned above, a circuit model [25] and several models for VCSEL arrays [26] are also studied and applied in many research areas. They are helpful in providing some analytical methods to calculate important parameters.

2.3 Short Introduction of Our Model

Taking into consideration the literature review of the thermal models of VCSELs and the QD structure, we established a self-consistent model comprised of rate equations and the thermal conduction equation for the 1.3- μm QD VCSEL. According to the

review of other models based on the self-consistent approach [16-19], the temperature dependence of many physical parameters (including the thermal conductivity, the electrical resistivity, the threshold current, the quantum efficiency, the voltage drop at the p - n junction, and the thermal diffusion coefficient) are taken into account in the rate equations. In addition, the analytical method from Zhao and McInerney's model [7] (the direct approach) is also adopted to solve the thermal conduction equation.

The purpose of the model is to investigate the influence of self-heating over the carrier confinement (in different energy levels) and the output power. As mentioned above, the main heat source is generated from the non-radiative recombination and the absorption of spontaneous emission in the active region. Another significant heat source considered in 1.3- μm QD VCSELs is Joule heating, which is due to the relatively high resistance of the p -doped DBR mirrors [27] and is also seriously affected by the oxide-aperture. The variation of the temperature profile and the injection quantum efficiency is analyzed in the process of a self-consistent iteration. In this way, the thermal roll-over property of the population inversion and the output power is also investigated. The detail of the concept and construction of our self-consistent model for 1.3- μm InAs/GaAs QD VCSELs is contained in Chapter 3 and the simulation results are discussed in Chapter 4.

3. Construction of the Self-Consistent Thermal Model for 1.3- μm QD VCSELs

The theoretical thermal model for 1.3- μm QD VCSELs comprises two components: (1) rate equations and (2) the thermal conduction equation. Rate equations are helpful to express the carrier dynamics in the different energy levels of the QD active region which is sensitive to temperature. The injection quantum efficiency calculated by the rate equations determines the thermal conduction in devices. The thermal conduction equation is applied to obtain the thermal profile, which has a significant effect on carrier dynamics.

In this chapter, we introduce the structure of InAs/GaAs QD VCSELs for modeling. We next elaborate on the two components in Section 3.2 (the rate equations) and Section 3.3 (the thermal conduction equation). Finally, we demonstrate the self-consistent analysis process in Section 3.4.

3.1 Structure for Our Self-Consistent Thermal Model of QD VCSELs

Our established self-consistent thermal model for 1.3- μm InAs/GaAs QD VCSELs is based on the conventional top-bottom contact (TBC) VCSEL structure, in which the metal contacts are fabricated on the top of the p -doped distributed Bragg reflector (DBR) stacks and on the bottom of the n -doped substrate. Figure 3.1 shows the

schematic diagram of the 1.3- μm QD VCSEL for theoretical investigation. As shown in Figure 3.1, the structure is assumed to consist of 22 pairs of top p -doped DBRs and 33 pairs of bottom n -doped DBRs, which are formed by GaAs and $\text{Al}_{0.9}\text{Ga}_{0.1}\text{As}$. The doping concentration is $5 \times 10^{17} \text{ cm}^{-3}$ and $1 \times 10^{18} \text{ cm}^{-3}$ for the p - and n -doped DBR stacks, respectively. The oxide-confined layer is 30-nm AlAs. The lateral diameter is $80 \mu\text{m}$. The QD structure is comprised of self-assembled InAs QDs grown on GaAs and covered by 6-nm-thick $\text{In}_{0.15}\text{Ga}_{0.85}\text{As}$. The typical thickness of the wetting layer (WL) is 1.7 monolayer (ML) ($\sim 0.48 \text{ nm}$) [1].

Figure 3.1 The schematic diagram for theoretical investigation of 1.3- μm QD VCSELs.

3.2 Rate Equations for Multilayer QD VCSELs

A rate-equation model of one QD layer, which considers the carrier relaxation dynamics, has already been applied to analyze the threshold characteristic of edge-emitting QD lasers [2]. In this study, we have extended the analysis to multilayer QD VCSELs. The following factors are considered:

- i. all possible relaxation paths are considered and the relaxation time is assumed to be the same as long as the initial and final relaxation states remain the same;
- ii. electrons are injected into the QDs from the wetting layer (WL) and escape from the InGaAs cap layer (CL). Holes are injected from the CL into the QDs, and escape from the WL;
- iii. the multilayer QDs are distributed symmetrically in the inner-cavity of the QD VCSEL.

Equations (3.1)–(3.6), the rate equations for the multilayer QD VCSELs, are listed below and were obtained under the above conditions. The respective nomenclature and parameters of the rate equations are shown in Table 3.1.

Rate Equations:

$$\frac{dN_B}{dt} = \frac{J}{qb} + \frac{1}{t_{ewb}} \frac{g_w f_w}{b/n} (1 - f_B) - \left(\frac{1}{t_{bw}} + \frac{1}{t_{rB}} \right) N_B, \quad (3.1)$$

$$\frac{df_w}{dt} = \frac{(1 - f_w)}{g_w} \frac{N_B b/n}{t_{bw}} - \frac{f_w}{t_{ewb}} + \sum_{i=0}^2 \left[\frac{2p_i \rho}{g_w} ES_{iw} f_i (1 - f_w) - R_{wi} f_w (1 - f_i) \right] - \frac{f_w}{t_{rw}}, \quad (3.2)$$

$$\frac{df_2}{dt} = \frac{g_w}{2p_2 \rho} R_{w2} f_w (1 - f_2) - ES_{2w} f_2 (1 - f_w) + \sum_{i=0}^1 \left[\frac{p_i}{p_2} ES_{i2} f_i (1 - f_2) - R_{2i} f_2 (1 - f_i) \right] - \frac{f_2}{t_{r2}},$$

(3.3)

$$\begin{aligned} \frac{df_1}{dt} = & \frac{g_w}{2p_1\rho} R_{w1}f_w(1-f_1) - Es_{1w}f_1(1-f_w) + \left[\frac{p_2}{p_1} R_{21}f_2(1-f_1) - Es_{12}f_1(1-f_2) \right] \\ & + \left[\frac{p_0}{p_1} Es_{01}f_0(1-f_1) - R_{10}f_1(1-f_0) \right] - \frac{f_1}{t_{r1}}, \end{aligned} \quad (3.4)$$

$$\begin{aligned} \frac{df_0}{dt} = & \sum_{i=1}^2 \left[\frac{p_i}{p_0} R_{i0}f_i(1-f_0) - Es_{0i}f_0(1-f_i) \right] + \left[\frac{g_w}{2p_0\rho} R_{w0}f_w(1-f_0) - Es_{0w}f_0(1-f_w) \right] \\ & - \frac{f_0}{t_{r0}} - \frac{1}{2p_0nS_a\rho} \frac{v_g g_{\max}(f_{0e} + f_{0h} - 1)S}{1 + \varepsilon S}, \end{aligned} \quad (3.5)$$

$$\frac{dS}{dt} = \frac{v_g g_{\max}(f_{0e} + f_{0h} - 1)S}{1 + \varepsilon S} - \frac{S}{t_p}. \quad (3.6)$$

In Equation (3.5) and (3.6), if V_a is the volume of all QDs and Γ is the optical confinement factor, $\varepsilon = \varepsilon_m \Gamma / V_a$, where ε_m is the nonlinear gain coefficient which can be expressed as [3]:

$$\varepsilon_m = \frac{\hbar q}{n_r^2 m_0 \varepsilon_0} \frac{|P_{cv}|^2}{m_0 E_L} \frac{1}{F_{ho}} t_p, \quad (3.7)$$

where F_{ho} is the full-width at half maximum (FWHM) of the homogeneous

broadening of the QDs, $t_p = \frac{1}{v_g g_{th}}$ is the photon lifetime, g_{th} is threshold modal gain,

P_{cv} is the transition matrix, $\hbar$ is the Planck's constant and $\hbar = \frac{h}{2\pi}$.

Table 3.1 The nomenclature and parameters of the rate equations.

Symbol	Meaning	Value
f_i ($i=B,w,0,1,2$)	Carrier occupation probability in the barrier, WL (CL), QD ground state, first excited state, and second excited state, respectively	
N_B	Carrier concentration in the barrier layer	
g_w	Parameter describing the carrier concentration in the WL (CL)	See Reference [2]
J	Injected current density	
q	Electronic charge	1.60×10^{-19} C
b	Total thickness of the GaAs barrier in the active region	191 nm
t_{ewb}	Carrier escape time from WL (CL) to the GaAs barrier, which is a function of temperature	See Reference [2]
t_{bw}	Carrier transport time from cladding layer to the nearest WL (CL), which is a function of temperature	See Reference [2]
t_{ri} ($i=B,w,0,1,2$)	Carrier lifetime in the barrier, WL (CL), QD ground state, first excited state, and second excited state, respectively	1 ns
n	Number of QD layers	
ρ	QD surface density	
T	Temperature at the center of the active region	
p_i ($i=0,1,2$)	Degeneracy of the QD levels	$p_0=1, p_1=2, p_2=4$
R_{ij} ($i,j=0,1,2,w$)	Relaxation rate from the i th level to the j th level	
Es_{ji} ($i,j=0,1,2,w$)	Escape rate from the j th level to the i th level	
S	Photon number in the cavity	
S_a	Area of the active region	$78.53 \mu\text{m}^2$
v_g	Group velocity	8.8×10^7 m/s
g_{max}	Maximum modal gain of the QD laser	
$f_{0e} + f_{0h} - 1$	Degree of population inversion	
t_p	Photon lifetime	
F_{in}	FWHM of QD inhomogeneous broadening	24 meV
F_{ho}	FWHM of QD homogeneous broadening	15 meV
n_r	Refractive index of active material	3.409
m_0	Rest mass of electron	9.1×10^{-31} Kg
ϵ_0	Absolute permittivity in vacuum	8.854×10^{-12} F/m
h	Planck's constant	6.626×10^{-34} Js
E_L	Lasing energy	0.954 eV

Equation (3.6) describes the photon number in the QD VCSEL. Although the spontaneous emission factor can be increased in the QD VCSEL [4], the term containing the spontaneous emission factor is ignored due to the large transverse size of the QD VCSEL ($\sim 80 \mu\text{m}$) in our simulation. By solving the rate equations (Equations (3.1) – (3.6)), we obtain the carrier surface density in the barrier (n_B), the WL (CL) carrier surface density (n_w), and the QD levels (n_i , $i = 0, 1, 2$) at a steady state. These represent the radiative recombination carrier density. Here, $i = 0, 1$, and 2 represent the ground state, the first excited state, and the second excited state of the QDs, respectively. n_B , n_w and n_i ($i = 0, 1, 2$) can be expressed as:

$$n_B = \frac{1}{t_{bw}^{-1} + t_{rB}^{-1}} \left(\frac{J}{q} + \frac{ng_w f_w}{t_{ewb}} \right) \quad (3.7)$$

$$n_w = ng_w f_w \quad (3.8)$$

$$n_i = 2np_i \rho f_i \quad (3.9)$$

where the corresponding parameters are described in Table 3.1. Based on the definition of the internal quantum efficiency for quantum well (QW) lasers [5], the internal quantum efficiency of the QD VCSEL (η_{QD}) can be approximated as:

$$\eta_{QD} = \frac{\sum_{i=0}^2 n_i}{n_B + n_w + \sum_{i=0}^2 n_i} \quad (3.10)$$

As the carrier confinement in the QDs is asymmetrical, the internal quantum efficiency of the QD VCSEL used in the calculation is selected as the average value of η_{QD} of the electrons and holes.

The output power of the QD VCSEL can be obtained using the relationship between power and photon number [3]:

$$P_{out} = E_L \alpha_m v_g S \quad (3.11)$$

where E_L , α_m , and v_g are the lasing energy, mirror loss, and group velocity, respectively. S can be obtained from Equation (3.6) and (3.7), and from the formula on QD material gain [3,6]

$$S = 2.35\sqrt{2\pi} n S_a \rho \frac{F_{ho}}{F_{in}} [(f_{0e} + f_{0h} - 1) - f_{th}] \quad (3.12)$$

where S_a is the active region area and ρ is the QD surface density. F_{ho} and F_{in} are the full-width at half maximum (FWHM) of the homogeneous and inhomogeneous broadening of the QDs, respectively, and $(f_{0e} + f_{0h} - 1)$ is the degree of population inversion. f_{th} is the threshold population inversion of the QD VCSEL, which is the ratio of the threshold modal gain g_{th} and the maximum modal gain g_{max} . According to the definitions of g_{th} of a VCSEL [7] and the modal gain of QDs [3,6], f_{th} can be expressed as:

$$f_{th} = \frac{g_{th}}{g_{max}} = \frac{\alpha_a L_a + \ln\left(\frac{1}{\sqrt{R_t R_b}}\right)}{\frac{hq}{cn_r m_0 \varepsilon_0} \frac{|P_{cv}|^2}{m_0 E_L} \frac{1}{\sqrt{2\pi}} \left(\frac{2.35}{F_{in}}\right) \Gamma_r n \rho} \quad (3.13)$$

where α_a and L_a are the average absorption coefficient and the length of the inner-cavity, respectively. R_t and R_b are the reflectivity of the top and bottom DBR, respectively. It is assumed that the oxide-confined layer of the QD VCSEL is located at the optimized position, the oxide-aperture is the optimized size, and the lateral size of the VCSEL is large enough so that the losses from the oxide-aperture can be

ignored. Taking the absorption loss into account [8,9], $R_t R_b$ is about 0.995 for a 1.3- μm QD VCSEL with 22 pairs of p -doped DBR ($5 \times 10^{17} \text{ cm}^{-3}$) and 33 pairs of n -doped DBR ($1 \times 10^{18} \text{ cm}^{-3}$) according to the transfer matrix theory [10]. h , q , c , n_r , m_0 and ε_0 are the Planck's constant, electronic charge, velocity of light, refractive index of the active region, electron rest mass, and absolute permittivity in vacuum, respectively. P_{cv} is the transition matrix, and $|P_{cv}|^2$ is $\sim 2m_0 E_L$ for InAs QDs [6]. Γ_r is the relative optical confinement factor, which is in the range of 1~2 and is determined by the position of the QD layer [7]. In our calculation, Γ_r is set as 2 due to the assumption that all QD layers are located at the anti-node positions in the VCSEL cavity.

3.3 Self-Heating and Thermal Response

As mentioned in Chapter 2, the main heat sources in VCSELs include Joule heating in the DBR and the active region due to the nonradiative recombination and the absorption of spontaneous emission. The heat density due to Joule heating is expressed as [11]:

$$Q_J(J) = \left(\frac{JS_a}{S_p}\right)^2 \rho_p + \left(\frac{JS_a}{S_n}\right)^2 \rho_n \quad (3.14)$$

where J is the injected current density in the active region. S_a , S_p and S_n are the areas of the active region, the p -doped contact region, and the n -doped contact region, respectively. ρ_p and ρ_n are the resistivity of the p -doped DBR and the n -doped DBR,

respectively. The steady-state thermal density at the active region is expressed as [11,12]:

$$Q_a(J) = \frac{V(T)(1-\eta_{sp}f_{sp})}{nd_D} \{J_{th}(T) + [J - J_{th}(T)](1-\eta_{QD})\} \quad (3.15)$$

where n , d_D , and J are the number of QD layers, the thickness of each QD layer, and the injected current density, respectively. $J_{th}(T)$ is the threshold current density, which is a function of temperature (T). η_{sp} is the spontaneous quantum efficiency and f_{sp} is the spontaneous radiation escape factor [12]. $V(T)$ is the voltage at the centre of the active region and can be obtained from the following equation [11]:

$$V(T) = \frac{2k_B T}{q} \left(\ln \frac{J}{J_s} + \frac{r_0}{r_{01}} \right) \quad (3.16)$$

where k_B is the Boltzmann's constant and J_s is the reverse saturation current density. r_0 and r_{01} are the radius of the oxide-aperture and the device, respectively.

It is assumed that the temperature distribution in the VCSEL is continuous and no heat escapes through the sides and top of the VCSEL, which requires that the lateral diameter of the device is larger than $60 \mu\text{m}$ [13]. In our simulation, we select the lateral diameter as $80 \mu\text{m}$ to satisfy this assumption. A large lateral size is helpful to reduce the Joule heating (Equation (3.14)); however, it will also increase the capacity of the device and, hence, affect the modulation performance. The temperature response in the device can be calculated by the three-dimensional dynamic thermal conduction equation [14]:

$$\frac{1}{k_i} \frac{\partial T(r,t)}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left[r \frac{\partial T(r,t)}{\partial r} \right] + \frac{1}{\lambda_i} Q(J, r, t) \quad (3.17)$$

where r and t denote the radius and time, respectively. k_i and λ_i are the thermal diffusion coefficient and effective thermal conductivity, respectively. Equation (3.17) can be solved using the Green's function [14,15]. In this study, we will only focus on the temperature increase ΔT at the centre of the active region under a steady state. The nomenclature and parameters of self-heating and thermal response (Equations (3.14) – (3.17)) are shown in Table 3.2.

Table 3.2 The nomenclature and parameters of the heat generation equation and the thermal conduction equation.

Symbol	Meaning		Value
S_p	Area of p -contact region		$3.77 \times 10^{-5} \text{ cm}^2$
S_n	Area of n -contact region		$2.5 \times 10^{-3} \text{ cm}^2$
ρ_p	Resistivity of p -doped DBR		$0.23 \text{ } \Omega\text{-cm}$
ρ_n	Resistivity of n -doped DBR		$0.032 \text{ } \Omega\text{-cm}$
r_0	Radius of oxide-aperture		$5 \text{ } \mu\text{m}$
r_{0l}	Radius of device		$40 \text{ } \mu\text{m}$
d_D	Thickness of each QD layer, including the WL and CL		10 nm
f_{sp}	Spontaneous radiation escape factor (300 K)		0.667
η_{sp}	Spontaneous quantum efficiency (300 K)		0.5
η_{QD}	Internal quantum efficiency of the QD VCSEL		
k_B	Boltzmann's constant		$1.38 \times 10^{-23} \text{ J/K}$
k_i	Thermal diffusion coefficient (300 K)	GaAs	$0.267 \text{ cm}^2 \text{ s}^{-1}$
		$\text{Al}_{0.9}\text{Ga}_{0.1}\text{As}$	$0.521 \text{ cm}^2 \text{ s}^{-1}$
λ_i	Thermal conduction coefficient (300 K)	GaAs	$44 \text{ W/(m}\cdot\text{K)}$
		$\text{Al}_{0.9}\text{Ga}_{0.1}\text{As}$	$25.5 \text{ W/(m}\cdot\text{K)}$
J_s	Reverse saturation current density		$6 \times 10^{-5} \text{ Am}^{-2}$

3.4 Self-Consistent Analysis Process

The calculation is carried out self-consistently as shown in Figure 3.2. First, the values of the injected current density (J), the photon number (S) and the temperature at the center of the active region (T) are set. T should be higher than the ambient temperature (T_a). Below threshold, S is set as zero, otherwise S is set larger than zero. Following this, the value of $(f_{0e}+f_{0h}-1)$ is obtained from the rate equations (Equations (3.1)–(3.6)) and from Equation (3.12), respectively. Next, the value of S is revised until $(f_{0e}+f_{0h}-1)$ obtained from Equation (3.12) is equal to $(f_{0e}+f_{0h}-1)$ obtained from the rate equations. Thereafter, the internal quantum efficiency of the QD VCSEL (η_{QD}) is obtained from Equation (3.10).

The threshold current density (J_{th}) can be obtained under the condition of $(f_{0e}+f_{0h}-1) = f_{th}$. The values of quantum efficiency (η_{QD}) and J_{th} are applied to Equation (3.15) and (3.17) to obtain the temperature at the active region, which is then compared with the set value. The calculation is repeated until the calculated and the set values of the active region temperature are identical. Next, the active region temperature, carrier occupation probabilities, population inversion, and photon amount are obtained and, finally, the output power is calculated by Equation (3.11). The simulation results and discussion are shown in Chapter 4.

Figure 3.2 Flow chart of the self-consistent calculation.

4. Theoretical Simulation Results and Analysis

The thermal behavior of 1.3- μm InAs/GaAs QD VCSELs, its influence on carrier dynamics, and the threshold and output properties are investigated theoretically in the self-consistent model and described in Chapter 3. The significant roles of the surface density and the amount of QD layers are elaborated from simulation results. More important, the main reason for serious self-heating generation in QD VCSELs is analyzed in the view of carrier confinement, which is also important for structure optimization. In this chapter, the simulation results and the respective discussion are illustrated. Section 4.1 focuses on the threshold properties, including threshold population inversion and current density. The temperature profile and carrier dynamics and internal quantum efficiency are demonstrated in Sections 4.2 and 4.3, respectively. The influence of self-heating on output power is discussed in Section 4.4.

4.1 Threshold Properties

The threshold population inversion (f_{th}), which can be estimated by Equation (3.13) in Chapter 3, must be known before the simulation. This allows the threshold current density (J_{th}) of the QD VCSEL to be obtained using the rate equations (Equation (3.1) – (3.6) in Chapter 3) under the condition of $(f_{0e} + f_{0h} - 1) = f_{th}$. The energy band parameters used in this calculation are listed in Table 4.1 and the relaxation parameters are same as those reported in Tong *et al.* [1]. It is assumed that the center

wavelength of the QD ground state gain spectra completely matches the cavity mode wavelength at 300 K. Figure 4.1 shows the calculated f_{th} (solid squares) and J_{th} (hollow circles) as a function of the number of QD layers (n) at 300 K. The QD density is $5 \times 10^{10} \text{ cm}^{-2}$, and the full-wave half-magnitude (FWHM) of inhomogeneous (F_{in}) and homogeneous (F_{ho}) broadening are 24 meV and 15 meV [2], respectively. It is seen that f_{th} (solid squares) decreases following an increase in the number of QD layers. There exists an optimized number of QD layers for the lowest J_{th} (hollow circles). This number is between 10 and 15. This can be understood as follows: as the number of QD layers is increased, the f_{th} will decrease, and this reduces the threshold current density per QD layer. However, the device threshold current density (J_{th}) is proportional to the number of QD layers as well as to the threshold current density per QD layer. For a high number of QD layers ($n > 10$), the improvement in f_{th} following an increase in the number of QD layers becomes insignificant as shown in Figure 4.1 (solid squares). Therefore, J_{th} increases for $n > 10$.

Table 4.1 The energy band parameters for 1.3- μm InAs/GaAs QD VCSELs.

Energy Band	Symbol	Energy Level
<i>Conduction band</i>	E_{0w}	0.225 eV
	E_{1w}	0.159 eV
	E_{2w}	0.093 eV
	E_{2l}	0.066 eV
	E_{20}	0.132 eV
	E_{10}	0.066 eV
<i>Valence band</i>	E_{0w}	0.146 eV
	E_{1w}	0.135 eV
	E_{2w}	0.124 eV
	E_{2l}	0.011 eV
	E_{20}	0.022 eV
	E_{10}	0.011 eV

Figure 4.1 The calculated threshold population inversion (f_{th} , solid squares) and threshold current density (J_{th} , hollow circles) as a function of the number of QD layers (n) at 300 K.

We also calculated the value of f_{th} and J_{th} of the 10-layer QD VCSEL with high QD density ($\sim 10^{11} \text{ cm}^{-2}$), which are about 0.147 and 1.1 kA/cm^2 , respectively. The relatively high J_{th} is due to the requirement for more carriers to occupy the QDs for lasing [1].

4.2 Temperature Profile

The effect of the injected current density (J) on the temperature increase (ΔT) at the center of the active region is shown in Figure 4.2. The QD density (ρ) is $5 \times 10^{10} \text{ cm}^{-2}$ (solid symbols) and 10^{11} cm^{-2} (solid line), respectively. The diameter of the oxide-aperture (d) is $10 \text{ }\mu\text{m}$. It is seen that an increase in the number of QD layers (n) can improve ΔT , especially at a high-injected current density. For the same number of QD layers (solid circles and solid line), a high QD density (solid line) shows a lower self-heating effect at an injected current density above 4 kA/cm^2 ($\sim 3.1 \text{ mA}$).

Figure 4.2 Effect of the number of QD layers (n) and the density (ρ) on the temperature increase (ΔT) at the center of the active region due to self-heating.

4.3 Carrier Confinement

To examine the influence of the number of QD layers (n) and the density (ρ) on the self-heating effect, we have calculated the quantum efficiency of the QDs (η_{QD}) at different injected current densities (Equation (3.7) – (3.10) in Chapter 3), as shown in Figure 4.3(a).

Figure 4.3 (a) The quantum efficiency of the QD VCSEL (η_{QD}) as a function of injected current density (J) for a different number of QD layers (n) and density (ρ); (b) An energy band diagram of a 1.3- μm InAs/GaAs QD with 6-nm $\text{In}_{0.15}\text{Ga}_{0.85}\text{As}$ cap layer (from Tong *et al.* [1]).

A common characteristic observed in Figure 4.3(a) is a decrease in η_{QD} following an increase in the injected current density (J). For the same injected current density, a higher number of QD layers (n) will result in a higher internal quantum efficiency (η_{QD}). However, the difference in η_{QD} is not obvious for a number of QD layers greater than ten ($n > 10$). High QD density ($\sim 1 \times 10^{11} \text{ cm}^{-2}$, stars) exhibits the highest quantum efficiency. The η_{QD} of holes (hollow symbols) is much lower than that of electrons (solid symbols), reflecting the weak hole confinement in the QD system. It is worth noting that the weak hole confinement in the QD system cannot be attributed to the close energy spacing of the discrete hole levels (Figure 4.3(b), from Tong *et al.* [1]), which is generally thought to be the reason for poor hole occupation in QD levels [3]. Instead, we believe that the weak hole confinement is related to the thin wetting layer (WL) ($\sim 0.48 \text{ nm}$). According to an investigation of thermionic emission [4], the carrier escape rate in a quantum well (QW) is inversely proportional to the QW thickness. The thin WL in the InAs/GaAs QD system results in a high hole escape rate, which is about three times that of the electrons according to our calculation. For further clarification, we have calculated the fraction of the recombined carriers (η_i) in the barrier (η_B), the WL (η_w), and the three QD levels ($\eta_{0,1,2}$) as a function of the injected current density. This is shown in Figure 4.4(a) for electron and (b) for hole levels. The indication of parameters (η_i) in different energy levels on conduction (η_{ie}) and valence (η_{ih}) bands are shown in Figure 4.4(c). In Figure 4.4(a), it can be seen that η_{0e} (solid squares) initially reduces and then stabilizes to a value which is lower than that of the first excited state (solid circles)

and higher than that of the other levels. The low η_{ie} in the barrier (solid diamonds) and cap layer (CL, downward triangles) indicate that the majority of the injected electrons are recombined in the QDs. However, in the case of holes, Figure 4.4(b) (hollow diamonds) shows that η_{Bh} increases almost linearly following an increase in the injected current density (J). This suggests that many injected holes escape into the GaAs barrier. Furthermore, η_{0h} (hollow squares) is the lowest amongst the three hole levels in the QDs, which can be attributed to the close energy spacing of the hole levels. Therefore, the poor hole confinement in InAs/GaAs QDs is most likely the result of the thin WL and close energy spacing of the hole levels. It is expected that the hole occupation will be further adversely affected by the self-heating effect in the device.

Figure 4.4 The fraction of the recombined (a) electrons and (b) holes in the barrier (η_B), the WL (η_w), and the three QD levels ($\eta_{0,l,2}$), as a function of the injected current density (J); (c) shows the indication of parameters on each energy level on the conduction (η_{ie}) and valence (η_{ih}) bands.

The carrier confinement for electrons and holes is also reflected in Figure 4.5(a), which shows the influence of self-heating on the electron (solid symbols, $f_{0e, 1e, 2e, we}$) and hole (hollow symbols, $f_{0h, 1h, 2h, wh}$) occupation probabilities in the QD system. The indication of parameters (f) in each energy level on the conduction (f_{ie}) and valence (f_{ih}) bands is shown in Figure 4.5(b). The parameters are mainly described in rate equations (Equation (3.1) – (3.6), Chapter 3), but are also seriously

affected by self-heating. In Figure 4.5(a), following a rapid rise at the beginning, a turning point occurs when the injected current reaches a certain level corresponding to the threshold. Beyond that, the probabilities undergo a gradual change followed by a slight reduction. This trend is due to heat being generated at the active region, which leads to a greater escape of carriers from the QD energy levels. When the number of escaped carriers is larger than that of injected carriers, the occupation probabilities start to reduce. The influence of self-heating on the occupation probabilities of the hole levels is more significant than that of electron levels, which is consistent with the analysis from Figures 4.3 and 4.4.

Figure 4.5 (a) The occupation probabilities of 1.3- μm InAs/GaAs QD VCSEL electron and hole levels as a function of the injected current density (J) taking the self-heating effect into account; (b) shows the indication of parameters on each energy level on the conduction (f_{ie}) and valence (f_{ih}) bands.

4.4 Output Power

The roll-over of the carrier occupation probability due to self-heating will result in the roll-over of output power. The calculated output power (p , calculated based on Equation (3.11) and (3.12) in Chapter 3) as a function of the injected current density (J) for a different number of QD layers (n) and density (ρ) is shown in Figure 4.6. It is seen that the saturated output power increases rapidly following an increase in the number of QD layers (n , solid symbols). When the number of QD layers is greater than ten ($n > 10$), the improvement in output power becomes less significant. It then worsens when the number of QD layers is greater than 17 ($n > 17$). The results show an optimized number of QD layers to achieve the highest output power (roll-over) of 2 mW. This is achieved with $n \sim 15$ for a QD density of $\sim 5 \times 10^{10} \text{ cm}^{-2}$. The VCSEL with 10 layers of high density QDs (hollow squares) shows the highest output power (roll-over) of $\sim 3.2 \text{ mW}$ and a slope efficiency of ~ 0.437 , which is due to the high quantum efficiency as shown in Figure 4.3. Hence, the output power is affected by both the threshold current density and the quantum efficiency, with the latter apparently playing a more dominant role. High QD density and an optimized number of QD layers are needed to achieve high output power in the QD VCSEL.

Figure 4.6 The calculated output power of 1.3-μm InAs/GaAs QD VCSELs with a different number of QD layers and density as a function of the injected current density (J).

In summary, the above results on steady-state temperature response and quantum efficiency show that an increase in the QD density and the QD layer number significantly improves the self-heating effect and increase the quantum efficiency of the device. This can be attributed to the fact that increasing the number of QDs in the active region reduces the effect of hole thermalization resulting from the thin wetting layer (WL). While a high output power can be achieved using a high QD density and number of QD layers, there exists an optimum number of QD layers for the highest output power from the device. Due to serious hole thermalization and escape, the

p-type modulation doping in the active region was applied and is effective for improvement in the performance of long-wavelength QD edge-emitting lasers [5-7], which is also adopted in our experimental wafer structure of QD VCSELs. The details of the wafer structure and the fabrication process are shown in Chapter 5.

5. Wafer Structure and Device Fabrication

Procedures of QD VCSELs

As noted in the investigation in theoretical self-consistent modelling (Chapter 4), the p -type modulation doping is adopted in the active region of the epitaxial wafer of the QD VCSEL in order to compensate for the weak hole confinement. The device fabrication procedures are developed based on the review of previous processing of QD VCSELs [1-6]. Selective wet oxidation is also an important procedure in the device fabrication as it obtains good electrical and carrier confinement. Other procedures consist of mesa forming, insulation layer deposition, contact layer deposition, etc. In this chapter, the wafer structure and the device fabrication process of 1.3- μm p -doped oxide-confined InAs/GaAs QD VCSELs are introduced in Sections 5.1 and 5.2, respectively.

5.1 Wafer Structure

The schematic cross-section diagram and its scanning electron microscopy (SEM) image of a 1.3- μm oxide-confined p -doped InAs/GaAs QD VCSEL are shown in Figure 5.1(a) and (b), respectively. The epitaxial wafer structure is grown on n^+ -GaAs (100) substrate by Molecular Beam Epitaxy (MBE). The etched mesa structure with the upper and bottom contact has been introduced to enhance the uniformity of the current injection. The QD active region is sandwiched within 24 pairs of p -doped and

33.5 pairs of n -doped $\text{Al}_{0.9}\text{Ga}_{0.1}\text{As}/\text{GaAs}$ distributed Bragg reflector (DBR) mirrors. The p -type and n -type dopant is carbon and silicon, respectively. Seventeen (17) layers of p -doped InAs/GaAs QDs are located within the 3λ intercavity active region of the QD-VCSEL. As shown in Figure 5.1(c), there are five 3-layer QD groups and two separate QD sheet layers, and each group is located around the antinode position of a standing wave. The QDs are grown directly on GaAs and are capped by a 6-nm-thick $\text{In}_{0.15}\text{Ga}_{0.85}\text{As}$ layer. Each 5-nm-thick p -doped GaAs layer is grown between two undoped GaAs layers, whose thickness is 5 nm and 12 nm, respectively. There is a 12-nm-thick layer of AlAs between the top DBR stacks and the active region, which is used to create the Al_xO_y native oxide-aperture. The bottom DBR is separated from the n -GaAs 200- μm -thick substrate by the 500-nm buffer n -GaAs layer and the doping level of substrate and buffer layer is up to $5 \times 10^{18} \text{ cm}^{-3}$. Both the top and bottom DBRs are graded ones to reduce electrical resistance: their AlAs mole fraction is changed linearly along the 10-nm segment of increased doping up to $5 \times 10^{18} \text{ cm}^{-3}$. The GaAs layers within both DBRs are doped up to $2 \times 10^{17} \text{ cm}^{-3}$, whereas the doping level in the AlGaAs layers is up to $5 \times 10^{17} \text{ cm}^{-3}$. The upper p -side ring (Ti/Au contact) is separated from the upper DBR by the carbon-doped p -GaAs contact layer. The bottom n -side Au-Ge-Ni contact is deposited on the entire bottom substrate layer. SiN_x is deposited as insulation layer. The laser is mounted on the copper heatsink by using silver paint.

(a)

(b)

Figure 5.1 (a) Schematic cross-section diagram of a 1.3- μm oxide-confined InAs/GaAs QD VCSEL; (b) scanning electron microscopy (SEM) image; (c) the distribution of QD layers in the cavity with p -type modulation doping.

5.2 Fabrication Process

The fabrication process of 1.3- μm oxide-confined p -doped GaAs-based QD VCSELs is demonstrated in Figure 5.2 – 5.7. The epitaxial wafer (including the p -type distributed Bragg reflector mirrors (p -DBR), the AlAs layer for selective oxidation, the p -doped InAs/GaAs QD active region, the n -type DBR mirrors (n -DBR), and the GaAs substrate), is first cleaned by acetone, isopropyl alcohol (IPA), and deionized water (DI-water) one after another. Usually, the cleaning of the wafer by acetone

occurs twice under a temperature greater than 150°C while the cleaning by IPA and DI-water occurs 3 – 4 times but at room temperature (RT).

A mesa is then etched on the top DBR (*p*-DBR) region (Figure 5.2(a)). It has three parts: (1) the laser's main body, (2) a bond pad, and (3) a linked bridge (Figure 5.2(b)). The diameter (d) of the main body varies from 48~60 μm , while the diameter of the bond pad is 80 μm . The forming procedures of the mesa shape include photolithography and wet etching. MJB3 Karl Suss Mask Aligner (MJB3) performs the photolithography while the wet etching composition is H_3PO_4 : H_2O_2 : Di-Water = 3: 3: 10. The etching rate is around 34 nm/second. The etching process ends when the AlAs layer is exposed (the duration is around 2.5 minutes).

(a)

(b)

Figure 5.2 Mesa forming by photolithography and wet etching: (a) schematic cross-section diagram; (b) microscopic image from top view.

The exposed AlAs layer is oxidized in wet N₂, which is ambient to form the oxide-aperture (Figure 5.3(a)). The reaction equations are shown below:

The size of the oxide-aperture is mainly determined by the furnace temperature and the oxidation time. The pressure of the N₂ flow and the water vapor must be controlled precisely. The image of a sample after the AlAs layer oxidation and the removal of the top DBR stacks is shown in Figure 5.3(b), where the size of oxide-aperture can be observed and measured by a microscope.

(a)

(b)

Figure 5.3 The forming of the oxide-aperture: (a) schematic cross-section diagram; (b) microscopic image from the top view of a sample after AlAs layer oxidation and removal of the top DBR stacks.

The next step is to form the SiN_x insulation layer and the emitting aperture (Figure 5.4(a) and (b)). The procedures include SiN_x deposition, photolithography, and wet etching. The Plasma Enhanced Chemical Vapor Deposition System – PlasmaTherm790 (PECVD 790) deposits SiN_x . The thickness measures around 300 nm. The light emitting aperture is formed on the insulation layer by photolithography and wet etching. Photolithography is also performed by MJB3 while the wet etching composition is HF: Di-water = 1: 20. The etching process lasts approximately 20 seconds to expose the emitting aperture.

(a)

(b)

Figure 5.4 The deposition of the insulation layer and the forming of emitting aperture: (a) schematic cross-section diagram; (b) microscopic image from top view.

The *p*-contact layer is deposited on the insulation layer and emitting aperture by the Electron Beam Evaporator System (Figure 5.5(a) and (b)). The composition is Titanium (Ti) and Gold (Au) with a thickness of 50 and 250 nm, respectively. The *p*-contact is formed in a ring-shape by photolithography (MJB3) and wet etching. The etching composition of Au is KI: I₂: Di-H₂O = 8 g: 2 g: 80 ml and this takes ~45 seconds. The etching of Ti is performed by a solution with a volume composition of HF: HNO₃: Di-H₂O = 1: 2: 60 and this takes ~40 seconds.

(a)

(b)

Figure 5.5 The forming of the p -type contact ring: (a) schematic cross-section diagram; (b) microscopic image from top view.

The Electron Beam Evaporator System also deposits the n -contact layer (Figure 5.6) on the bottom of the device. The metal deposition sequence and the respective thicknesses of each layer are Ni (5 nm) – Ge (25 nm) – Au (100 nm) – Ni (20 nm) – Au (300 nm).

Figure 5.6 The forming of the n -contact.

Finally, the device is mounted to the heatsink using silver paint. The top view of the device and the microscopic image of one fabricated mesa are shown in Figure 5.7(a) and (b), respectively. The detail of the measurement and characterization of the wafer and the device is demonstrated in Chapters 6 – 8.

(a)

(b)

Figure 5.7 (a) The top view of a fabricated $1.3\text{-}\mu\text{m}$ oxide-confined p -doped InAs/GaAs QD VCSEL and (b) the microscopic image of one fabricated mesa.

6. Temperature Characterization of Multi-Mode 1.3- μm *P*-Doped QD VCSELs

The temperature characteristics of the fabricated 1.3- μm *p*-doped InAs/GaAs QD VCSELs (multi-mode) is demonstrated in this chapter. The elaboration starts from the characterization on the photoluminescence of the epitaxial wafer at different temperatures (Section 6.1). The temperature dependence of the device output power and the threshold current are demonstrated in Section 6.2. From the red-shift of the lasing spectrum with an increase in temperature, the thermal profile of the devices can be obtained and compared with the results from the theoretical simulation, which are shown in Section 6.3.

6.1 Photoluminescence (PL) Measurement on the Epitaxial Wafer of 1.3- μm *P*-Doped QD VCSELs

In order to obtain the thermal characteristics of the epitaxial wafer for our device fabrication, the measurement of the photoluminescence (PL) spectra was carried out on both the cavity mode and the QD active region at different temperatures. The spectrum of the cavity mode was obtained from the measurement of the whole wafer sample; while the results of the QD emission was from the wafer sample, whose top distributed Bragg reflector (DBR) stacks were etched off so that the QD active region

was exposed. The structures of the two samples are shown in Figure 6.1(a) and (b), respectively.

(a)

(b)

Figure 6.1 The schematic cross-section diagrams of two wafer samples: (a) with top DBR mirror (cavity mode); (b) without top DBR mirror (QD mode).

6.1.1 Cavity Mode

The temperature dependence of the PL spectra of the cavity mode is shown in Figure 6.2. Figure 6.3 shows how the peak wavelength of the cavity mode and the normalized intensity varies with temperature. The peak wavelength is red-shifted with the rate of 0.086 nm/K from 1272 to 1276 nm when the temperature increases from 295.7 K to 323.7 K. The normalized intensity reduces rapidly in this temperature region.

Figure 6.2 The PL spectra of the QD VCSEL at different temperatures, which reflects the influence of temperature on the cavity mode of the QD VCSEL.

Figure 6.3 The center wavelength (solid squares) and normalized intensity (solid circles) of the cavity mode as a function of temperature.

The red-shift of cavity mode is due to the change of refractive index in distributed Bragg reflectors (DBR). To express the shift of wavelength with temperature, it is necessary to obtain the thermal dependence of refractive index (dn/dT). The respective value of GaAs and AlAs is shown below [1]:

$$\left(\frac{dn}{dT}\right)_{GaAs} = (2.67 \pm 0.07) \times 10^{-4} / ^\circ\text{C} \quad (6.1)$$

$$\left(\frac{dn}{dT}\right)_{AlAs} = (1.43 \pm 0.07) \times 10^{-4} / ^\circ\text{C} \quad (6.2)$$

The relationship between emission wavelength (λ) and refractive index (n) can be written as [2]:

$$nL = \frac{m\lambda}{2} \quad (6.3)$$

where L is the effective inner cavity length, m is an even integer ($m \geq 2$). From Equation (6.3), the temperature dependence of emission wavelength is

$$\frac{d\lambda}{dT} = \frac{2L}{m} \frac{dn}{dT} \quad (6.4)$$

With the consideration of the 3λ inner cavity of our epitaxial wafer, as well as the concentration of AlAs and GaAs, the value of $d\lambda/dT$ can be calculated, which is around 0.081 nm/°C, and close to the measurement results of PL spectra shown in Figure 6.3.

In general, the rapid reduction in the normalized intensity of the cavity mode with an increase in temperature (Figure 6.3) should be attributed to the mismatch between the cavity mode and the QD emitting wavelength. This suggests that, when the temperature is increasing, both the matched cavity and the QD modes will undergo red-shift with different rates. This will result in mismatch (Figure 6.4). Therefore, in this case, the red-shift effect on the PL spectra of the QD emission mode should be more rapid and obvious compared to the red-shift effect on the PL spectra of the cavity mode. This is depicted in Figure 6.4 and will be verified in Section 6.1.2.

Figure 6.4 A mismatch of the cavity mode and the QD mode due to red-shift. The shift in the wavelength of the QD mode should be more rapid than the one in the wavelength of the cavity mode following a temperature increase.

6.1.2 QD Mode

To verify the assumption in Section 6.1.1, PL measurement was performed on the wafer sample with the QD region exposed. The corresponding results (the temperature dependence of the PL spectra and the normalized intensity) are shown in Figures 6.5 and 6.6, respectively.

Figure 6.5 The PL spectra of the QDs in a QD VCSEL at different temperatures.

Figure 6.6 The normalized intensity of the peak of the QD PL spectra as a function of temperature.

From Figures 6.5 and 6.6, it is obvious that there is little red-shift in the QD mode following a temperature increase. However, its normalized intensity is reduced rapidly from 1.0 to 0.2 when the temperature rises from 295.7 K to 323.7 K. Therefore, for our wafer, the assumption in Section 6.1.1 is not correct. The reduction in the emission intensity of the cavity mode following an increase in temperature is not primarily caused by the mismatch between the cavity mode and the QD mode but, rather, by the deterioration of the QD emission with an increase in temperature. This deterioration of the QD emission is the dominant factor (see Figure 6.7(a)). In conclusion, in order to improve the device performance, the operation temperature of our QD VCSEL should be kept below 295.7 K (22.7°C). For example, for 1.3- μm *p*-doped QD VCSELs with the oxide aperture diameter of 10 μm , the saturated output power at 295 K is calculated as 1.09 mW, based on the self-consistent model elaborated in Chapter 3 and 4. If there is an increase in the operating temperature by 10°C, the calculated saturated power will deteriorate by 33.4%, which is shown in Figure 6.7(b). The thermal behavior of the fabricated device is presented in Section 6.2.

Figure 6.7 (a) Reduction in the intensity of the cavity mode with an increase in temperature is mainly due to the deterioration of the QD emission. (b) The calculated light-current ($L-I$) performance of 1.3- μm QD VCSELs with the oxide aperture diameter of 10 μm . The operating temperature is 295 and 395 K, respectively.

6.2 Temperature Dependence of Device Output Power and Threshold Current

The PL measurement in the epitaxial wafer of the QD VCSEL shows the high sensitivity of the QD emission to temperature, which is also revealed in the light–current (L – I) measurement on the fabricated devices. The diameter of the oxide-aperture in the fabricated $1.3\text{-}\mu\text{m}$ p -doped InAs/GaAs QD VCSELs is about $10\text{ }\mu\text{m}$. The measurement results of the output power and threshold current from 15 to 37°C are shown in Figure 6.8. The inset shows the temperature dependence of the threshold current and the characteristic temperature (T_0) is also calculated.

Figure 6.8 Temperature dependence of the output power and the threshold current.

Figure 6.8 shows that, for devices with oxide-aperture diameters of 10 μm , the highest output power at 25°C exceeds 0.74 mW and the threshold current (I_{th}) is 0.88 mA. This corresponds to the threshold current density (J_{th}) of 1.1 kA/cm² or 65 A/cm² per QD layer (there are 17 layers of QDs in the active region, according to Chapter 5). The slope efficiency of this device is 0.148 W/A. The characteristic curve at 37°C shows the thermal roll-over of the output power, with the saturated output power measuring around 0.5 mW. The thermal roll over is not shown for characteristic curves below 37°C due to the limitation of the measurement equipment.

Although the output power is highly influenced by temperature, the threshold current (I_{th}) is much less sensitive to temperature. It measured around 0.9 mA from 15 – 37°C and is depicted in the inset of Figure 6.8 together with its linear fitting curve. The characteristic temperature (T_0) of this device is about 510 K from 15 – 37°C. The calculation of T_0 is based on the well-known relationship:

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

where I_{th} is the threshold current, I_0 is a constant, T is the absolute temperature, and T_0 is the absolute characteristic temperature.

The temperature stability of I_{th} is commonly attributed to the detuning between the gain spectra and the cavity resonance wavelength [3]. Therefore, the wide gain spectra might result in less temperature sensitivity of I_{th} . However, in our case, according to the temperature dependence of the PL spectra in the QD emission depicted in Figures 6.5 and 6.6, the normalized intensity reduces rapidly following an

increase in temperature, which should result in an increase in I_{th} with temperature. Therefore, for our device, the reason for the temperature stability of I_{th} is different.

Let us consider the effect of the p -type modulation doping in the QD active region. Referring to Fathpour *et al.* [4] for both undoped and p -doped 1.3- μm QD lasers, there are two important contributing components of I_{th} . These are: (1) the recombination in the barrier/waveguide regions and (2) the Auger recombination. The contributing components on I_{th} resulting from the recombination in the barrier/waveguide regions will keep on increasing with temperature for both undoped and p -doped 1.3- μm QD lasers. However, for the p -doped structure, the contributing current component from Auger recombination keeps on decreasing with temperature while the one for the undoped structure does not. That is, when the temperature is increasing, the decreasing component from the Auger recombination will compensate for the increasing component from the recombination in the barrier/waveguide regions. Therefore, for our fabricated devices, the temperature stability of I_{th} should be attributed to the p -type modulation doping in the QD active region.

6.3 Lasing Spectrum and Temperature Profile

Figure 6.9 shows the lasing spectrum of our fabricated devices under different injection current levels with the heatsink temperature at 28°C. The y -axis plots the normalized laser emission intensity, which assumes the highest intensity of 1.0 at injection current of 2 mA. The threshold current of the device at 28°C is about 0.89

mA (see Figure 6.8). The device almost operates under single-mode emission at injection current of 2 mA. When the injection current is increased to 2.5 mA, the device operates under multimode emission and the intensity increases by almost 60 times. The full-wave half-magnitude (FWHM) of the central mode is about 0.028 nm. The multimode emission is due to the large oxide-aperture diameter of 10 μm . According to Sarzala's theoretical calculation and analysis [5], an oxide-aperture diameter of less than 6 μm is required to achieve single-mode operation at room temperature (RT). The investigation of single-mode emission in 1.3- μm *p*-doped QD VCSELs will be demonstrated in Chapter 7.

Figure 6.9 Spectral emission from the QD VCSEL at the heat-sink temperature of 28°C at different injection current levels.

The temperature profile in the active region of the fabricated QD VCSELs with the heatsink temperature at 28°C can be estimated from the spectrum emission at different current injection levels (Figure 6.9) and the temperature dependence of the cavity mode wavelength (Figure 6.3). From Figure 6.9, the wavelengths of the central emission mode can be obtained at different current injection levels. Figure 6.3 shows the red-shift rate of the cavity mode. Therefore, a temperature increase with current injections can be obtained (depicted as hollow squares in Figure 6.10) together with the result based on our theoretical modeling (solid line). The strategy of this self-consistent model is elaborated on in Chapter 3.

Figure 6.10 The temperature profile of the active region of a 1.3- μm *p*-doped InAs-GaAs QD VCSEL operating at a heat-sink temperature of 28°C. The hollow squares and the solid lines represent the experimental and calculated results, respectively.

Figure 6.10 illustrates that the calculated and experimental results are in good agreement. According to Figure 6.10, when the injection current level increases to 8 mA, the temperature at the active region can rise as high as 55°C. This shows that self-heating is one of the main factors that limits the performance of *p*-doped QD VCSELs. Although a high temperature stability of the threshold current is obtained due to the *p*-type modulation doping, no significant improvement is found in the QD emission and output power. It has been reported in Fathpour *et al.* [4] that more carrier loss will occur in the GaAs barrier in a *p*-doped QD laser above 310 K. This suggests that the carrier loss in the GaAs barrier may play an important role in the thermal roll-over of the output power in *p*-doped QD VCSELs. The theoretical calculations described in Chapter 4 showed that, when the temperature increases, many holes will escape to the GaAs barrier from the wetting layer (WL) of the QDs due to the poor carrier confinement in the WL. According to the analysis in Chapter 4, this weak hole confinement can be attributed to the thin WL and its finite potential barrier. Therefore, in order to improve the output power of QD VCSELs, it is necessary to either enhance the carrier confinement in the WL or to try to improve the self-heating effect. We attempt to reduce the self-heating generation by modifying the device morphology design, which represents the dielectric-free approach [6]. Chapter 9 contains the details of this modification.

7. The Temperature Characteristics of 1.3- μ m *P*-Doped QD VCSELs with Single-Mode Lasing

The multi-mode operation of 1.3- μ m *p*-doped InAs/GaAs QD VCSELs and its thermal behavior have already demonstrated in Chapter 6. The *p*-type modulation doping is applied to improve the carrier thermalization and the temperature stability of the threshold current. However, for applications of modern fiber communication and optical interconnect, long-wavelength VCSELs with single-mode operation are much more favorable. The single-mode lasing requires a precise control in the oxide-aperture size in order to achieve a better optical confinement. We investigate this first in order to direct our fabrication.

This chapter presents the temperature characteristics of 1.3- μ m *p*-doped QD VCSELs with single-mode operation. Section 7.1 presents the literature review on the influence of the oxide-aperture size on the lasing mode. From this review, we decide on the critical size of the oxide-aperture for the fabrication of single-mode QD VCSELs. Section 7.2 describes the spectrum measurement and the temperature characteristics of the output power of our fabricated devices. These factors also aid the discussion of the role of the oxide-aperture size in single-mode lasing.

7.1 Decision regarding the Oxide-Aperture Size in the Fabrication of 1.3- μm QD VCSELs with Single-Mode Operation

The fabricated and characterized device demonstrated in Chapter 6, whose emission is multi-mode, has an oxide-aperture diameter of 10 μm . To achieve single-mode lasing, it is necessary to review previous investigations on single-mode operation in 1.3- μm QD VCSELs and to establish the critical size of the oxide-aperture for device fabrication.

R. P. Sarazla *et al.* established a three-dimensional self-consistent model for 1.3- μm oxide-confined (OC) QD InAs/GaAs VCSELs [1]. From the theoretical simulation, the diameter of the oxide-aperture should be less than 4 μm to obtain stable single-fundamental-mode operation under continuous-wave (CW) current injections at room temperature (RT). Y. H. Chang *et al.* have already fabricated 1.3- μm InAs/GaAs QD VCSELs (undoped) with single-mode operation [2]. The diameters of the oxide-apertures in these VCSELs measure 5 ~ 6 μm . The side-mode suppression ratio (SMSR) is larger than 30 dB from the input current injection of 1.6 to 4 mA (Figure 7.1). The saturated output power measured from the device with the heatsink temperature at 20°C is up to 0.33 mW (Figure 7.2). Therefore, in order to achieve single-mode operation in 1.3- μm QD VCSELs, the diameter of the oxide-aperture might be less than 6 μm .

Figure 7.1 The emission spectra of QD VCSELs (undoped) reported in Chang *et al.* [2] at room temperature.

Figure 7.2 The temperature-dependent output light–current (L – I) relationship of the QD VCSEL reported in Chang *et al.* [2].

However, according to the investigation of E. R. Hegblom *et al.* [3], if the oxide-aperture size of VCSELs is too small (that is, if the radius measures smaller than $1.5\text{ }\mu\text{m}$), serious scatter loss will occur. A mismatch between the mode profiles from the one-dimensional (*1-D*) propagation model (for abrupt apertures) and a uniform slab waveguide will also occur. Hegblom *et al.*'s demonstration is presented in Figures 7.3.

Figure 7.3 Scattering loss in one-dimension ($1-D$) versus the aperture half-width and in two dimensions ($2-D$) versus the aperture radius calculated using the approximate model (Approx.), which involves summing up the scattered energy from one pass of a uniform waveguide mode through the aperture. A comparison with the results of the propagation model (Prop.) in $1-D$ is also shown. Δn_d and w refer to the distributed index difference and the taper waist, respectively (from Hegblom *et al.* [3]).

It is obvious that, if the radius of the oxide-aperture (r), which is same as the aperture half-width (w) in Figures 7.3, is smaller than $3 \mu\text{m}$, the scatter loss will increase rapidly (referring to the curve in Figure 7.3: $\Delta n_d = 0.06$, 2D Approx.). The loss of the device with $r = 1.5 \mu\text{m}$ is almost three times the loss of the ones with $r = 3$

μm . That is, the size of the oxide-aperture in QD VCSELs cannot be too small (r cannot be less than $2.5 \mu\text{m}$).

Therefore, the diameter of oxide-aperture might be chosen around $5\sim 7 \mu\text{m}$ to achieve single-fundamental-mode operation in our fabrication of $1.3\text{-}\mu\text{m}$ p -doped InAs/GaAs QD VCSELs. The characterization of the device will be presented and analyzed next in Section 7.2.

7.2 Results and Discussion

According to the literature review on the critical oxide-aperture size in single-mode QD VCSELs, we decided to fabricate two sets of device samples differing in oxide-aperture areas. The oxide-aperture area of the first one measures $5\times 6 \mu\text{m}^2$ and the other measures $7\times 8 \mu\text{m}^2$. Both samples were characterized in output power and spectrum in order to further investigate the critical size of the oxide-aperture of $1.3\text{-}\mu\text{m}$ p -doped InAs/GaAs QD VCSELs with single-fundamental-mode operation.

7.2.1 Oxide-Aperture Measuring $5\times 6 \mu\text{m}^2$

For p -doped InAs/GaAs QD VCSELs with an oxide-aperture area of $5\times 6 \mu\text{m}^2$, the temperature-dependent (20 to 60°C) light-current (L - I) characteristics are shown in Figure 7.4. The characteristic curve for continuous-wave (CW) operation at 20°C shows that the thermal roll-over of the output power saturates at 0.435 mW at an

injection current of 7.6 mA. With pulsed current injection (frequency (f) = 500 Hz and duty cycle is 1%) at room temperature (RT), the saturated output power is 0.546 mW at around 10 mA. The inset shows that the saturated output power (P_{max} , hollow squares) reduces almost linearly (0.01 mW/°C) with temperature and is attributed to the deterioration in the QD emission at high temperature discussed in Chapter 6. From 20 to 40°C, the threshold current (I_{th}) of the QD-VCSELs (inset, solid squares) exhibits negative temperature-dependent behavior, or negative characteristic temperature (T_0), and the lowest threshold current is 1.2 mA. This value is lower than the reported threshold current of 1.8 mA in 1.3- μ m undoped InAs/GaAs QD-VCSELs [4]. The threshold current increases to 1.6 mA as the temperature increases to 60°C. This is due to the higher probability of the carriers escaping from the QDs and recombining at the barriers, which is consistent with the elaboration in our self-consistent model (Chapters 3 and 4).

Figure 7.4 The L - I characteristics of a 1.3- μm p -doped InAs/GaAs QD-VCSEL with a $5 \times 6 \mu\text{m}^2$ oxide-aperture measured at different temperatures. The inset shows the influence of temperature on the threshold current and the saturated output power.

The reason for the observed negative characteristic temperature (T_0) should be similar to the one discussed in fabricated p -doped QD VCSELs with multi-mode operation (Chapter 6). The observed reduction in threshold current (I_{th}) from 20 to 40°C might be due to the presence of Auger recombination in the p -doped InAs/GaAs QDs, which is one important component contributing to I_{th} and has been reported to reduce with an increase in temperature [5]. The other important contributing component is the recombination in the barrier/waveguide regions, which increases with temperature. Therefore, for p -doped InAs/GaAs QD lasers, the reduction effect with an increase in temperature from the Auger recombination will compensate for

the contribution from the recombination in the barrier/waveguide regions. This effect might lower the threshold current of the QD laser and result in the negative T_0 behavior as seen in our device.

Figure 7.5 shows the lasing spectrum measured at (a) room temperature (RT) and (b) 50°C for the device with an oxide-aperture area of $5 \times 6 \mu\text{m}^2$. The injection currents are 2.5 and 2.0 mA, respectively. Single-mode operation with a side-mode suppression ratio (SMSR) of 34 dB is achieved at RT. The lasing wavelength is 1280.3 nm and the full-width at half maximum (FWHM) of the single mode spectrum is 0.046 nm. The difference between the lasing wavelength and the cavity mode (from 1272 to 1276 nm, according to Figure 6.2 in Chapter 6) might be caused by device heating. The SMSR will degrade with a large injection current or high temperature. As shown in Figure 7.5(b), as the temperature increases to 50°C, the lasing wavelength shifts to 1282.2 nm and the FWHM increases to 0.087 nm. The corresponding SMSR reduces to 5.7 dB as a result of the increased temperature and the reduced output power. In Figure 7.4, the saturated output power at 50°C is 0.139 mW for the same device. The low signal coupling into the measurement equipment and the higher noise intensity also contribute to the lower SMSR as compared to the value at RT.

Figure 7.5 The lasing spectrum of the 1.3-μm *p*-doped InAs/GaAs QD-VCSEL with a $5 \times 6 \mu\text{m}^2$ oxide-aperture measured at (a) RT and (b) 50°C.

7.2.2 Oxide-Aperture Measuring $7 \times 8 \mu\text{m}^2$

For the device with the larger oxide-aperture size of $7 \times 8 \mu\text{m}^2$, the saturated output power (P_{max}) and the threshold current (I_{th}) at room temperature (RT) increase to 0.63 mW and 1.6 mA (Figure 7.6), respectively. The higher threshold current is due to the larger current injection area resulting from the larger oxide-aperture. Nevertheless, the threshold current density of the device with a $7 \times 8 \mu\text{m}^2$ oxide-aperture (210 A/cm² per QD layer) is actually lower than the threshold current density of the device with a $5 \times 6 \mu\text{m}^2$ oxide-aperture (300 A/cm² per QD layer). In addition, at an injection current of 4.0 mA, the RT differential resistance of the device with a $7 \times 8 \mu\text{m}^2$ oxide-aperture

(265 Ω) is smaller than the RT differential resistance of the device with a $5 \times 6 \mu\text{m}^2$ oxide-aperture (369 Ω). Note that the light-injected current ($L-I$) curve slope efficiency of the device with a $7 \times 8 \mu\text{m}^2$ oxide-aperture (0.106 W/A) is also higher as compared to the $L-I$ of the device with a $5 \times 6 \mu\text{m}^2$ oxide-aperture (0.099 W/A). The lower differential and thermal resistance in the device with a larger oxide-aperture helps to improve the self-heating effect [6], hence lowering the threshold current density and increasing the quantum efficiency. The inset of Figure 7.6 shows that the device with an oxide-aperture of $7 \times 8 \mu\text{m}^2$ operates in multi-mode at an injection current of 1.9 mA at RT.

Figure 7.6 The output power characteristic of the 1.3- μm p -doped InAs/GaAs QD VCSEL with a $7 \times 8 \mu\text{m}^2$ oxide-aperture. The inset shows the multi-mode lasing spectrum at an injection current of 1.9 mA.

In summary, for 1.3- μm p -doped InAs/GaAs QD VCSELs with single-mode operation, the p -type modulation doping plays an important role in the high temperature stability of the threshold current, which is similar to multi-mode operation. The property of the emission mode is significantly affected by the oxide-aperture area, which represents one of the key factors in self-heating generation and distribution and which further influences the output power. For further research and device optimization, the influence of self-heating on the output power and the effect of the oxide-aperture area on self-heating generation and distribution are characterized by theoretical modeling (described in Chapter 3) and measurement under pulsed current injection.

The details of the characterization and analysis will be elaborated on in Chapter 8. In addition, we also attempted to enhance the fundamental mode emission in the device with the relative larger oxide-aperture by introducing a slight modification into the fabrication process. This modification is the surface-relief technique [7] and will be demonstrated in Chapter 9.

8. Characterization of the Influence of the Self-Heating Effect on the Output Power in 1.3- μm *P*-Doped QD VCSELs

In Chapter 3, we described a self-consistent model based on rate equations and the thermal conduction equation, which was built to analyze the influence of self-heating on the carrier occupation, the quantum efficiency, and the output characteristics in QD VCSELs. The simulation results (Chapter 4) indicate that poor hole confinement is one of the key factors that limit the threshold current and the output power in QD VCSELs. To improve the hole confinement, the *p*-type modulation doping (*p*-doping) was used in our fabricated devices (Chapter 5). Because of the *p*-doping, a high temperature stability of the threshold current is obtained in both single-mode and multi-mode QD VCSELs (demonstrated in Chapters 6 and 7, respectively). However, we found that the QD emission deteriorates following an increase in temperature, resulting in a degradation of the output power. In other words, self-heating still strongly influences the output power performance of *p*-doped QD VCSELs. Further investigations utilizing both theoretical modeling and experimental characterization are necessary to understand this problem.

In this chapter, the characterization of the influence of self-heating on the output power of 1.3- μm *p*-doped QD VCSELs will be demonstrated from the performance of the output power under pulsed current injection with different duty

cycles. Pulsed current with different duty cycles stands for different levels of self-heating. The measurement results will be analyzed together with theoretical simulation based on the self-consistent model described in Chapter 3. Section 8.1 presents the light–current (L – I) measurement results under pulsed operation and compares these results with the results of theoretical simulation. The self-heating and injection efficiency of the QD region under pulsed operation were characterized and are shown in Section 8.2. The influence of the oxide-aperture area is also discussed in both sections.

8.1 Output Power Performance under Pulsed Operation

The 1.3- μm emission p -doped InAs/GaAs QD VCSELs were fabricated with oxide-aperture areas of $5\times 6\ \mu\text{m}^2$, $7\times 8\ \mu\text{m}^2$, and $15\times 15\ \mu\text{m}^2$, respectively. The light–current (L – I) measurements were carried out under pulsed operation at a frequency (f) of 500 Hz at different duty cycles, which are 1%, 2%, 5%, 10%, and continuous-wave (CW, 100%). All measurements were performed at room temperature (RT). Figure 8.1 shows the measured L – I curves at different duty cycles for devices with oxide-aperture areas of (a) $5\times 6\ \mu\text{m}^2$, (b) $7\times 8\ \mu\text{m}^2$ and (c) $15\times 15\ \mu\text{m}^2$. For the device with an oxide-aperture size of $5\times 6\ \mu\text{m}^2$ (Figure 8.1(a)), which operates with a single-longitudinal-mode emission (described in Chapter 7), the saturated output power is 0.364 mW at 7.5 mA under a 100% duty cycle (CW). If the injected carriers are reduced by lowering the duty cycle, the saturated output power can be

increased up to 0.571 mW, which corresponds to the duty cycle of 1% where self-heating is almost eliminated. This shows that with an oxide-aperture of $5 \times 6 \mu\text{m}^2$, the CW output power of the 1.3- μm p -doped InAs/GaAs QD-VCSEL (single-mode) can be improved by nearly 60% if the self-heating effect can be eliminated completely. The output power improvement is about 55% and 48% for the devices with an oxide-aperture area of $7 \times 8 \mu\text{m}^2$ (Figure 8.1(b)) and $15 \times 15 \mu\text{m}^2$ (Figure 8.1(c)), respectively. Figure 8.1 illustrates that the threshold currents (I_{th}) did not show a significant dependence on the duty cycle. The currents measured 1.3, 1.5, and 3.5 mA corresponding to the three aperture sizes, respectively. This could be due to the presence of p -doped QDs in the active region and the details have been discussed in Chapters 6 and 7. That is, for the p -doped QD lasers, the contributing component of I_{th} from Auger recombination reduces following an increase in temperature, and therefore compensates for the heat contribution from the recombination at the barrier and the waveguide, which increases following an increase in temperature. The minor abnormality in some L - I - V curves' shape might be due to uncertain conditions during measurement.

Figure 8.1 The L – I characteristics of QD VCSELs at different pulsed duty cycles for different sized oxide-aperture areas: (a) $5 \times 6 \mu\text{m}^2$, (b) $7 \times 8 \mu\text{m}^2$, and (c) $15 \times 15 \mu\text{m}^2$.

The output power performance of the p -doped QD-VCSELs with different sized oxide-apertures (see Figure 8.1) was simulated based on the self-consistent theoretical model described in Chapter 3. The calculated maximum output powers (P_s) are depicted in Figure 8.2(a) as solid lines and the experimental results are represented as symbols. Figure 8.2(a) shows a good agreement between the experimental results and the theoretical simulation. The maximum output power does not vary linearly with the duty cycle. To demonstrate the improvement in output power under pulsed operation, the power improvement ratio $((P_s - P_{s_cw})/P_{s_cw})$ is shown in Figure 8.2(b) where P_{s_cw} is the maximum power under CW operation. A higher power improvement ratio is achieved for a duty cycle less than 10%, indicating that the

self-heating effect is reduced when the pulse time is below 0.2 ms. A larger aperture area results in lower power improvement, indicating a low self-heating effect in devices with larger apertures. This is consistent with the thermal resistance in the VCSEL [1], which is calculated by the consideration of our device configuration and is shown in the inset of Figure 8.2(b) as a function of the oxide-aperture size.

Figure 8.2 (a) Maximum output power at different duty cycles and with different oxide-aperture areas; (b) improvement on the maximum output power by controlling the pulsed duty cycles and the oxide-aperture sizes. The inset shows the thermal resistance as a function of the oxide-aperture size.

8.2 Characterization of Self-Heating Effect and Injection Quantum Efficiency

This change of maximum output power with pulsed duty cycles reveals different levels of self-heating as well as different levels of injection quantum efficiency. In this section, the self-heating and the injection quantum efficiency in 1.3- μm p -doped QD VCSELs under pulsed operation will be characterized theoretically. This simulation is based on the self-consistent model comprised of rate equations and the thermal conduction equation (see Chapter 3).

8.2.1 Self-Heating Effect

The calculated temperature increase (ΔT) in the active region of the p -doped InAs/GaAs QD-VCSEL is shown in Figure 8.3. We observed that, for devices with the same oxide-aperture area, the variation in ΔT is more evident for duty cycles ranging from 1% to 10%. For devices with an oxide-aperture area of $5 \times 6 \mu\text{m}^2$, the difference in ΔT between the 10% and the 100% duty cycles is around 4.67 K at an injection current of 6 mA. Between the 1% and the 10% duty cycles, the difference in ΔT increases to 5.45 K. The same trend was also observed in devices with oxide-aperture areas measuring $7 \times 8 \mu\text{m}^2$ and $15 \times 15 \mu\text{m}^2$, indicating that the change of self-heating effect is more significant at duty cycles below 10%. In this region, the dissipated and generated heat densities are comparable and any change in the duty cycle will result in a significant change in the self-heating effect. This is consistent

with the observation in Figure 8.2(b), which shows that the influence of self-heating on the output power is more significant in this region.

Figure 8.3 The temperature increase due to the self-heating effect in the active region of 1.3- μm *p*-doped InAs/GaAs QD VCSELs at different duty cycles and with different oxide-aperture sizes.

Figure 8.3 shows that self-heating is also dependent on the oxide-aperture area. The variation in ΔT at the same current injection and duty cycle differs according to the oxide-aperture area. For an oxide-aperture area of $5 \times 6 \mu\text{m}^2$, ΔT is 19.50 K at 6 mA and at a 10% duty cycle. It reduces to 13.21 K and 6.42 K for oxide-aperture areas of $7 \times 8 \mu\text{m}^2$ and $15 \times 15 \mu\text{m}^2$, respectively, at the same injection current level and duty cycle level. The decrease in ΔT in devices with larger oxide-aperture areas at the same current injection level is mainly due to the reduction in current density (J). A smaller current density (J) leads to a lower heat generation in both the DBR and the QD regions [2,3]. Furthermore, according to Nakwaski and Osiński [1] and as shown in the inset of Figure 8.2(b), an effective reduction in thermal resistance (R_{th}) can be obtained when the oxide-aperture area is enlarged. In this case, the self-heating effect is less serious and thereby reduces the ΔT . The results of the different oxide-aperture sizes and duty cycles also show that the variation in ΔT at power saturation from 30 K to 35 K is less obvious. For example, for devices with oxide-aperture areas of $5 \times 6 \mu\text{m}^2$ at a 1% duty cycle, the power saturation occurs at around 10 mA and the ΔT is 34.12 K.

8.2.2 Injection Quantum Efficiency

The calculated QD injection efficiencies (η_{QD}) at different duty cycles and with different oxide-aperture areas are shown in Figure 8.4. We observed that, for devices with the same oxide-aperture area and current injection level, there is an obvious

difference in η_{QD} at duty cycles which are less than 10%. For example, for devices with an oxide-aperture area of $5 \times 6 \mu\text{m}^2$ at a 6 mA injection current, the average η_{QD} variation rate ($= \frac{\Delta\eta_{QD}}{\Delta(\text{duty_cycle})}$) is about 2.33×10^{-4} between the 10% and the 100% duty cycles. Between the 1% and 10% duty cycles, the average η_{QD} variation rate increases to 1.77×10^{-3} . Since η_{QD} is closely related to the self-heating effect, the high variation rate of η_{QD} indicates a serious self-heating effect at a less than 10% duty cycle for the same oxide-aperture size. According to the analysis on Figures 8.2 and 8.3, when heat dissipation is comparable to heat generation, the change in thermal energy is significant even with a slight change in the duty cycle, indicating a larger variation in the carrier thermalization and recombination. As a result, for devices with the same oxide-aperture area, the variation in η_{QD} is more evident between the 1% and the 10% duty cycles under a particular current injection level.

Figure 8.4 The QD injection efficiency of 1.3- μm p -doped InAs/GaAs QD VCSELs at different duty cycles and with different oxide-aperture sizes.

Figure 8.4 illustrates that η_{QD} is also influenced by the oxide-aperture area. For example, η_{QD} is 0.746 for devices with an oxide-aperture area of $5 \times 6 \mu\text{m}^2$ at a 6 mA injection current level and a 10% duty cycle. η_{QD} increases to 0.767 and 0.825 for oxide-aperture areas of $7 \times 8 \mu\text{m}^2$ and $15 \times 15 \mu\text{m}^2$, respectively, at the same injection current level and duty cycle level. Similar to the analysis from Figure 8.3, for devices with larger oxide-aperture areas at the same duty cycle, the increase in η_{QD} is mainly attributed to the reduction in current density (J). Since heat generation is reduced with smaller current density (J) [2,3], the influence of self-heating on the carrier confinement is less significant. Furthermore, according to Nakwaski and Osiński [1] and the inset of Figure 8.2(b), an effective reduction in the thermal resistance (R_{th}) can

be obtained when the oxide-aperture area is larger, thus improving the carrier confinement and the thermalization. Therefore, at the same duty cycle, a higher η_{QD} can be obtained in devices with larger oxide-aperture areas.

In summary, the influence of self-heating on the performance of 1.3- μm p -doped QD VCSELs is characterized from both a theoretical and an experimental investigation. Although p -doping helps to obtain a high temperature stability in the threshold current, the output power is still seriously limited by self-heating. For 1.3- μm p -doped QD VCSELs with single-mode operation (oxide-aperture areas of $5 \times 6 \mu\text{m}^2$, see Chapter 7), the output power can be improved by 60% with the complete elimination of self-heating. Less improvement is obtained for devices with multi-mode operation (oxide-aperture areas of $7 \times 8 \mu\text{m}^2$ and $15 \times 15 \mu\text{m}^2$). The similar phenomenon is also observed in the analysis of the temperature response at the active region (Figure 8.3) and the QD injection efficiency (Figure 8.4). To improve the output power, we tried to modify the device morphology or the fabrication process to achieve two targets. The first target is to lower the self-heating effect by adopting the dielectric-free approach [4]. The second target is to apply the surface-relief technique [5] to enhance the fundamental mode emission in devices with larger oxide-aperture areas, which have less self-heating generation but multiple transverse oscillations. The application of these two methods in our fabrication will be demonstrated in Chapter 9.

9. Improving Thermal Behavior by Adopting the Dielectric-Free Approach with the Surface-Relief Technique

As elaborated on in Chapter 7, we have already achieved single-mode emission of 1.3- μm QD VCSELs and have demonstrated that the oxide-aperture size is a crucial factor in influencing the emission mode. For conventional devices, single mode emission can only be achieved with an oxide-aperture diameter of less than 6 μm . However, the smaller oxide-aperture size causes serious self-heating, which deteriorates 60% of the output power (see Chapter 8). The optimization of the device morphology and processing is necessary to improve its thermal behavior and, thereby, its output performance.

In our case, two approaches are considered in the device design and fabrication: (1) the dielectric-free approach [1] and (2) the surface-relief technique [2]. By adopting the dielectric-free approach, the differential resistance of VCSELs can be reduced effectively and, thereby, less Joule heating is generated so that the output power can be improved. The surface-relief technique is used to enhance the fundamental-mode emission of 1.3- μm QD VCSELs with larger oxide-apertures. In this way, the current density and the differential resistance are decreased and, therefore, the self-heating effect is improved and a higher output power can be obtained. Both techniques are applied in 1.3- μm QD VCSELs for the first time and

the respective processing and characterization are demonstrated in this chapter. The two approaches are briefly introduced in Sections 9.1 and 9.2; followed by an elaboration of the fabrication procedures in Section 9.3 and a demonstration of the characterization and analysis in Section 9.4.

9.1 The Dielectric-Free Approach

We proposed the dielectric-free approach in 2010 and it was applied in 850-nm quantum-well (QW) VCSELs [1]. Instead of the deposition of dielectric materials (such as silicon compound and polymer) in conventional dielectric-dependent (DD) fabrication, by the adoption of the dielectric-free (DF) approach, electrical isolation is achieved by utilizing the oxidation in the AlAs layer between the top distributed Bragg reflectors (DBRs) and the QD active region (Figure 9.1). The self-insulation process not only effectively reduces the fabrication cost and complexity; it also helps to achieve better features.

Figure 9.1 Schematic cross-section diagram of a 1.3-μm oxide-confined InAs/GaAs QD VCSEL. The oxide-aperture is formed in the AlAs layer between the *p*-DBR layers and the QD active region.

The self-insulation fabricated in the dielectric-free (DF) approach is realized by a modification in the device morphology. As illustrated in Figure 9.2, similar to devices developed by the dielectric-dependent (DD) approach (Figure 9.2(a)), the mesa of 1.3-μm QD VCSELs (Figure 9.2(b)) should be formed by photolithography and unselective wet etching. The mesa includes three parts: (1) the laser's main body, (2) the bond pad, and (3) the linked bridge. However, when the DF approach is adopted, the big circular portion of the mesa becomes the main body and the small one becomes the bond pad, which is opposite to the DD approach. The most important aspect is that, when the DF approach is adopted, the difference in the area of the main body and the bond pad must be larger than the area of the oxide-aperture. In this way,

self-insulation parts that are formed can be fully built in the AIAs layer after selective oxidation with no leakage current occurring under the wire bonding area or the bridge connector during the device operation. In contrast, when the DD approach is utilized, after oxidation beside the oxide-aperture in the main body, current leakage will occur in the bond pad without the deposition of dielectric materials. Figure 9.3 shows the samples after oxidation and the removal of the top DBR stacks. It is obvious that, by utilizing the DD approach, another aperture remains in the bond pad besides the oxide-aperture (Figure 9.3(a)). This other aperture will lead to current leakage without the deposition of dielectric layer and can be avoided by full oxidation in the DF approach (Figure 9.3(b)).

The procedures following oxidation are similar to the DD approach described in Chapter 5, including *p*-type contact metal (Ti/Au) deposition, substrate thinning, *n*-type contact metal (Au/Ge/Ni) deposition, and metal annealing. In the whole process utilizing the DF approach, dielectric material deposition and its relevant procedures (such as etching, polymer spin coating, contact and light output window opening) are not required. Therefore, the fabrication cost and the fabrication complexity of the device are effectively reduced.

Figure 9.2 Microscopic images from the top view of fabricated 1.3- μm QD VCSELs: (a) by the dielectric-dependent (DD) approach; (b) by the dielectric-free (DF) approach.

Figure 9.3 Microscopic images from the top view of a sample 1.3- μm QD VCSEL after oxidation in the AlAs layer and the removal of the top DBR stacks: (a) the dielectric-dependent (DD) approach; (b) the dielectric-free (DF) approach.

Besides its flexible process, the dielectric-free (DF) approach is also promising in that it realizes better output features compared with the conventional dielectric-dependent (DD) approach. We previously demonstrated this in 850-nm quantum-well (QW) VCSELs. Figure 9.4 shows the light-current-voltage ($L-I-V$) characteristics comparison at room temperature (RT) between 850-nm QW VCSELs by DF and DD approaches, which are based on the same epitaxial wafer and have similar square oxide-aperture sizes of $\sim 17\ \mu\text{m}$. Herein, SiN_x film is used in the DD

approach as the dielectric layer. The threshold current of the DF VCSEL (1.42 mA) is slightly lower than that of the DD VCSEL (1.49 mA). At an injection current of 10 mA, the differential resistance of the DF VCSEL (49 Ω) is also lower than that of the DD VCSEL (64 Ω). From the threshold current to the 10 mA, both $L-I$ curves are linear and their slope efficiencies are approximately 0.62 W/A and 0.57 W/A, respectively. The lower differential resistance and higher slope efficiency in the DF VCSELs might be due to the large area of current channel in the top DBRs and to the simple processing, which helps to reduce the Joule heating and the device failure rate, respectively. The improved performance also encourages us to apply the dielectric-free approach in the fabrication of 1.3- μm QD VCSELs in order to produce better features.

Figure 9.4 The $L-I-V$ characteristics of 850-nm QW VCSELs with oxide-aperture sizes of $17\ \mu\text{m}$. Solid lines denote the DF VCSEL and dashed lines correspond to the DD VCSEL.

9.2 The Surface-Relief Technique

Another important technique is the surface-relief (SR) technique, which was first proposed by Chalmers University of Technology and Ulm University in 1999 [2]. This method only involves a slight modification to the standard VCSEL fabrication. A shallow surface-relief ring is etched into the top distributed Bragg reflectors (DBRs) around the central VCSEL region, where only the fundamental transverse mode possesses high intensity. The device with the surface-relief etched ring on its mesa is shown in Figure 9.5 and the purpose of this modification is to increase the mirror loss or the threshold gain on the etched region, which corresponds to a higher-order

transverse mode. The mirror loss is quite sensitive with etching depth [3-7]. Hence, a similar variation should be observed in the threshold gain. Figure 9.6(a) and (b) show the plots of the normalized mirror loss (or threshold gain) versus the etch depth in 850- [4] and 1300-nm [6] QW VCSELs, respectively, which are calculated by a *I-D* transfer matrix program. The results show periodic variation: a narrow local maximum is obtained when the etching depth is $\lambda/4$ (about 58 and 85 nm for 850- and 1300-nm QW VCSELs, respectively). That is, the onset of lasing in the region with the $\lambda/4$ etching depth needs a higher modal gain as compared to the central region without a shallow etching. Therefore, the onset of high-order-mode lasing can be suppressed by shallow etching with a depth of $\lambda/4$ so that the emission from the fundamental mode can be enhanced.

Figure 9.5 Microscopic images from the top view of the VCSEL with an etched surface-relief shallow ring.

Figure 9.6 (a) Calculated threshold gain and emission wavelength versus etch depth for the surface-etch optimized 850-nm structure (from Unold *et al.* [4]); (b) calculated normalized mirror loss as a function of etching depth for the oxide-confined 1.3- μm VCSEL structure (from Haglund *et al.* [6]).

The surface-relief technique has been applied in 850- and 1300-nm QW VCSELs [2-7] in order to achieve single-mode operation in relatively larger oxide-apertures and with higher output power compared to standard VCSELs. However, to the best of knowledge, no such report exists in QD VCSELs. We apply this technique together with the dielectric-free approach in 1.3- μm InAs/GaAs QD VCSELs and the fabrication procedures are demonstrated in Section 9.3.

9.3 Fabrication Procedures

The QD VCSEL structure is shown in Figure 9.7. The epitaxial wafer is grown on n^+ -GaAs (100) substrate by molecular-beam epitaxy (MBE). The device consists of 24 pairs of p -doped and 33.5 pairs of n -doped $\text{Al}_{0.9}\text{Ga}_{0.1}\text{As}/\text{GaAs}$ distributed Bragg reflectors (DBR). Seventeen layers of p -doped InAs/GaAs QDs are contained in the 3λ intercavity region. Each standing wave position coincides with three layers of QDs and two adjacent QD layers are separated by 32 nm of GaAs. The QDs are grown directly on GaAs and are capped by a 6-nm-thick $\text{In}_{0.15}\text{Ga}_{0.85}\text{As}$ layer. The 5-nm-thick p -doped GaAs layers are sandwiched between undoped GaAs layer thicknesses of 5 and 12 nm, respectively.

Figure 9.7 The schematic cross-section diagram of 1.3- μm QD-VCSELs by the dielectric-free approach utilizing the surface-relief process.

The fabrication procedures are as follows. First, mesas were formed by photolithography and unselective wet etching as shown in Figure 9.8(a). The solution used for the wet etching is $\text{H}_3\text{PO}_4: \text{H}_2\text{O}_2: \text{H}_2\text{O} = 3: 3: 10$ and the etching duration is about 2.5 minutes. The mesa includes three parts (Figure 9.8(b)): (1) the big circular portion with a diameter of 105~115 μm is the lasers' main body, (2) the relatively small circular portion with a diameter of about 90 μm is used for the bond pad mesa, and (3) a bridge is used to connect these two portions and to form a conjunct plane.

(a)

(b)

Figure 9.8 Mesa forming by photolithography and wet etching: (a) schematic cross-section diagram; (b) microscopic image from top view.

Next, an oxide-aperture was formed by wet oxidation in the laser's main body with an oxidization condition of 450°C under 1 L/min N_2 gas bubbled through 90°C deionized water (Figure 9.9(a)). The reaction principle was described in Chapter 5 (Equations (5.1) and (5.2)). The size of the oxide-aperture should be smaller than

the difference of the two circular portions. It is to ensure that the self-insulation parts formed by the AlAs layer oxidization can be fully built after the oxidation process. Therefore, no leakage current will occur under the wire bonding area or the bridge connector during the device operation. The duration of the oxidation should not be less than 28 minutes. The image of a sample after the AlAs layer oxidation and the removal of the top DBR stacks is shown in Figure 9.9(b), where the size of the oxide-aperture can be observed.

(a)

(b)

Figure 9.9 The forming of the oxide-aperture: (a) schematic cross-section diagram; (b) microscopic image from the top view of a sample after the oxidation of AlAs and the removal of the top DBR stacks.

Next, the *p*-contact layer is deposited on the insulation layer and emitting aperture by an electron-beam evaporator system (Figure 9.10(a)). The composition is Titanium (Ti) and Gold (Au), with thicknesses of 50 and 250 nm, respectively. The *p*-contact is formed in a ring-shape (Figure 9.10(b)) by photolithography and wet etching. The etching composition of Au is KI: I₂: Di-H₂O = 8 g: 2 g: 80 ml, and the time is ~45 seconds. The etching of Ti is performed by a solution with a volume composition of HF: HNO₃: Di-H₂O = 1: 2: 60 and the time is ~40 seconds.

(a)

(b)

Figure 9.10 The forming of the *p*-type contact: (a) schematic cross-section diagram; (b) microscopic image from top view.

Next, a surface-relief shallow ring is formed on the centre of the top layer by photolithography and wet etching (H_3PO_4 : H_2O_2 : DI-Water = 1: 1: 10 for 10 seconds), which is shown in Figure 9.11(a) and (b). Its diameter (d_{SR}) is $\sim 3.5 \mu\text{m}$, which should match $1/e$ -decay of the fundamental mode intensity profile [8]. The depth is about 85 nm ($\lambda/4$) to reach the local maximum of the mirror loss for a high-order mode [6].

(a)

(b)

Figure 9.11 Etching of the surface-relief ring: (a) schematic cross-section diagram; (b) microscopic image from top view.

Au-Ge-Ni are deposited as n -contact after device thinning (Figure 9.12(a)). At the end, the laser is mounted on a copper heat sink and the top view of the fabricated 1.3- μm QD VCSEL by the dielectric-free approach with the surface-relief technique is shown in Figure 9.12(b). Section 9.4 contains the measurement results as well the corresponding discussion.

(a)

(b)

Figure 9.12 (a) *N*-contact deposition; (b) microscopic image from top view of the fabricated 1.3-μm QD VCSEL by the dielectric-free approach with the surface-relief technique.

9.4 Results and Discussion

The comparison between the dielectric-free (DF) and conventional dielectric-dependent (DD) approaches on the light–current–voltage (L – I – V) characteristics are illustrated in Figure 9.13. The measured devices are based on the same epitaxial wafer, and the measurement is at room temperature (RT) and under continuous-wave (CW) current injection. It can be seen that, for the same oxide-aperture diameter ($d_{OA} \sim 10 \mu\text{m}$) fabricated without surface-relief (SR), by DF approach, the threshold current (I_{th}) is 2.15 mA. Its output power (P_{out}) is saturated with 1.28 mW at 14 mA, which is 77.78% better than the maximum P_{out} achieved by the VCSEL built by the DD approach (0.72 mW at 10 mA). The significant improvement can be attributed to the enlarged area on contact and the increased current spreading in the p -DBR layers, which decreases the differential resistance and thereby lowers the Joule heating. In I – V curves, for devices fabricated by the DF approach without SR, the differential resistance is 79.4 Ω and 36.47% lower than the device fabricated by the DD approach (125.1 Ω). A high P_{out} by the device built by the DF approach is also obtained under pulsed injection (inset of Figure 9.13). At a frequency (f) of 1000 Hz and 2% duty cycle, the P_{out} at RT are saturated with 1.92 and 3.42 mW for devices with oxide-aperture diameters of $\sim 10 \mu\text{m}$ and $15 \mu\text{m}$, respectively.

Figure 9.13 Comparison of the L – I – V characteristics between the dielectric-free (DF) and the dielectric-dependent (DD) approaches, as well as the influence of the surface-relief (SR) technique in 1.3- μm QD VCSELs. The inset shows the L – I properties achieved by the DF approach in pulsed operation.

The influence of the surface-relief (SR) on the L – I – V characteristic is also demonstrated in Figure 9.13. By the dielectric-free (DF) approach, for a device with SR, the I_{th} is slightly increased (2.47 mA), and the P_{out} is lower (0.995 mW) compared to the one without SR. The reason is that, by the application of the SR technique, mirror loss is increased in higher-order transverse modes whose emission is suppressed and more current injection is required for lasing. Furthermore, from the I – V curves, it can be seen that the differential resistance of devices by the DF

approach with SR ($87.7\ \Omega$) is a little larger than the one without SR ($79.4\ \Omega$). It should be due to the introduced discontinuity in the current channel by the etched SR ring on the top surface. Although the L – I – V characteristics are influenced by the SR technique, the lasing of the fundamental mode can be strongly favored. Figure 9.14 and its inset present the spectra of devices by the DF approach with and without SR, respectively. For the device with SR, the central wavelength is 1266.64 nm with a full-wave at half-maximum (FWHM) of 0.123 nm. The side-mode suppression-ratio (SMSR) is 7 dB at 5 mA, which indicates the significant enhancement of the fundamental emission compared with the one without SR. Further improvement on the spectrum might be carried out by electron-beam lithography and ion-beam etching [5], which provide more critical precision on pattern alignment and etching depth in device processing, respectively.

Figure 9.14 The lasing spectrum of 1.3- μm QD VCSELs fabricated by the dielectric-free (DF) approach with the surface-relief (SR) technique. The inset shows the one fabricated without the SR technique.

The small signal modulation response of devices by the dielectric-free (DF) approach (without SR) is shown in Figure 9.15. For devices with oxide-aperture diameters (d_{OA}) of 10 μm , the 3-dB modulation bandwidth at room temperature (RT) increased from 8 mA and saturated around 12~14 mA. The saturation is due to the serious self-heating effect at high current injection, which decreases the carrier lifetime and the modulation gain and, hence, suppresses the damping rate. The maximum 3-dB bandwidth is about 2.5 GHz, which is comparable to the best result we have achieved by the dielectric-dependent (DD) approach with the same oxide-aperture area [9] (inset of Figure 9.15) except that the required current in the

DD approach is only 7 mA. This is because of the enlarged area of the laser pad and the current distribution fabricated by the DF approach, which increases the parasitic capacitance and results in the limitation in modulation bandwidth. Further improvement can be carried out by optimizing the mesa morphology or introducing proton implantation for the present devices [10,11].

Figure 9.15 The small signal modulation response of fabricated QD VCSELs by the DF approach. A maximal 3-dB modulation bandwidth of 2.5 GHz is obtained at 14 mA. The inset shows the response of the device by the DD approach at 7 mA.

In summary, by adopting the dielectric-free approach with the surface-relief technique, the output power in 1.3- μm QD VCSELs is effectively improved because of a reduction in the differential resistance, which helps to decrease the Joule heating. The emission from the fundamental mode can be significantly enhanced due to the surface-relief technique, and further optimization in the side-mode suppression-ratio is also expected to be realized by the application of electron-beam lithography and ion-beam etching. However, the increase in parasitic capacitance limits the 3-dB modulation bandwidth in the device by the dielectric-free approach, which might be improved by optimizing the mesa morphology or by introducing proton implantation for the present devices.

10. Conclusions and Recommendations for Future Research

The self-heating effect, its influence on 1.3- μm InAs/GaAs QD VCSELs, and its relevant optimization are demonstrated in Chapters 1 – 9. These are based on both theoretical and experimental investigations. This chapter provides the conclusions of this project and some recommendations for future research on 1.3- μm QD VCSELs. The conclusions are presented in Section 10.1 and the recommendations are presented in Section 10.2.

10.1 Conclusions

This doctor of philosophy research project focuses on the self-heating effect and its influence on the output and the threshold performance in 1.3- μm InAs/GaAs QD VCSELs. In summary, the study includes both theoretical and experimental investigations. For the theoretical study, based on the literature review on previous thermal models from other research groups and institutes, a self-consistent model comprised of rate equations and the thermal conduction equation was established. The simulation results showed that the threshold current and the output power are significantly influenced by the self-heating effect in QD VCSELs. The reasons for this serious self-heating in QD VCSELs are their small oxide-apertures and the hole thermalization arising from their thin wetting layers. Therefore, in the experimental

study, the p -type modulation doping (p -doping) in the QD active region is applied to the wafer structure and a high temperature stability of the threshold current is obtained in both the single-mode and the multi-mode p -doped QD VCSELs. However, the output power is still significantly limited by self-heating in the p -doped QD VCSELs due to the serious deterioration of the QD emission at a high temperature. To better understand this problem, the characterization of the influence of self-heating on the output power of 1.3- μm p -doped InAs/GaAs QD VCSELs is investigated from the device measurement under the pulsed current injection, together with the theoretical simulation based on the established self-consistent model. The corresponding optimization is based on the dielectric-free approach and the surface-relief technique, which helps to reduce the Joule heating and enhance the fundamental mode emission, respectively. The details of the above investigations are now summarized.

The theoretical study began with a literature review on heat generation and conduction mechanisms and modeling by other research groups. These provided many useful analysis strategies and calculation methods for us to establish a thermal model for 1.3- μm InAs/GaAs QD VCSELs. The established model comprises rate equations and the thermal conduction equation and the simulation is based on a self-consistent process. The purpose is to investigate the influence of self-heating on the carrier occupation, the quantum efficiency, and the output power. The simulation result shows that an increase in the QD density and the number of QD layers significantly lowers the self-heating effect and improves the quantum efficiency of the device. This is due to the fact that increasing the number of QDs in the active region

reduces the effect of hole thermalization arising from the thin wetting layer (WL). While high output power can be achieved using a high QD density and a high number of QD layers, an optimum number of QD layers exists to achieve the highest output power from the device.

In order to improve the carrier thermalization due to the weak hole confinement, the p -type modulation doping (p -doping) is applied in the QD active region of the wafer structure. The temperature characteristics are investigated in both multi- and single-mode QD VCSELs. The characterizations of multi-mode QD VCSELs were demonstrated at room temperature (RT) continuous-wave (CW) operation with a high characteristic temperature (T_0) of ~ 510 K and a low threshold current density of ~ 65 A/cm² per QD layer. The highest output power exceeded 0.74 mW. An analysis of the photoluminescence (PL) spectrum shows that the temperature sensitivity of the QD emission contributes to degradation in the device performance at a high temperature. Therefore, the temperature stability of the threshold current (I_{th}) is not due to the detuning between the cavity resonance wavelength and the wide gain spectra. The main reason for the high T_0 is the p -type modulation doping, which results in a reduced Auger recombination following an increase in temperature. The real temperature of the QD VCSEL active region above the threshold is estimated from the experimental shift in the lasing wavelength and is calculated using the established self-consistent model. A good agreement is obtained between the experimental and theoretical results. The temperature-dependent light-current ($L-I$)

characteristics indicates that enhancing the carrier confinement in the QD wetting layer (WL) will improve the saturated output power.

The single-mode emission of the 1.3- μm p -doped QD VCSELs in continuous-wave (CW) is achieved in devices with oxide-aperture areas of $5 \times 6 \mu\text{m}^2$. The side-mode suppression-ratio (SMSR) is 34 dB and 5.7 dB at room temperature and at 50°C, respectively. Similar to the observation in QD VCSELs with multi-mode emission, a high temperature stability of I_{th} is also achieved in single-mode devices due to the contribution of the p -doping. The saturated output power is 0.435 mW, which is better than the reported result for undoped QD VCSELs in Chang *et al.* [1]. The device with a larger oxide-aperture of $7 \times 8 \mu\text{m}^2$ exhibits multimode operation with higher output power and slope efficiency and lower threshold current density.

Although the p -type modulation doping leads to a high temperature stability of the threshold current, the output power is still significantly influenced by self-heating. In order to better understand this problem, the influence of the self-heating effect on the output power of 1.3- μm p -doped QD VCSELs is characterized in both device measurement and theoretical analysis. The light–current (L – I) measurement occurs under pulsed current injection with different duty cycles while the theoretical analysis is based on the established self-consistent model. At room temperature (RT) and at a frequency of 500 Hz, the self-heating effect is reduced significantly and a higher output power can be achieved when the current injection time is less than 0.2 ms. For devices with oxide-aperture areas of $5 \times 6 \mu\text{m}^2$, which represents single-mode emission, the CW operation power can be improved by

nearly 60% if the self-heating effect can be eliminated completely. The influence of self-heating on the output power is less serious in devices with larger oxide-aperture areas. A similar trend is also observed in the analysis of the temperature response in the active region and in the analysis of the QD injection efficiency.

According to the serious self-heating effect and its significant influence, we tried to apply the dielectric-free approach with the surface-relief technique in device fabrication for optimization. To the best of our knowledge, these two optimization methods are realized in 1.3- μm InAs/GaAs QD VCSELs for the first time. Adopting the dielectric-free approach not only helps to reduce the fabrication cost and complexity, but it also effectively decreases the Joule heating by lowering the differential resistance and it thereby improves the output power. The surface-relief technique significantly enhances the fundamental mode emission in devices with larger oxide-apertures compared with standard VCSELs. A comparison of the 1.3- μm QD VCSELs fabricated by the dielectric-free (DF) approach with the surface-relief technique and with oxide-aperture diameters of 10 μm to the devices fabricated by the conventional dielectric-dependent (DD) method reveals that, in the DF QD VCSELs, the differential resistance (79.4 Ω) is reduced by 36.47% and the output power (1.28 mW) is improved by 78.32% under continuous-wave (CW) operation. The output power reaches up to 3.42 mW under pulsed operation when the oxide-aperture diameter measures 15 μm . Although the light–current–voltage (L - I - V) characteristics are negatively influenced by the surface-relief technique, the emission of the fundamental mode is effectively enhanced. The maximum 3-dB modulation

bandwidth is 2.5 GHz in devices fabricated by the DF approach, which is comparable with the result in the devices fabricated by the conventional DD approach. However, more power consumption is required in the fabrication of the device by the DF approach due to the increased parasitic capacitance in the large area of the laser pad.

10.2 Recommendations for Future Research

In Chapter 9, we have demonstrated the first realization of the 1.3- μm InAs/GaAs QD VCSELs fabricated by the dielectric-free (DF) approach with the surface-relief (SR) technique and have improved the output power and enhanced the fundamental mode emission significantly. However, the improved side-mode suppression ratio (SMSR) by the SR technique is still much lower than the one we achieved in the standard QD VCSELs without SR (34 dB at room temperature, elaborated on in Chapter 7). Therefore, the operation of fabricated QD VCSELs with SR cannot be considered as single-mode emission. In addition, in QD VCSELs fabricated by the DF approach, the maximal 3-dB bandwidth is comparable with the one achieved in conventional dielectric-dependent (DD) QD VCSELs but an additional 5-mA input current injection is required for the same oxide-aperture area (Chapter 9). Therefore, for future research on 1.3- μm InAs/GaAs QD VCSELs, our recommendations focus on the following two aspects: (1) the improvement of the SMSR in SR-QD VCSELs to achieve single-mode emission ($\text{SMSR} \geq 20 \text{ dB}$), and (2) the optimization of

small-signal modulation characteristics in devices fabricated by the DF approach. These recommendations are described in Sections 10.2.1 and 10.2.2, respectively.

10.2.1 Improvements of SMSR in SR-QD VCSELs

By reviewing the previous investigations on the application of SR in 850-nm [2-7] or 1.3- μm [8,9] quantum-well (QW) VCSELs, as well as the experimental source in our fabrication laboratory, two recommendations can be generated for further research and optimization in 1.3- μm InAs/GaAs QD VCSELs with SR.

- (a) As demonstrated in Chapter 9, the requirement of the position and depth in the SR etching ring is very strict. The ring must be located exactly in the centre of the top surface to keep the fundamental transverse mode without suppression; and the depth must be exactly a quarter of a wavelength to provide the local maximal threshold gain for high-order modes and to thereby suppress them. To precisely control the etching ring's position and depth, some fabrications of 850-nm and 1.3- μm QW VCSELs with SR are based on electron-beam lithography (EBL) and dry etching (reactive ion beam etching (RIE)) [2-4,8], instead of conventional photolithography and wet etching, respectively, as employed in our fabrication. This is because EBL can provide a much higher precision in pattern alignment than photolithography, while the etching depth produced by RIE is much more precise than wet etching. EBL has been already equipped in our fabrication laboratory and is now under equipment calibration. However, GaAs-etching by

RIE is not yet equipped in our lab. That is why we used photolithography and wet etching in this research project. We hope that, in the future, single-mode operation with higher output power in 1.3- μm QD VCSELs can be realized based on EBL and RIE.

- (b) Another suggestion is to apply the inverted-surface-relief (ISR) technique, which might be more effective and has already been used in 850-nm [6,7,10] and 1.3- μm [9] QW VCSELs to achieve single-mode emission. The principle of ISR is to add an extra layer with a thickness of a quarter wavelengths ($\lambda/4$) on top of a conventional VCSEL structure during epitaxial growth. The reflections from this topmost layer will be in anti-phase with respect to the reflections further down in the mirror stack. A shallow surface-relief, in the form of a disk or hole, is then etched in the center of the device (Figure 10.1, from Kroner *et al.* [10]). The advantage of this approach is that it utilizes the high thickness precision in the epitaxial growth to reach a narrow local maximum in the mirror losses. This will then relax the required etch depth precision since a local minimum in the mirror loss is much broader (Figure 10.2, from Haglund *et al.* [6] and Soderberg *et al.* [9]). Besides the etching depth of the ISR hole, according to Figure 10.2, the thickness of the additional GaAs-layer epitaxy must be also exactly $\lambda/4$ so that the cavity loss (or threshold gain) fundamental mode is local minimum. Therefore, besides electron-beam lithography (EBL) and dry etching (reactive ion beam etching (RIE)), the equipment of GaAs epitaxy is also an essential requirement.

(a)

(b)

Figure 10.1 850-nm QW VCSELs with inverted-surface-relief (ISR): (a) cross-section of the device layout and (b) optical microscopical top view of a finished VCSEL (from Kroner *et al.* [10]).

(a)

(b)

Figure 10.2 Calculated mirror loss as a function of etching depth for the VCSEL structure with inverted-surface-relief technique. This loss is designed to produce an anti-phase reflection from the topmost layer when unetched and the local minimum locates at $\lambda/4$: (a) 850-nm QW VCSEL ($\lambda/4 \approx 58$ nm) from Haglund *et al.* [6]; (b) 1300-nm QW VCSEL ($\lambda/4 \approx 90$ nm) from Soderberg *et al.* [9].

10.2.2 Optimization of the Small-Signal Modulation Response in QD VCSELs by the DF Approach

As discussed at the end of Chapter 9, since the area of the laser pad and the current spreading is enlarged by the dielectric-free (DF) approach, additional parasitic capacitance is introduced and limits the carriers to reach the active region, thereby reducing the small-signal modulation response. This improvement can be carried out in two ways: (1) to optimize mesa morphology or (2) to introduce proton implantation for the present devices, which has been applied in 850-nm QW VCSELs [11,12]. Proton implantation helps to compensate for the reduction in electrical charges across the active region by the parasitic capacitance. Therefore, a broader 3-dB modulation bandwidth can be obtained since there are sufficient carriers in the active region. The implanted H^+ ion must penetrate the pad metal and the top distributed Bragg reflectors (DBRs), and eventually reach the active region. Therefore, enough implantation energy is pre-required in this approach.

In summary, the recommendation for future research on 1.3- μm QD VCSELs mainly includes two aspects: (1) the improvement of the SMSR in DF VCSELs with SR by EBL and RIE in fabrication or by the adoption of the ISR technique; and (2) the optimization of small-signal modulation response in DF VCSELs by introducing proton implantation. Besides the above two ways, photonic crystal is also a potential approach to achieve single mode operation with higher output power. Photonic crystal has been applied in QW VCSELs [13-17] and might be adopted in the future research of 1.3- μm InAs-GaAs QD VCSELs.

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