Long Cavity Quantum Dot Laser Diode And Monolithic Passively Mode-locked Operation

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LONG CAVITY QUANTUM DOT LASER DIODE AND MONOLITHIC PASSIVELY MODE-LOCKED OPERATION

by

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Major Professor: Dennis G. Deppe
ABSTRACT

Advantage of the single QD active layer is its potential for very low threshold current density, which in turn can produce low internal optical loss. The low threshold current density and low internal loss thus enable a significant increase in laser diode cavity length. Because of the importance of the threshold current density in heatsinking, future technology of broad-area monolithic laser diodes can be implemented.

The dissertation describes the development and the unique characteristics of single QD active layer laser with long cavity. The data are presented on single layer QD laser diodes that reach threshold current densities values of 11.7 A/cm² in a p-up mounted 2 cm long cavity and as low as 10 A/cm², with CW output power of 2 W in a p-down mounted 1.6 cm long cavity. The 8.8 A/cm² in a p-down mounted 2 cm long cavity is reported. To our knowledge the value 8.8 A/cm² is the lowest threshold current density ever reported for a room temperature laser diode. These single layer QD laser diodes reach an internal loss of ~0.25 cm⁻¹, which is also the lowest ever reported for a room temperature laser diode.

These unique characteristics of single layer QD and laser diode size are potentially promising for the monolithic mode-locked laser because of relatively high peak power with a low repetition rate that is on the order of a few GHz, which can be the novel device for external clocking in the optical interconnect applications. In this dissertation, the stable optical pulse train in a 40 μm wide stripe with a repetition rate of 3.75 GHz with 1.1 cm cavity length through the passive mode-locked onto the monolithic two-section device fabricated from this single layer QD laser is observed.
To my parents: Jarunee Sae-Lim and Udom Shavitranuruk,

To my wife: Sirinun Seosakul

and family
ACKNOWLEDGMENTS

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From the bottom of my heart, my deep appreciation is dedicated to my parents for their lifelong support and unconditional love. They always give me a freedom to do whatever I love.

Last but not least, I am deeply grateful to my wife for her love, support, and encouragement. She always gives me a strength and cheerfulness when I need one. This dissertation would not have been possible without her.
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<tr>
<th>Acronym</th>
<th>Definition</th>
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<tbody>
<tr>
<td>AFM</td>
<td>Atomic Force Microscope</td>
</tr>
<tr>
<td>BCB</td>
<td>Bisbenzocyclobutene</td>
</tr>
<tr>
<td>CTE</td>
<td>Coefficient of Thermal Expansion</td>
</tr>
<tr>
<td>CW</td>
<td>Continuous Wave</td>
</tr>
<tr>
<td>DHS</td>
<td>Double Hetero-Structure</td>
</tr>
<tr>
<td>DI</td>
<td>Deionized</td>
</tr>
<tr>
<td>EL</td>
<td>Electroluminescence</td>
</tr>
<tr>
<td>FWHM</td>
<td>Full-Width-at-Half-Maximum</td>
</tr>
<tr>
<td>GRINSCH</td>
<td>Graded Refractive Index Separate Confinement Heterostucture</td>
</tr>
<tr>
<td>GVD</td>
<td>Group-Velocity Dispersion</td>
</tr>
<tr>
<td>L-I</td>
<td>Light output – Injected current</td>
</tr>
<tr>
<td>MBE</td>
<td>Molecular Beam Epitaxial</td>
</tr>
<tr>
<td>PL</td>
<td>Photoluminescence</td>
</tr>
<tr>
<td>QD</td>
<td>Quantum-Dot</td>
</tr>
<tr>
<td>QW</td>
<td>Quantum-Well</td>
</tr>
<tr>
<td>RF</td>
<td>Radio Frequency</td>
</tr>
<tr>
<td>RIE</td>
<td>Reactive Ion Etching</td>
</tr>
<tr>
<td>SA</td>
<td>Saturable Absorber</td>
</tr>
<tr>
<td>SK</td>
<td>Stranski-Krastanow</td>
</tr>
<tr>
<td>SPM</td>
<td>Self-Phase Modulation</td>
</tr>
<tr>
<td>TBP</td>
<td>Time Bandwidth Product</td>
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CHAPTER 1: INTRODUCTION

Semiconductor quantum dot active region takes full advantage of the quantum confinement effect. The three-dimensional quantum confinement of the carriers results in discrete carrier energy level structure in a quantum dot (QD) active region [1-3]. The discrete energy level leads in the delta-function-like density of the states, allowing suppression of the excited states. Consequently, the QD laser diode offers the potential performance in low threshold current density [2, 4], high differential gain [1, 2], high characteristic temperature [1, 5], and low value of alpha factor [6, 7]. In particular, the low threshold current density is merely considered in this present work and is theoretically predicted to be \( \sim 5 \, \text{A/cm}^2 \) for QD active region with 10% size distribution [8]. So far, the high threshold current density comes from the low modal gain saturation of the ground state due to band filling in the excited state. Therefore, most semiconductor QD laser diodes now being researched is based on stacked QD active layers to increase their optical gain to keep lasing at ground state at high temperature or high current density. However, if the single QD active layer is sufficient for lasing due to enough QD density, the laser diode can reach the lower threshold current density and lower internal optical loss in single QD active layer. The low threshold current density and low internal loss can increase in laser diode cavity length, which can maximize the output power. Additionally, the QD active region plays very important role in the mode-locking operation due to the low threshold current density, low internal loss, low value of alpha factor, high gain saturation energy, low absorption saturation energy, fast gain and absorption recovery. As a result, the QD active region can improve performances of monolithic passively mode-locked laser diode.
1.1 Literature Reviews of Threshold Current Density, Internal Optical Loss of Waveguide and Monolithic Passively Mode-Locked operation in Laser Diode

1.1.1 Literature Review of Threshold Current Density

The development of semiconductor heterostructure laser is shown in figure 1.1. The double heterostructure (DHS) is a key structure in the development of laser diode from bulk, quantum well and quantum dot active region. In 1968, the \( J_{th} \) of 4.3 kA/cm\(^2\) is reported by Alferov et al with a bulk DHS at CW room temperature. Later in May 1970, the \( J_{th} \) of 940 A/cm\(^2\) for broad area laser is reported. It is the first injected DHS laser at CW room temperature operation by Alferov et al. [9]. A month later in 1970, Hayashi and Panish [10] independently report the DHS broad area laser diode under CW operation with diamond heatsink with similar \( J_{th} \) values. For the impact of QW active region, the short-period superlattices for the graded-refractive-index-separate–confinement-heterostucture (GRINSCH) are achieved in \( J_{th} \) of 52 A/cm\(^2\) and some small optimization can reach \( J_{th} \) of 40 A/cm\(^2\) by Alferov et al [11]. For the first observation of QD lasers by Kirstaeter et al.[5], the \( J_{th} \) of 950 A/cm\(^2\) at room-temperature and the \( J_{th} \) of 120 A/cm\(^2\) under pulsed operation at 77 K are reported. In 1996, for an actual QD size variation of approximately 10 \%, theory predicts typical of 5A/cm\(^2\) at room-temperature by Asryan et al. and Grundmann et al. [12, 13]. Surpassing the \( J_{th} \) of QW active region, the \( J_{th} \) of 26 A/cm\(^2\), the single InAs QD layer contained within a strained In\(_{0.15}\)Ga\(_{0.85}\)As quantum well, is achieved at pulse room-temperature by Liu et al.[14]. In 2000, the oxide-confinement is effectively used to prevent lateral current spreading, thus reducing the threshold current density,
and the 1.3 µm InGaAs-GaAs QD active region grown by using submonolayer deposition of In, Ga, and As is achieved at CW room-temperature reaching at the $J_{th}$ of 19 A/cm$^2$ by Park et al. [15]. In the same publication by Park et al., the $J_{th}$ of 6 A/cm$^2$ is obtained with facet coating under pulsed operation at 4 K, which is very close to the transparency current density. A high growth temperature step used for the GaAs spacer layer in three layers of InAs of thickness 1.3 µm within a strained InGaAs quantum well is achieved to reach $J_{th}$ of 17 A/cm$^2$ at CW room-temperature with coated high-reflectivity facets by Sellers et al. [16].

Figure 1.1 Development of semiconductor heterostructure laser
1.1.2 Literature Reviews of Low Internal Optical Loss ($\alpha_i$)

Theoretical study shows that internal optical loss of waveguide ($\alpha_i$) in high power semiconductor laser is reduced by making the waveguide thicker and the cavity longer by Pikhtin et al. [17]. The broad waveguide structure experimentally showed the low threshold current density of 73 A/cm$^2$ per QW and the internal loss of 1.3 cm$^{-1}$ by Garbuzov et al. [18]. Furthermore, theory predicts use of asymmetric waveguide 4 µm thick which results in the low internal optical loss of waveguides of 0.2 cm$^{-1}$ for $\lambda = 1.08$ µm by Slipchen et al. [19]. Owing to asymmetric heterostructure, $\alpha_i$ of 0.3 cm$^{-1}$ with broad waveguide of 1.7 µm thick and 16 W continuous waves were experimentally achieved by Pikhtin et al. [19]. Shifting the optical mode to n-cladding is decreasing the cladding loss due to less free carrier absorption in n-type material. Furthermore, the resistive losses are reduced by increasing doping in p-type material. Similar to Pikhtin et al. work, JDS Uniphase succeeded in the optical internal loss of waveguide of 1 cm$^{-1}$ since they may also use a novel asymmetric structure to reduce the cladding loss.

1.1.3 Literature Review of Monolithic Mode-Locked Lasers in QD Active Region

Experimentally, first demonstration in two-section passively mode-locked laser diode with oxide-confined two InAs QD layers is achieved as 1.3 µm by Huang et al. [20]. The stable mode-locked pulses are observed at 7.4 GHz with pulse duration of 17 ps along the 4.73-mm gain section long and 0.85-mm absorber section long. After the first demonstration, the subsequent researches are explored in QD monolithic passively mode-locked laser. Many aspects
of performance include pulse duration, repetition rate, peak output power, and timing jitter. In
the literature reviews in this dissertation, the pulse duration, repetition rate and peak output
power are only focused. The observations of subpicosecond pulse duration of 800 fs by Gosset et al. [21], 780fs by Thomson et al. [22], and 390fs by Rafailov et al.[23] are achieved. Pulse
duration of 390 fs by Rafailov et al. is the shortest pulse duration to our knowledge. For
repetition rate, the 4.95 GHz is reported by Zhang et al. [24] along with 8.2-mm cavity long, 3.9
ps pulse duration and time-bandwidth product (TBP) of 3. The 5 GHz is observed by Gubenko et
al. [25] with 8-mm cavity long.

Presently, to our knowledge, the highest peak power of 1.7 W (pulse energy of 5.3 pJ) is
reported at 60 °C with 8-mm cavity long, used as HR/AR and a pulse width of 3.2ps at 5 GHz by
Gubenko et al. [25]. For tapered gain structure with a narrowed absorber section, the 780 fs and
500 mW peak power is achieved by Thompson et al. [22]. The difficulty of achieving high
output power and short pulse duration at the same time is investigated by Thompson et al. [22]
and Xin et al. [26]. Thompson et al. study the ratio of gain and section length to simultaneous
decrease in the pulse duration and increase in the peak power whereas Xin et al. investigate the
multi-section monolithic mode-locked laser configurations in QD active region to achieve these
performances as well.

1.2 MBE Growth of Self-organized Quantum Dots

Molecular Beam Epitaxial (MBE) crystal growth is used to grow the high-purity epitaxial
layers of III-V compound semiconductor with extremely abrupt interfaces, excellent in
controlling of doping, thickness and composition. The ultrahigh vacuum environment in the background-pressure less than $10^{-10}$ Torr and in growth-pressure under less than $10^{-6}$ Torr are critically controlled to obtain the extremely pure material sources. The Applied Epi Gen II MBE system at the University of Central Florida at College of Optics and Photonics is shown in figure 1.2.

Figure 1.2 MBE system in the Deppe’s group at University of Central Florida at College of Optics and Photonics

In lattice-mismatched system, the Stranski-Krastanow (SK) growth mode is used to grow the self-organized QDs in this research work [27]. The SK growth mode starts with the two-dimensional growth of wetting layer such as InAs. At this growth mode, the substrate surface energy ($\gamma_{SV}$) is more than the sum of the epitaxial layer energy ($\gamma_{EV}$) and the interface energy ($\gamma_{ES}$).
After the growth thickness reaches the critical thickness of 1.5 ML, the three-dimensional islands is formed by increasing the thickness of InAs layers due to the significant strain occurring, where $\gamma_{SV}$ is less than the sum of $\gamma_{EV}$ and $\gamma_{ES}$. The form of three-dimensional islands can partially relax the elastic strain from the crystal to the dots. Figure 1.3 shows Atomic Force Microscope (AFM) image of InAs on GaAs in SK growth mode and figure 1.3b shows the surface energy consideration in SK mode. Typically, lattice-mismatch between InAs and GaAs is 7%. The InAs dot sizes are between 20 nm and 50 nm [29, 30]. The InAs dot densities are in range of $10^{10}$ cm$^{-2}$ and $10^{11}$ cm$^{-2}$. The QD dot diameter and density are significantly affected by the growth temperature. The optimum growth temperature for forming dislocation free dots is between 490° and 530°[31].

Figure 1.3 SK growth mode (a) Atomic Force Microscope (AFM) image of InAs on GaAs (b) surface energy consideration

Wetting layer: $\gamma_{SV} > \gamma_{EV} + \gamma_{ES}$
1.3 Motivation and Objectives

1.3.1 Broad Area Long Cavity Single Layer Quantum Dot Laser

One of the major factors that limit the maximum output power of the laser diode is the cavity length. The cavity length is limited by efficiency and heating. Possibility of fabricating long cavity requires high efficiency and excellent thermal management. To reach high efficiency and excellent heat sinking, the low threshold current density, which in turn can produce low internal optical loss, is significantly required. Thus, the low threshold current density and low internal optical loss require a significant increase in laser diode cavity size under the CW room temperature operation. In addition, the low operating current density can reduce the resistive losses.

Quantum dot active region is attracted as promising material to achieve low threshold current density and low temperature sensitivity due to low transparent carrier density \[4],[2] . Typically, the threshold current density of QW laser is around 50 A/cm\(^2\) whereas the threshold current density of 19 A/cm\(^2\) and 17 A/cm\(^2\) are reported in QD laser. Owing to discrete density of the states, QD transparency carrier density is order of magnitude lower than the planar QW active region. Furthermore, single QD active layer is very attractive for its potential for lowest threshold current density due to very low value of transparency current density. The internal optical loss of waveguide in semiconductor also limits the optical extraction efficiency, in other words the cavity length. The optical loss of the waveguide in planar QW is typically 1 cm\(^{-1}\). The optical loss of waveguide in QD may potentially be lower than in QW due to the lower transparency carrier density. The optical scattering loss can be minimized by the broad
waveguide structure. The losses in cladding layer are minimized by the careful optimization in doping level, however, sufficiency to lasing condition. For these useful properties of QD active region, the goal of this research work is the development and improvement of 1.22 μm long cavity single layer quantum dot laser diode in edge-emitting laser aiming at very low threshold current density and the very low internal loss, which allows studying characteristics of the long cavity in a few centimeter regimes.

1.3.2 Passive Mode-locked Two-section Long Cavity Quantum Dot Laser

QDs active region has several advantages and acts as a promising candidate for the mode-locked operation. The advantages are of low threshold current density, low internal loss, broad-gain spectrum, low linewidth enhancement factor (α-factor), ultrafast carrier dynamics, high gain saturation energy and low absorption saturation energy [32]. The low loss and low threshold current density reduces the noise. QD active region inherently offers higher saturation energy of gain section than the QW material due to the discrete density of the states. The broad gain spectrum is a result of a variation of the dot sizes which come from the self-assembly QDs technique. This inhomogeneous broadened gain spectrum results in a broader lasing spectrum in which locking the phases of modes can generate ultrashort pulses [33, 34]. The low linewidth enhancement factor is experimentally achieved [35, 36]. The low chirp of < 0.01 nm in a QD laser is found comparing to typical value of 0.2 nm in a QW laser [37, 38]. Therefore, closer to transform limited pulse can be achieved by using a QD gain media in the mode-locked laser. The saturation energy of absorber ($E_{sat}^a$) is proportional to the pulse duration. The larger differential
gain in QD active region comparing to QW active region can reduce the absorption saturation energy. The experiments show the saturation energy of the absorber in QD laser is 2-5 times smaller than of QW laser so the pulse duration is reduced [32]. Therefore, the unique properties of QD active region especially broad gain spectrum and fast absorption recovery time are promising for a monolithic passively mode-locking operation.

Since the processing performance in computer chip still dramatically increases, Intel and AMD have interest in the multi-core processing, which work in parallel. Consequently, the on-chip optical clock distribution inside multi-core processor is needed. Therefore, a continuous wave mode-locked laser diode plays a key role in generating a stable external clock in a repetition rate of a few GHz, average output power of more than 100 mW, and a pulse-duration of a few picoseconds. Until now, the low repetition rate below 10 GHz is very difficult to fabricate for the bulk or QW monolithic mode-locked laser whereas the QD mode-locked laser is already demonstrated at 5GHz with 8 mm cavity long [25]. Due to the cavity length limitation, the monolithic passively mode-locked laser diode with repetition rate less than 5 GHz and reasonably high peak power are challenging. Owing to the low threshold current density and low internal loss, the single QD layer laser diode in previous section has increase in the cavity length of few centimeters. Thus, subsequent work from the long cavity single QD layer laser diode to develop the two-section passively mode-locked laser diode with the repetition rate of a few GHz is the goal of the mode-locked operation in this dissertation.
1.4 Dissertation Outline

The focus of the research work is experimental demonstration of the very low threshold current density resulting in very low internal optical loss of waveguide and long cavity in single QD layer laser diode. The subsequent work aims at the two-section passively mode-locked laser diode in single InAs QD layer. Therefore, the dissertation is organized into chapter by chapter.

Chapter 2 presents how the transparency carrier density in QD active region relates to the low threshold current density, low internal loss and long cavity length is important. The difference between the QW and QD active region is discussed in term of the transparency carrier density. The physics of the efficiency and threshold current density is outlined to understand the relationships. The thermal management and packaging designs are addressed to efficiently remove heat waste from the devices. The fabrication of broad-area QD lasers for p-up and p-down mounting is detailed. Finally, the characteristics and performances of single InAs QD layer laser in CW room temperature are presented with very low current density and very low loss in a few centimeters regimes.

Chapter 3 reports the operation of two-section passively mode-locked operation in single InAs QD layer laser diode. The long cavity reduces the fundamental cavity frequency to a few GHz. The mode-locked performances and characteristics of long cavity are first demonstrated in single QD layer. These successes present the novel devices in mode-locked operation with long cavity QD laser diode.

Chapter 4 summarizes the research work in this dissertation and future direction of development and improvement in the devices to fulfill the ongoing researches in the field.
CHAPTER 2: LONG CAVITY QUANTUM DOT LASER DIODES

The major limitation of extending cavity length in the laser diode comes from the efficiency and heating. High efficiency and excellent heat sinking requires significant reduction of threshold current density of the laser diode. The quantum dot active region offers a way to achieve the low threshold current density, resulting in the low internal optical loss of waveguide, via the transparency carrier density. The broad waveguide structure also contributes to low internal optical loss of waveguide by minimizing optical scattering to interface roughness [19]. The careful optimization of sufficient doping level in cladding layers to reasonable conductivity condition can minimize the free carrier losses as well.

In the present chapter, the importance of transparency carrier density in the QD laser diode is emphasized and how it affects the internal loss and the cavity length is discussed. The comparison of quantum well and QD transparency carrier density is reviewed. The difference of transparency carrier density between single layer QD and stacked layer QDs has been discussed. The long cavity in laser diode is very important in the implementation of high power laser application. Therefore, the discussion of how to increase cavity length without degrading the wall plug efficiency is mentioned. The broad waveguide structure in the optical losses is covered. The thermal management of the lasers is outlined. The device fabrication and packaging are detailed. The device characteristics in p-up and p-down mounted devices are reported.
2.1 Importance of Transparency Carrier Density

The transparency carrier density is the fundamental limitation of the internal loss in the laser diode. In other words, the low transparency carrier density allows the low internal loss. Consequently, the low internal loss can lead to longer cavity length while keeping both maximum optical extraction efficiency and minimum electrical resistance. The transparency current density of laser diode is determined by

\[ J_n = \frac{qn_{e,tr}}{\tau} \]  

(2.1)

where q is the elementary charge, \( n_{e,tr} \) is the transparency carrier density and \( \tau \) is the radiative lifetime. The value of the transparency carrier density relies on the laser hetero-structure, the intrinsic property of the active region and the growth quality [19]. In this section, the discussion of the intrinsic property of material between quantum dot and quantum well is emphasized.
QD has a delta-function-like density of the states resulting in discrete energy levels whereas a planar quantum well has a staircase-like density of the states arriving in a continuous energy spectrum [1-4]. Figure 2.1 shows the density of the states in the planar quantum well and the quantum dot. The key difference in the density of states directly contributes to the significant reduction in the transparency current density compared to a planar quantum well.

The transparency carrier density indicates the major differences between the quantum well active material and the quantum dot active material which turn into to produce the minimum loss that can be achieved in the active region. As with the decrease in the loss, the cavity length is allowed to increase so that the threshold gain is decreased. Therefore, the additional injected number of electron-hole pair into the active region is less for the quantum dot than for the planar quantum well. The difference transparency carrier density originates from the density of the
states that must be occupied to compensate optical losses for the planar quantum well or the quantum dot. For the single planar quantum well, the transparency carrier density is defined as

\[ n_{\text{tr},w} = (\text{PlanarQuan tumWell} ) \approx \frac{4\pi m_{\text{red}}}{h^2} k_B T \]  

(2.2)

Here \( m_{\text{red}} \) is the reduced mass, \( k_B \) is Boltzmann’s constant, \( T \) is the active region temperature and \( h \) is Planck’s constant. As the temperature rises, the transparency carrier density proportionally increases, in other words the threshold current density increases, due to the thermal broadening of electrons and holes in these states. On the other hand, the transparency carrier density of the quantum dots is given by

\[ n_{\text{tr},s} (\text{QuantumDot} ) \approx n_{\text{QD}} \]  

(2.3)

Here \( n_{\text{QD}} \) is the quantum dot density which is independent of temperature. Presently our optimized quantum dot densities of \( n_{\text{QD}} \approx 5 \times 10^{10} \) cm\(^{-2}\) are obtained. As substituting the actual parameters in equation (2.2) and (2.3), the reduction in the transparency carrier density is order of magnitude lower in the quantum dot than in the planar quantum well active region. Typically, the radiative lifetimes (Einstein A coefficients) of quantum dot and planar quantum well active materials are similar. Along with the radiative lifetime, the smaller carrier densities are required to reach transparency in QD laser diode leading to a significant reduction in the threshold current density.
2.2 Optical Losses, Threshold Current Density, and Wall Plug Efficiency in Laser Diode

In this section, we will explain how the optical losses, threshold gain and wall plug efficiency are correlated. Introducing the internal optical loss of waveguide as

\[
\alpha_{\text{WG}} = \alpha_{\text{active}} + \alpha_{\text{cladding}} + \alpha_{\text{scattering}} \tag{2.4}
\]

\[
\alpha_{\text{active}} = \frac{\Gamma_{\text{act}}}{\Delta z} (\sigma_e n_{th} + \sigma_h p_{th}) \tag{2.5}
\]

\[
\alpha_{\text{cladding}} = \Gamma_n \sigma_e n_{\text{dope}} + \Gamma_p \sigma_h p_{\text{dope}} \tag{2.6}
\]

where \(\alpha_{\text{active}}\), \(\alpha_{\text{cladding}}\), \(\alpha_{\text{scattering}}\) are the active region loss, the free carrier loss in the cladding layer, and the refractive index variation scattering of the optical waveguide respectively, \(\Gamma_{\text{act}}\), \(\Gamma_n\), \(\Gamma_p\) are optical confinement factor in active region, n-cladding layer and p-cladding layer respectively, \(\Delta z\) is the thickness of gain region, \(n_{th}\) is threshold carrier density that will be discussed later, \(n_{\text{dope}}\), \(p_{\text{dope}}\) are doping carrier density in the cladding layer, \(\sigma_e\) and \(\sigma_h\) are free carrier scattering cross-sections for the electron and the hole respectively.

The internal optical loss of waveguide in equation (2.4) consists of active region loss, cladding loss and scattering loss. Active region loss and cladding loss is part of free carrier absorption mechanism due to indirect transitions of electron to electron and hole to hole with the same sub-bands. The active region loss is inherent property of its material and depends on the injected carrier density, which is required to reach the lasing threshold in other word the threshold current density. Therefore, the reduction of threshold carrier density by keeping transparency carrier density as low as possible in the active region minimizes the active region loss.
The cladding loss depends on the doping in cladding layers. The technology of precisely controlling the doping is the effective way to reduce the cladding loss. Additionally, the optimization of waveguide thickness and optical confinement factor can minimize the cladding loss. The free carrier absorption loss is a major loss in semiconductor lasers. The reduction of both the active region loss and the cladding loss allow a longer cavity length in the QD laser diode.

In semiconductor material, ionized impurities, phonons, alloy, interface roughness are four important sources of scattering due to the imperfections [39]. However, the alloy and interface roughness are only concerned in the laser diodes. The alloy source is a small compositional fluctuation in alloy semiconductors. The interface roughness source occurs because the oxygen contaminates the semiconductor materials. In the laser diode, electrons move close to a rough interface which causes the scattering. The scattering losses can be reduced by optimizing the crystal growth condition to smooth an epitaxy interface and using a broad optical waveguide.

Generally, the laser diode design is preferred by maximizing the optical confinement factor in the active region, which represents the fraction of the mode energy confined in the active region. However, the overlap of optical field into region of the waveguide and cladding also increase, in other words both the free carrier absorption and the scattering loss increase. Using the broad optical waveguide structure, the scattering loss will decrease faster with the increasing the waveguide thickness while the free carrier absorption loss as in equation (2.5) and (2.6) will decrease with decreasing the optical confinement factor [40]. In addition, the doping level in the cladding layers can be also decreased to a reasonable value for p- and n- conductivity
in order to reduce the free carrier absorption loss. Therefore, the certain waveguide thickness can compensate the free absorption loss and scattering loss along with the optimized doping level.

The threshold gain is the optical gain needed for the laser to oscillate. The gain condition is expressed as

\[ 1 - \sqrt{R_L R_B} \exp(gL) = 0 \]  

(2.7)

As a result, the optical gain coefficient \( g \) equals to the mirror loss, \( \alpha_m \). The threshold gain is also determined by

\[ g_{th} = \alpha_{WG} + \alpha_m \]  

(2.8)

where \( \alpha_{WG} \) is the internal optical loss of the waveguide due to absorption in the cladding layer and in the active region and the scattering from the heterointerface. \( \alpha_m \) is mirror loss due to the portion of light transmitted at the threshold value \( n_{th} \) since the gain is pinned at the threshold gain and the internal optical loss is ignored due to the dominance of the mirror loss. On the other hand, the threshold gain is defined as

\[ g_{th} = \frac{\Gamma}{\Delta z} \left( n_{e,th} - n_{e,tr} \right) \]  

(2.10)

where \( \Gamma \) is the optical confinement factor, \( \Delta z \) is the active layer thickness, \( g_0 \) is the gain coefficient, \( n_{e,th} \) is the threshold carrier density, \( n_{e,tr} \) is the transparency carrier density; therefore the threshold current density can be related to the threshold carrier density as
\[ J_{th} = \frac{q}{\tau(n_{th})} n_{z,w} + \frac{q}{\tau(n_{th})} \frac{\Delta z}{g_s \Gamma L} \ln \left( \frac{1}{\sqrt{R_s R_p}} \right) \]  

(2.11)

\[ \tau(n_{th}) = \frac{1}{A_n + B n \times C n^2} \]  

(2.12)

where \( \tau(n_{th}) \) is radiative lifetime, \( A n_{nr} \) is due to nonradiative processes, \( B n^2 \) is due to spontaneous radiative recombination rate, and \( C n^3 \) is due to nonradiative Auger recombinations.

The difference in the threshold current density and transparency current density is the mirror loss since the negligible losses in waveguide is considered due to above the threshold condition. It is clearly seen that a decrease in the transparency carrier density and an increase in cavity length lead to a decrease in threshold current density. The quantum dot material has an order of magnitude of transparency density lower than the planar quantum well as we discussed in section 2.1. In addition, the value of radiative lifetimes \( \tau(n_{th}) \) of quantum dot is similar to the planar quantum well. Therefore, the threshold current density of quantum dot material can be lower than the planar quantum well.

The central goal of the laser diode performance is the wall plug efficiency. The wall plug efficiency is determined by

\[ \eta_{WP} = \frac{P_r}{P} = \eta \eta_{opt} \eta_{elec} \]  

(2.13)

In which \( \eta \), \( \eta_{opt} \), and \( \eta_{elec} \) are the internal injection efficiency, the optical extraction efficiency, and the electrical efficiency respectively. The internal injection efficiency indicates how effectively the active region captures the injected carriers to radiatively recombine. The optical extraction efficiency describes how well the photon travels through the laser cavity and the facets which escape as useful output power. The electrical efficiency tells how effectively the
injected current is used to induce a population inversion and pump the photon to radiatively recombine.

The other expression of the wall plug efficiency is given by

$$\eta_{wp} = \eta_i \frac{(h\nu_{ph}/q) J - J_{th}}{J \rho_s + V_F} \frac{\ln(1/R_F)}{J} + \frac{\ln(1/R_B)}{J} + \frac{\alpha_i L}{2}$$

where $L$ is the laser cavity length, $W$ is the stripe width, $R_F$ is the front mirror reflectivity, $R_B$ is the back mirror reflectivity, $h\nu_{ph}/q$ is the voltage related to the radiated photon energy, $V_F$ is the forward voltage at the p-n junction active region with $V_F \geq h\nu_{ph}/q$, $I$ is the electrical current, $I_{th}$ is the threshold current, $\rho_s$ is the electrical contact sheet resistance, and $\alpha_i$ is the internal optical loss of the waveguide.

The maximum wall plug efficiency is expressed by

$$\eta_{wp,\text{max}} = \eta_i \frac{\ln(1/R_F)}{2\alpha_i L + \ln(1/R_F R_B)} \frac{h\nu_{ph}}{q \rho_s J_{th}} \left(1 + \frac{V_F}{\rho_s J_{th}}\right)^2$$

The output power is given by

$$P_o = \eta_i \times \frac{\ln\left(\frac{1}{R_F}\right)}{2\alpha_i L + \ln\left(\frac{1}{R_F R_B}\right)} \times \frac{h\nu_{ph} (J - J_{th})WL}{q}$$

It obviously shows that wall-plug efficiency depends on both the operating power level and the intrinsic device parameters. The resistive losses $J \rho_s$, and waveguide losses $2\alpha_i L$,
fundamentally limited by threshold current density $J_{th}$, set the limit on the wall-plug efficiency $\eta_{wp}$. In equation (2.16) the level of output power depends proportionally on the cavity length. On the other hand, there is a decrease in wall-plug efficiency associated with an increase in cavity length [41]. However, decrease in $\alpha_i$ compensates the longer cavity length without degrading $\eta_{wp}$. The electrical losses can actually be related to the material conductivities and the operating current density. Therefore, the advantage of the low threshold current density is the ability to reach high efficiency at low current density, thus reducing the resistive losses, which is $I^2R$.

2.3 Single Quantum Dot Active Layer and Long Cavity

In previous section, we discuss the relationship between the transparency carrier density and the threshold current density in term of the active region material and the cavity length. Now, we focus on the transparency carrier density between the stacked quantum dot and the single layer quantum dot active region. Fundamentally, the transparency carrier density of stacked quantum dot active region is the product of surface quantum dot density and the numbers of active region layer. In other words, the single QD active layer as shown in figure 2.2 has lower transparency carrier density than stacked QD active layer due to lower quantum dot surface density. Increase in number of quantum dot layers also leads to the degradation of threshold current density due to point defects caused by too high strain accumulated in the active region. The benefit of the single QD layer active region, however, is clear from the very low internal optical loss of the waveguide coming from the fundamental low transparency carrier density as long as the surface density of QDs is enough to lasing condition.
Introducing the series resistance is expressed by

\[ R_s = \frac{\rho_s}{WL} \quad (2.17) \]

As shown in (2.15), the increase in cavity length is beneficial because of the low internal optical loss of the waveguide and the low operating current density. Therefore, the optimization in the internal loss of the waveguide and the cavity length is very important to achieve maximum wall plug efficiency and is possible with a few centimeters of cavity length. Beside the reduction in threshold gain, the longer cavity length can simultaneously reduce the series resistance as shown in (2.17). The high electrical efficiency and reliability is improved due to the low threshold current density in other word operating current density. As a result, the long cavity is important for broad area laser diode in the high power and high quality factor applications.
2.4 Device Fabrication

The QD p-n heterostructures are grown on an n-type GaAs substrate using molecular beam epitaxy in Applied Epi Gen III MBE system. Figure 2.3 shows a schematic of QD broad area laser diode. The p- and n-cladding layer is $\text{Al}_{0.85}\text{Ga}_{0.15}\text{As}$. The top p-cladding is doped with Be at $5 \times 10^{16}$ cm$^{-3}$. The bottom n-cladding is doped with Si at $5 \times 10^{16}$ cm$^{-3}$. The waveguide layer is $\text{Al}_{0.1}\text{Ga}_{0.9}\text{As}$ and the width is 3000 Å. The active region consists of a single layer of InAs QDs that operates at the emission wavelength of 1.22 μm. The QD wafers are processed in the broad area laser diodes by using the existing III-V material processing technology. They are fabricated having stripe width of 120 μm and cavity lengths that vary between 1 and 2 cm. The p- and n-ohmic contacts are formed for carrier injection. The choices of stripe width, ridge height and metallization are very important for device performance.

The processing starts by consequently cleaning a surface by Acetone, Isopropyl alcohol, and DI water to remove organic residues and dusts. Then the wafer is heated in the oven for 10
minutes at 90 °C and cooled down for 5 minutes to the room-temperature. A layer thickness of
1.4 µm of positive photo-resist of AZ 5214 from AZ Electronics Material is spun on the wafer at
4000 rpm for 40 sec and then baked inside an oven for 15 minutes at 90°C. The stripe widths and
lengths are patterned by contact UV lithography and developed by AZ 726 MIF developer for 65
sec. For the p-metallization, the device is plunged into the solution HCl:H2O (1:1) to remove a
native oxide layer and followed by e-beam evaporating the p-contact metallization of Titanium
(Ti, 300A°)/ Platinum (Pt, 200A°)/ Gold (Au, 500A°)/ Silver (Ag, 2500A°)/ Gold (Au, 500A°).
Ti layer is used as an adhesion and Pt layer is used as diffusion barrier to prevent the Au
diffusing into the semiconductor material at high temperature annealing. Au layer provides the
electrical contact and oxidized prevention layer [42]. The thick Ag is used for better thermal
conductivity and stability in high current operation. The metal lift-off is then processed by
immersing the wafer into acetone. The p-contact is used as the etching mask to define the ridge
waveguides. The nonselective etchant of H2SO4:H2O2:H2O at the ratio of 1:8:80 for a minute is
used as wet-etching in this work. The etch rate of this solution is approximately 85 A°-110 A°/
sec on the GaAs and AlGaAs at room-temperature. The ridge waveguide is etched for 0.5-0.6
µm. Next, the positive photo-resist is spun and baked for 30 minutes at 90° to protect the p-side
during the n-side etching. To decrease the device resistivity, the n-substrate is etched by
H2SO4:H2O2:H2O at the ratio of 1:8:80 for 20 minutes. Then, the photo-resist is removed by
plunging into the acetone. The device is immersed into the HCl: H2O solution at the ratio of 1:1
for 5 sec before n-contact. The n-contact metallization of Germanium (Ge, 200A°)/ Gold (Au,
1800A°) is deposited. The Ge layer allows diffusion of alloyed contact. Finally, the Rapid
Thermal Annealing is used to form contact alloying for 30 sec at 400 °C. The Ge diffuses into
GaAs and provides a heavily n⁺ dopant during the annealing process [43].
In case of p-down mounted laser diode, the dry-etch B-staged bisbenzocyclobutene (BCB) monomers from DOW chemical company is used as insulating layer. It is deposited to confine current flow. The processed device is coated by the adhesion promoter for 40 sec at 4000 rpm and then followed by the BCB for 40 sec at 4000 rpm. The n-substrate is cleaned by a backside solvent (T1100) to remove any contamination after coating and then quickly dried by nitrogen gun. The polymer films are thermally cured at 250°C inside a convection oven with the N₂ environment for more than one hour. The purpose of the thermal curing is to ensure resistance to subsequent processing operation. The multi-step heating sequence is programmed and applied to allow enough time for the convection oven to purge with nitrogen. BCB layer on the stripe is removed by a reactive ion etcher (RIE). The p-metal acts as a mask. The plasmas gas mixture of CF₄/O₂ at the ratio of (5:10) is used at the etching rate of 150 nm/min with RF power of 100W, DC of 273 V, and 50 mTorr [44]. The etching time varies due to nonuniform layer thickness of BCB. Therefore, it depends on the step-height of the ridge which indicates the BCB is completely removed from the stripe. Additionally, the device yields are small percentage for the dry-etch BCB. Hence, the photo-BCB is considered to overcome this problem in the future work. Finally, the second p-contact metallization of Titanium (Ti, 300Å)/ Platinum (Pt, 200Å)/ Gold (Au, 500Å)/ Silver (Ag, 2500Å)/ Gold (Au, 500Å) is deposited in order to have the ridge higher than the planar BCB.
2.5 Packaging and Thermal Management

The laser diode typically generate the large heat flux density at least in kW/cm², which can degrade the threshold current, slope efficiency, wavelength, output power, and reliability. The increase in temperature shifts the lasing wavelength and mode such as ~ 0.32 nm/K for 980 nm pump laser [45]. The thermal rollover limits the maximum optical output power and the output beam quality. The causes of thermal rollover are temperature sensitivity of the threshold current density and excessive heat fluxes in active region. Therefore, the thermal management is very important to its performance and reliability. Understanding of the mechanism of thermal behavior is crucial to the devices. The heat sources in laser diodes include nonradiative recombination, reabsorption of radiation, Joule heat, and thermoelectric effects [46]. However, Joule heat is a key parameter in this section. The Joule heat is proportional to the thermal resistance ($R_{th}$). The temperature ($\Delta T$) difference between heat source and heat sink is expressed by

$$\Delta T = R_{th} P_{th}$$  \hspace{1cm} (2.18)

$$P_{th} = P_{elec} - P_{opt}$$  \hspace{1cm} (2.19)

where $P_{th}$, $P_{elec}$, $P_{opt}$ are thermal power, electrical power, and optical power respectively. The $R_{th}$ depends on the epitaxial structure of laser. Generally, the GaAs n-substrate contributes the largest thermal resistance due to the low thermal conductivity (45 W/cm K), and large thickness. Therefore, the thinned GaAs thickness can decrease the thermal resistance and the junction temperature [47], for example, the GaAs substrate is chemically etched away as discussed in section 2.4. In addition, the p-down mounted devices is useful to reduce $R_{th}$ since the active
region is normally placed much closer the p-side surface than n-side surface [48]. The generation of waste heat from active region naturally dissipates downward into p-side surface due to lower temperature, higher thermal conductivity and closer contact of the heatsink. Later, the waste heat is spread through the p-metal contact, solder, and heatsink.

Previously, the thermal aspects of packaging are discussed. An excellent thermal contact for laser mounting requires a good mechanical contact, which is formed by a solder joint. The mechanical aspects imply the right selection of solder, thermal conductivity and coefficient of thermal expansion (CTE) in a heatsink. There are two main solders: (a) Indium (In) soft solder (b) Gold-Tin (AuSn) hard solder. In solder is very soft, wettability, and ductile whereas AuSn eutectic alloy is relatively stiff and high yield strength [49]. In solder can compensate stress caused by the mismatch between laser diode and the copper heatsink. On the other hand, AuSn has a good thermal fatigue giving good reliability. Typically, the heatsink CTE in range of 6 to 9 ppm/K is acceptable for matching to GaAs [50]. Therefore, the beryllium oxide (BeO) heatsink is used to match CTE between laser diode and heatsink in which CTE of BeO is 8-8.5 ppm/K and of GaAs is 5.8 ppm/K to resolve the stress problem[50]. In solder from Indium corporation has a melting point at 157 ºC, however, AuSn (80:20) solder from Applied Thin-Film Products has a melting point at 280 ºC. The experiments of both solders are evaluated. The results shows In solder severely contaminates both facets by migrating the residues from the solder contact. Furthermore, a non-parallel between laser diode and heatsink occurs due to the softness. The voids and bubbles, causing a local heating, are observed in the experiments of In solder usage. On the other hand, the AuSn solder minimizes these problems.
The heatsink consists of BeO as substrate material (0.635 mm), TiW (400-800 Å)/Au (3 µm) and pattern of predeposited AuSn (4-6 µm) at the center as shown in figure 2.4. The thermal conductivity of BeO is 280 W/cm K. The heatsink has a 2 cm long and 1 cm wide. Figure 2.5 shows the schematic of the packaging of the long cavity QD laser diode. The AuSn solder is used to mount between laser diode chip and BeO heatsink. The large force of 3 kg is applied to effectively bond the large device on the BeO heatsink. The careful alignment between the facet of laser and edge of heatsink is taken in order to have a good thermal contact. The In solder is
used to mount between BeO and the copper block since the mechanical support for clamping on the optical table is needed for the measurement setup.

2.6 Device Characteristics

A number of devices have been designed, grown, fabricated and measured in order to understand the fundamental physics of threshold current density. The optimized performance of p-up and p-down mounted devices are selectively analyzed and presented. The device characterization in this work includes the photoluminescence (PL), the electroluminescence (EL), the injected current-voltage (I-V), the light output – injected current (L-I), and the inverse of slope efficiency- cavity length.

The photoluminescence is characterized to understand the dot quality. He-Ne laser is used to excite electrons into the conduction band, which generates the spontaneous emission of light. The PL signal is collected in real time by the spectrometer and then detected by germanium photo-detector. The liquid nitrogen is used to cool the sample down to very low temperature at 77 K. The PL spectrum provides the useful information of the available energy levels to electrons. The intensity of the PL signal gives the information of the relative rate of radiative and nonradiative recombination [51]. The PL peak position can be used to evaluate the composition of QDs and other layers. In addition, the PL linewidth provides the measurement of inhomogeneous broadening. Unlike the PL, in EL, electrical excitation of the laser diode is performed to generate the photons. The lasing signal is obtained above threshold current density when the EL linewidth is significantly narrowed.
I-V characterization is used to inspect the current leakage, short circuiting, and the turn-on voltage of the device. I-V characterization is performed by a curve tracer. The forward turn on voltage is approximately 0.75 volts for InAs quantum dot laser diode. The threshold current density and slope efficiency are extracted from the L-I. Finally, the internal optical loss and internal injection efficiency is also extracted from the plot of inverse of slope efficiency and the cavity length. These techniques are used to give an important feedback of the device performances to laser designer and MBE crystal grower.

2.6.1 P-up mounted Device Characteristics

The processed samples have been cleaved into lasers of different cavity lengths of either 1 or 2 cm. The lasers are tested with the facets as cleaved and mounting p-side up on a copper heatsink. The gallium-indium liquid is used as electrically conductive material among device, copper block, and the probe tip. Bonding material is not applied between the substrate and laser diode. The waste heat is removed via the contact between the stripe and probe tip. The probe tip was coated with the gold in order to have a good contact or low resistance.
Figure 2.6 Photoluminescence spectra of InAs QDs at 300 K and 77 K

Figure 2.6 shows photoluminescence spectra of InAs QDs at 300 K and 77 K. The full-width-at-half-maximum (FWHM) of 44 meV is peaked at 1.208 µm corresponding to the QD ground-state transitions at the room-temperature. There is a shoulder indicative of a blue-shifted peak by 73 meV on the high energy side. The PL peak shifts to the shorter wavelength as the temperature decreases. Therefore, the ground state FWHM of 49 meV is peaked at 1.122 µm at 77 K. In a bulk semiconductor material or quantum well, the PL spectra is typically broadened as increasing temperature. However, the behavior of QD PL-spectra is reversed. The slightly narrowed PL-spectra at room-temperature is explained by partial thermalization of charge carriers within the QD ensemble. As the temperature increases, carriers are thermally excited out of the small QDs into wetting layer. By the time, some carriers will probably relax again into
larger dots with low-localized energy states. Some carriers in wetting layer can be irreversibly lost either through nonradiative recombination or interband radiative recombination [52]. As a result of this, the FWHM is narrowed when the temperature is increased [53].

Figure 2.7 Light versus current curve for p-up mounted QD laser diode at room-temperature for continuous wave operation of 1.6 cm cavity length and 120 µm stripe width used as cleaved. Inset: lasing spectra for 12.5 A/cm² at 1.22 µm

Figure 2.7 shows L-I curve for p-up mounted QD laser diode at room-temperature for continuous wave operation of 1.6 cm cavity length and 120 µm stripe width used as cleaved. The inset in Figure 2.7 shows the lasing spectra for 12.5 A/cm² at 1.22 µm. The L-I curve clearly shows the threshold current of 0.28 A corresponding to a lasing threshold current density of 11.7 A/cm²[54]. The maximum slop efficiency of more than 40 % is extracted from L-I curve. The maximum room-temperature continuous wave output power is over 0.42 W.
Figure 2.8 Electroluminescence spectra at room-temperature for different injected current density in below, near, and above threshold current.

Figure 2.8 shows the electroluminescence spectra at room-temperature for injected current density of 2.08, 8.33, 10.42, and 12.50 A/cm² with cavity length of 2 cm and stripe width of 120 µm p-up mounted on a copper heatsink. The evolution of spectral narrowing is obviously observed from spontaneous emission to lasing stimulated emission. The central wavelength of 1.22 µm is observed in lasing spectra and FWHM of this lasing is 1.7 meV at injected current density of 12.5 A/cm².
Figure 2.9 shows the FWHM of emission spectral versus current density. Due to preferential emission coming from the peak of the QD ensemble emission, the linewidth is initially reduced at injected current density from 2 A/cm$^2$ to 5 A/cm$^2$. The light output spectrum grows and narrows simultaneously as an increase in current injection. For current density greater than 6 A/cm$^2$, the spectral narrowing is due to stimulated emission. The linewidth is rapidly reduced in level of a few meV for current density greater 10A/cm$^2$. The rapid reduction indicates the lasing stimulated emission. The onset of lasing occurs at 11.7 A/cm$^2$. Therefore, in figure 2.9, the spectral narrowing indicates the transparency current density is less than 6 A/cm$^2$ under CW room-temperature.
2.6.2 P-down mounted Device Characteristics

In previous section, the very low threshold current density is obtained and other aspects of laser characteristics are studied. Now, the p-down mounted devices are interested for further study that how the threshold current density will change. The same wafer as the p-up laser diode is fabricated. The BCB is deposited on the wafer and acts as an insulting layer and confinement for the mounting purpose as mentioning in the section 2.4. All of the lasers are tested with the facets as cleaved and mounting p-side down on BeO heat sinks.
First, the sample is cleaved into 1 cm cavity length and 120 µm stripe width. Figure 2.10 shows L-I curve for p-down mounted QD laser diode on BeO heatsink at room-temperature for continuous wave operation. The threshold current is observed at 0.16 A corresponding to 13.3 A/cm². The maximum slope efficiency of 0.38 W/A is extracted from the curve. Slightly over 1 W output power for both facets is shown.
As shown in Figure 2.11, the single layer QD laser diodes with cavity length of 1.6 cm have threshold current density as low as 10.4 A/cm² for CW room-temperature operation, with light output of more than 2 W (both facets). Single layer QD laser diodes with the same stripe width and 2 cm long cavities have threshold current densities slightly lower at 10 A/cm². The slope efficiency of 0.356 W/A is obtained for the 1.6 cm length.
Figure 2.12 Lasing spectra at 1.22µm at 12.5 A/cm$^2$ of 1.6 cm cavity length and 120 µm stripe width of QD laser diode under CW room-temperature operation and p-down mounted on BeO heatsink.

Figure 2.12 shows the lasing spectra at 1.22µm at 12.5 A/cm$^2$ of 1.6 cm cavity length and 120 µm stripe width of QD laser diode under CW room-temperature operation and p-down mounted on BeO heatsink.
Figure 2.13 Light versus current curve for p-down mounted QD laser diode on BeO heatsink at room-temperature for continuous wave operation of 1.9 cm cavity length and 120 µm stripe width used as cleaved.

Figure 2.13 shows L-I curve for p-down mounted QD laser diode on BeO heatsink at room-temperature for continuous wave operation of 1.9 cm cavity length and 120 µm stripe width used as cleaved. The threshold current density of 8.8 A/cm² is reported[55]. To our knowledge, the threshold current density is the lowest ever reported in laser diode. The maximum slope efficiency of 1.9 cm cavity length is 0.326 W/A which is lower than 0.38 W/A of 1 cm cavity length and 0.356 W/A of 1.6 cavity length. The maximum output power is over 0.7 W. The output power of 1.9 cm cavity length is lowest among the other two cavity lengths. The reason of less output power can be the heatsinking in the longer cavity.
The different cavity lengths are characterized and evaluated the efficiency dependence on the cavity length. Figure 2.14 shows a plot of the inverse efficiency vs. length for three different lengths of cavities. From the change in slope efficiency with cavity length, an internal optical loss of $\sim 0.25 \text{ cm}^{-1}$ and an injection efficiency of $\sim 47\%$ are extracted. So far low injection efficiency values have been a characteristic trait of most QD laser diodes. In section 2.2, the reduction in active region loss and cladding layer loss allows the longer cavity length. Therefore, low internal optical loss of waveguide depends on the cavity length. In case of optimized doping and waveguide, the internal optical loss depends on the free carrier in QD active region only. In this case, the free carrier density of threshold current density of 8.8 A/cm$^2$ for 1.9 cm cavity length is less than of 13.3 A/cm$^2$ for 1 cm cavity length due to free carrier density –threshold current density dependence. Therefore, the actual relationship among the internal loss of waveguide, cavity length, slope efficiency, and injection efficiency in the quantum dot laser diode is more complicated than in the planar quantum well laser diode in which the internal loss
is independent of the geometrical properties of laser diode, such as the cavity length or the stripe width and the injection efficiency is close to 100%.

2.7 Summary

The importance of the transparency carrier density has been discussed in this chapter. The interdependence among transparency carrier density, optical losses, threshold current density, cavity length and wall plug efficiency has been well understood. The careful optimization of growth condition and broad waveguide design may contribute to the low loss in cladding and scattering of laser diode. Due to the material property, the single QD layer active region can have the lowest transparency density carrier, which gives the low loss in active region. Therefore, the threshold current density of single QD layer laser can possibly be the lowest. For high current density application, the thermal management of the active region has been realized by mounting p-side down which improves the laser performance. After considering the optimized parameters, using a single QD layer active region, the p-up mounted laser diode shows the CW performance of the threshold current density of 11.7 A/cm² in room-temperature. For the p-down mounted laser diode, we report what is to our knowledge the lowest threshold current density of 8.8 A/cm² that has ever been achieved in a room-temperature laser diode. We also report the internal loss of ~0.25 cm⁻¹, which is also the lowest ever reported for room-temperature CW operation of a laser diode. The low internal optical loss of the waveguide is closely related to the low threshold current density due to the low free carrier scattering loss within the waveguide.
CHAPTER 3: PASSIVE MODE-LOCKING OF TWO-SECTION LONG CAVITY INAS QUANTUM DOT LASERS

The unique characteristics, such as low threshold current density, low internal loss, low absorption saturation energy, high gain saturation energy, and ultrafast carrier dynamics, of single QD layer and laser diode long cavity in chapter 2 are potentially promising for the monolithic mode-locked laser. The difficulty of fabrication of long cavity length in two-section passively mode-locked laser diode is achieved by the low threshold current density and low loss laser diode, which also enhances noise [56]. Relatively high peak power with a low repetition rate that is of the order of a few GHz for these two-section passively mode-locked QD laser diodes, which plays a key role as a source for generating a stable external clock inside a multicore processor.

In the present chapter, the benefit of the low loss design and long cavity by using the single layer QD is implemented into the two-section passively mode-locked laser diode. The dynamics of gain and absorption in pulse shaping are covered. The stability parameter of passive mode-locking is explained. The limitation of average output power in mode-locked laser is discussed. The device fabrication is detailed. In device characteristic section, the stable optical pulse train in a 40 µm wide stripe and 1.1 cm cavity length with a repetition rate of 3.75 GHz is reported through the passive mode-locked onto the monolithic two-section device fabricated from this single QD layer laser.
3.1 Passive Mode Locking

Mode-locking technique is usually used to generate coherent ultrashort pulse from resonant response of laser cavity. In mode-locking, loss or phase element is implemented to lock the longitudinal modes results in oscillations at a pulse-train repetition frequency. There are two commonly used mode-locking techniques, active and passive mode-locking. The active mode-locking is modulated by the external signal such as the electro-optic effect while the passive mode-locking is optically modulated by using the nonlinear properties of material such as a saturable absorber (SA). The passive mode-locking, which gives the shortest pulse due to no modulation of radio frequency (RF) source, is mainly emphasized in this dissertation.

3.1.1 Principles of Passive Mode-Locked Two-Section Laser Diode Operation

The passive two-section mode-locked laser diode consists of a gain section and a saturation absorber section. The gain section is generally injected by a constant forward current in order to produce a gain to lasing. Saturation absorber section is supplied by a dc reverse bias voltage in order to decrease the absorber recovery time. The SA section is a key element due to nonlinear properties of material which provides the self-starting mode-locking and shortening mechanisms for the pulses. The semiconductor material is considered as a slow saturable absorber. The slow saturable absorber requires the following properties[57]:
(1) The absorption recovery time ($\tau_a$) is much longer than the pulse width ($\Delta\tau$) [58].

(2) The saturation energy of both gain and SA must be low to allow two medium to be saturated by the laser pulse.

(3) The saturation energy of gain section ($E_{g\text{sat}}^s$) is much higher than the saturation energy of absorber section ($E_{a\text{sat}}^s$) [57] where the saturation energy of gain and absorber are defined by

$$E_{g\text{sat}}^s = \frac{h \nu}{d g / dn} \sigma_g$$

$$E_{a\text{sat}}^s = \frac{h \nu}{d a / dn} \sigma_a$$

where $E_{g\text{sat}}^s$, $E_{a\text{sat}}^s$ are the saturation energy of gain and the saturation energy of absorber respectively, $h$ is the Planck’s constant, $\nu$ is the optical frequency, $d g / dn$, $d a / dn$ are the material differential gain in the gain section and in the SA section. $\sigma_g$, $\sigma_a$ are the mode cross-section area in gain section and in SA section respectively. Normally, $\sigma_g$ and $\sigma_a$ are the same for the two-section passively mode-locked laser [58].
The dynamics of absorption and gain in pulse shaping are important. Figure 3.1 shows the gain and loss dynamics and the optical output. Before the incoming of the optical pulse, the unsaturated loss is higher than the gain at steady state as shown in figure 3.1. Therefore, the leading edge of the pulse experiences a net loss. After the optical pulse passes through the SA, the loss saturates faster than the gain so that a net gain window begins. The saturated loss must recover to unsaturated loss by spontaneous decay [60]. Therefore, the trailing edge is attenuated. During the same time interval, the trailing edge experiences a net loss again when the gain becomes saturated below the unsaturated loss and recovers by pumping the active region. The
process of these pulses shortening by the saturable absorption mechanism repeats every passage of the pulse through each round trip in the cavity. Until it reaches the steady state, the pulse shortening mechanism and the pulse broadening are balanced by the finite-gain bandwidth and the passively mode-locked laser generates a train of mode-locked pulse. For pulse shortening, QD gain material has an advantage of shorter absorption recovery time than QW material in the passively mode-locked operation. In other word, the QD gain material produces a shorter pulse.

3.1.2 Condition for Stable Mode-Locking

An increase in injected current into gain section causes the pulse broadening whereas the increases in reverse bias into SA section affects the pulse shortening. Stability of mode-locking depends on the balance between pulse shortening and pulse broadening [58]. The stability parameter ($s$) of mode-locking operation is expressed by

$$ s = \frac{E_a^{sat}}{E_{sat}} = \frac{\frac{h\nu}{da/dn}}{\frac{h\nu}{dg/dn}} = \frac{da/dn}{dg/dn} > 1 \quad (3.3) $$

Stability is increased by changing the ratio of $\frac{da/dn}{dg/dn}$ to a high value[61, 62]. Owing to the delta-function-like density of the states, the differential gain of the QD active region decreases with an increase in carrier density. Therefore, $E_a^{sat}$ is higher than $E_{sat}$ in QD active region due to the higher carrier density in the gain section. The QD active region has a good stability for generating mode-locked pulses.
3.1.3 Pulse Energy, Peak Power and Pulse Duration

Typically, the output power in mode-locking operation is lower than in the continuous wave operation due to the pulse energy. The saturation energy of gain section limits the pulse energy in passively mode-locked laser [63]. The increase in the saturation energy of gain results in the increase in pulse energy. Inherently, QD active region offers higher saturation energy of gain than the QW material due to the density of the states. Thus, QD active region has potentially higher pulse energy.

In the device characteristics, the pulse energy, the fundamental cavity frequency, and the peak output power is calculated. Therefore, the basic equations are provided for a convenience. The pulse energy from mode-locked laser is given by

\[
E = \frac{P_{\text{avg}}}{f_{\text{ML}}} \tag{3.6}
\]

\[
f_{\text{ML}} = \frac{c}{2 n_g L} \tag{3.7}
\]

where \(P_{\text{avg}}\) is an average output power, \(f_{\text{ML}}\) is the fundamental cavity frequency, \(n_g\) is the group velocity index, \(L\) is the cavity length and \(c\) is the light velocity. The peak power is related to the pulse energy by

\[
P_{\text{peak}} = \frac{E}{\Delta \tau} \tag{3.8}
\]

\[
\Delta \tau_a = 1.414 \Delta \tau \tag{3.9}
\]

where \(P_{\text{peak}}\) is the peak output power and \(\Delta \tau_a, \Delta \tau\) are the pulse duration from measurement and the pulse duration from assuming Gaussian pulse shape. Generally, the pulse duration is shortened by the low saturation energy of absorber section in QDs [64]. Saturation of QD
absorption is responsible to filling of ground state in QDs and depends on surface density of QDs, reverse bias, and inhomogeneous broadening. Experimentally, the saturation energy of the absorber in QD is 2-5 times smaller than the saturation energy of the absorber in QW [32]. Furthermore, the high reverse bias is also used to shorten the pulse duration and simultaneously reduces the average output power, which is attributed to electroabsorption [65]. High average output power can be increased by an increase in injected current due to higher saturation energy of gain section, however, the pulse duration can be broader [25]. The tradeoff between output power and pulse duration is unavoidably to achieve high output power and Fourier-limited short-pulse.

3.2 Device Fabrication

Mode-locking is studied on a different single QD layer laser structure which is used in the chapter 2. The QD wafer is grown on a (001) n⁺- GaAs substrate by Applied Epi Gen III MBE system. The two-section QD laser is fabricated by using the same processing steps in the broad area laser diode in chapter 2. To confine the injection current, a planarization of BCB is applied on the wafer.
Figure 3.2 shows the schematic of a two-section passively mode-locked QD laser diode. The devices have gain section and saturable absorber (SA) section with a 50 µm gap on the p-side surface. The two-section QD lasers have stripe widths of 40 µm and 10 µm, and the length of the gain section and saturable absorber section are 1.1cm and 1mm, respectively. No high reflection and antireflection coating are applied to the device. The laser is mounted p-side up on a copper block. The gallium-indium eutectic is used to conduct the current.
3.3 Device Characteristics

The threshold current density of these broad-area laser diodes is in the range of 20-33 A/cm² for the 120 µm stripe width and 1-cm cavity long under the CW room-temperature. The same wafer is used to fabricate the two-section passively mode-locked QD laser diodes. The laser characterization in this section consists of the light output-injected current (L-I), optical spectrum, radio frequency (RF) spectrum, sampling signal, and second-harmonic-generation (SHG) autocorrelation signal.

A dc current source is applied on the gain section to drive the device to lasing condition and a dc voltage source gives a reverse bias voltage to the absorber section to control the absorption loss and carrier sweep-out characteristics. The L-I curve is already discussed in the chapter 2. For optical spectrum, the light output is coupled into a single mode fiber (SMF) and then is measured by optical spectrum analyzer with 0.01 nm resolution. To verify the onset of mode-locked operation, RF spectrum analyzer is coupled with a 14 GHz bandwidth photodetector. The optical pulse train is measured by a digital high speed sampling oscilloscope. The time resolved optical pulse width measurements are obtained by using SHG background – free intensity autocorrelation technique by Femtochrome, Inc.
Figure 3.3 shows the light output versus injection current of two-section passively mode-locked QD laser diode without connecting a saturable absorber. The lasing threshold current is 230 A corresponding to 18 A/cm$^2$. For mode-locking, injected current of 360 A along with reverse bias of 13 V is applied. The average output power is 3.3 mW.
Stable passive mode-locking is obtained at dc currents of 360 mA with reverse bias of ~13 V. Figure 3.4 shows ground state mode locked optical spectrum with the 3-dB spectral bandwidth around the peak wavelength is 1.5 nm. The center of mode-locked spectra is red-shifted. The shift is possibly caused by self-phase modulation (SPM).
Mode-locked quality pulse with the lowest noise sidebands is obtained with injection current of 360 mA and reverse bias of 13 V. Figure 3.5 (a) shows the RF spectrum of wide span up to 20 GHz and figure 3.5 (b) shows the fundamental cavity frequency of 3.75 GHz with cavity length of 1 cm and SA length of 0.1 cm.
As shown in figure 3.6, sampling trace of optical pulse trains with the periodic time of 264 ps corresponding to a 3.75 GHz repetition rate is in an agreement with the RF spectrum of fundamental cavity frequency with injection current of 360 mA and reverse bias of 13 V.
Figure 3.7 shows the autocorrelation signal from ground state transition with initial pulse width is 31 ps by assuming a Gaussian pulse shape (22 ps) with a time-bandwidth-product of 6.15 under injection current of 360 mA and reverse bias of 13 V. Based on the 3-dB spectral bandwidth of 1.5 nm, the time-bandwidth-product is 6.15, which implies a highly chirped pulse. Due to long cavity length, group-velocity dispersion (GVD) might broaden the pulse duration and results in a chirped pulse [66]. The peak output power is 40 mW with pulse duration of 22 ps.
Preliminary measurements of the radiation pattern indicate that the 40 µm and 10 µm wide mode locked laser operates with the far-field dominated by a single narrow angle intensity spot centered at 0° from the facet. Figure 3.8 shows the multi-mode beam profiles in (a) 40µm stripe width and (b) 10µm stripe width at the injected current of 360 mA.

3.4 Summary
The dynamics of gain and absorption mechanisms in pulse shaping are detailed. The stability of mode-locking requires the saturation energy of the gain section higher than the saturation energy of the absorber. Due to discrete density of the states, QD active region has higher saturation energy of the gain section and lower saturation energy of the absorber section than the QW active region. Therefore, QD active region can potentially produce higher output power and shorter the pulse duration. The difficulty of fabricating long cavity in two-section passively mode-locked device is achieved by using QD active region due to the low threshold current density. The 1.1-cm cavity long with a 40 µm stripe width in single QD layer laser fabricated into two-section passively mode-locked laser is demonstrated at a 3.75 GHz mode locked repetition rate. The relatively wide pulse duration of 22 ps assuming a Gaussian pulse shape and large time-bandwidth-product of 6.15 may be caused by self-phase-modulation in the gain section and by GVD due to long cavity. Additionally, the low threshold current density and the low internal optical loss of the waveguide in the single QD layer reduce noise in the mode-locked laser diode. These preliminary data present the novel devices in mode-locked operation with long cavity QD laser diode at a few GHz repetition rate.
CHAPTER 4: SUMMARY AND FUTURE WORK

4.1 Summary

The goal of this dissertation is aimed at the development and understanding of the long cavity single QD layer laser diode with very low threshold current density and very low internal optical loss in the continuous wave and passively mode-locked operations.

The fundamental limit of making the long cavity laser diode is the optical extraction efficiency and waste heat generated from the device. The low threshold current density is the way to overcome efficiency and heating. Since the threshold current density proportionally relates to the transparency carrier current, QD active region has a lowest transparency carrier density, thus lowest threshold current density. Moreover, the single QD layer active region has less point defect caused by too high strain than the stacked QD layer. Consequently, the transparency carrier density in single QD layer is lower. Owing to the optical extraction loss, the increase in cavity length also reduces the threshold current density. In order to increase the cavity length, the low internal optical loss is achieved by minimizing the doping level in cladding layer for the cladding loss and using broad waveguide structure for the scattering loss. Obviously, the benefit of the single QD layer active region is clear from the very low internal optical loss, which is about a factor of four less than the ~1 cm$^{-1}$ value measured on most planar single quantum well lasers. Due to the transparency carrier density in QD material and broad waveguide structure, the development of heterostructure laser diode at 1.22 µm CW room temperature without facet
coating has achieved the threshold current density of 11.7 A/cm\(^2\) in p-up mounted 2-cm cavity long.

A nonradiative recombination, reabsorption of radiation, Joule heat and thermoelectric effects contributes to waste heat. The heat deteriorates the performance of the laser such as the threshold current density, slope efficiency, output power and reliability. In this dissertation, methods of reducing the Joule heat are focused. Thinning the GaAs substrate by chemical etching decreases the thermal resistance in Joule heat. In addition, the amount of heat flux in the active region is removed by mounting p-side down on the heatsink. The BeO heatsink and laser diodes are well bonded by the AuSn hard solder. Further study in p-down mounted shows the threshold current density of 10 A/cm\(^2\) in 1.6-cm cavity long with CW output power of 2 W. Finally, the record-low threshold current density of 8.8 A/cm\(^2\) and record-low internal optical loss of 0.25 cm\(^{-1}\) in 2-cm cavity long are demonstrated. Owing to the low transparency carrier density and broad waveguide structure, the cavity length is achieved up to 2 cm long in this dissertation.

Because of very low loss and very low threshold current density in the edge-emitting laser diode, the long cavity in two section passively mode-locked laser is achieved. Furthermore, QD active region inherently offers high saturation energy of gain section and low saturation energy of absorber section, which have an advantage to the mode-locking operation. The 3.75 GHz repetition rate with pulse width of 22 ps and time-bandwidth-product of 6.1 is demonstrated in 1.1-cm cavity long and 40-µm stripe width under condition of 360 mA and 13V reverse bias.
4.2 Future Work

There are still several challenging aspects which can be further improved including its low internal injection efficiency and high heterojunction voltage. The internal injection efficiency of 47% is still low in these results, which is in agreement with a characteristic of most of the QD laser diode results presented to date. It is still not clearly understood. Understanding and increasing the internal efficiency, which may be related to inhomogeneous broadening, is a challenging study both in modeling and experiment. Very high voltage of these devices is in a range of 3-4 volts. Build up of the heterojunction voltage due to misalignment of different heterobarriers in the epitaxial layers may cause this high voltage. The future research in engineering heterointerface for low resistance and doping profile along with an improvement of crystal quality can be conducted to reduce the high voltage.

In mode-locking operation, the pulse energy is limited by saturation energy of gain section. The increase in the mode cross-section area and length of gain section enhance the saturation energy of gain section. The tapered gain section is achieved to increase the cross-section area [22]. The ratio of gain length to absorber length in the saturation energy is studied [67]. The certain range of ratios simultaneously achieves both the increased output power and decreased pulse duration. The interplay of pulse duration and high peak output power is very important. The future research in the device geometry and configurations for increasing the output power and reduction in the pulse duration at the same time can be useful in passively mode-locked laser diode. Additionally, the p-side down mounting in the two-section passively mode-locked laser is a promising candidate for increase in output power and better heat sinking for the near future research [68].
In summary, the works presented in the long cavity single QD layer laser diode with the record-low threshold current density and record-low internal optical loss of waveguide prove the fundamental aspects in QD properties and provides valuable information. The low loss and low threshold current density design allows the increase in cavity length and consequently opens up the opportunities in high power laser diode and high peak power in passively mode-locked laser diode with repetition rate of a few GHz.
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