NANOLITHOGRAPHICALLY DEFINED SEMICONDUCTOR QUANTUM DOTS

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THESIS
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In this thesis, nanolithographically defined quantum dots are discussed including their fabrication process and optical properties. First, an introduction to the field of quantum dots (QDs), and the advantages of QD-based optoelectronic devices are provided. The research presents our recent work demonstrating carrier confinement in quantum nanostructures fabricated from epitaxially grown quantum wells (QWs) using a top-down nanosphere lithography, dry-etch and overgrowth fabrication process. Devices are characterized by a current density-voltage (JV) test, electroluminescence (EL) and photoluminescence (PL) spectroscopy. The quantum confinement is simulated by COMSOL.
To my parents, Zhihai Yu and Xin Wen, for their love and support
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CHAPTER 1

INTRODUCTION

1.1 Quantum Dots

The ability to confine charge carriers in nanoscale structures results in a quantization of the energies in the direction of the quantization. By nanos- tructuring material, we can effectively control the energy states of charges in the materials. This is perhaps the key characteristic of nanomaterials, namely the control of electronic and optical properties by control of length scales [1]. This is perhaps the primary appeal of nanomaterials, especially for electronic, optical, and optoelectronic applications. Unlike bulk materials, whose electronic states are determined solely by the lattice of the crystal, in a nanomaterial we are able to control electronic and optical properties by control of the material length scales. Three categories of nanostructures can be determined by where the carriers are confined in: one dimension (1D) (e.g., thin films or quantum wells), two dimensions (2D) (e.g., quantum wires), and three dimensions (3D) (e.g., quantum dots). Quantum confinement in quantum wells (QWs), though only 1D, has been responsible for great advances in semiconductor laser technology, such as lower threshold current, lower chirp, narrower linewidth and higher optical gain, compared with bulk material lasers [2]. The 3D confinement provided by quantum dots (QDs) has been shown to have the potential to improve the performance of electronic and optoelectronic devices such as lasers, detectors and biological sensors [3], [4], [5].

As a 3D confined structure, QDs have a sharper (δ-like) density of states (DOS) than less confined structures such as QWs (Figure 1.1), resulting in unique transport and optical properties, which allows QDs to be used as an optical gain medium with a low threshold current density and narrow gain bandwidth. In addition, QDs with high uniformity and quality hold the

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potential for optical encoding and multiplexing applications because of their narrow linewidth emission spectrum [6].

Quantum dots have been fabricated using a wide range of materials, such as InAs [7], Silicon [8], Gemanium [9] and CdS [10]. Also, numerous techniques have been demonstrated, including colloidal chemistry [11], top-down lithographically defined QDs [12] and bottom-up grown QDs [13]. Of those, self-assembled quantum dots [14] (SAQDs) grown by molecular beam epitaxy (MBE) or metal-organic chemical vapor deposition (MOCVD), formed in strongly lattice mismatched systems where 3D islands form to reduce the mismatch strain, have many favorable properties for device applications such as lasers and photodetectors [15], [16]. Since SAQDs have reasonably high uniformity and can be integrated into semiconductor optoelectronics, significant effort has been made to research and develop SAQDs-based optoelectronic devices for a variety of applications. However, it is difficult to attain accurate control of the uniformity, as well as the size and shape, of SAQDs, which results in inhomogeneous broadening of the electron and hole energies, and thus the optical properties of the QD ensemble. This difficulty has motivated research endeavors in the comparatively accessible alternative dot-fabrication method, nanolithographically defined (NLD) QDs. Nanolithography, such as electron-beam, x-ray, ion-beam and nano-imprint lithography, allows QDs grown on selected nucleation site (bottom up) [17] or fabricated by patterning of quantum wells (top down) [18].

However, the leading-edge lithographic techniques essential for nanoscale confinement in NLD QDs bear some particular downsides, especially in terms of the equipment cost and patterning time to achieve high-resolution, large-area NL. The cost and time associated with large-area QD lithography has motivated the development of nanosphere lithography (NSL) as a prospective substitute to the above NL techniques [19]. In NSL, highly uniform polystyrene nanospheres are self-assembled in a tightly-packed poly-crystalline array upon a planar surface. This poly-crystalline array can then serve as an etching (or deposition) mask for patterning of the underlying surface. The primary advantages of the NSL process are its comparative cost- and time-efficiency for achieving large-area nano-patterning of semiconductor surfaces. Past literature has documented top-down NSL for QD fabrication using first growth InGaAs QWs with photoluminescence (PL) studies illustrating both
Figure 1.1: Density of states of (a) bulk material, (b) quantum well, (c) nanowire, (d) quantum dots.

A lateral quantization of states in the patterned QW and a narrowing of the PL linewidth, corresponding with the transfer of the nanosphere (NS) array uniformity to the fabricated QDs. The ability to control the energy states in semiconductor QDs gives us the opportunity to design high-quality lasers with photon energies above the semiconductor bandgap. However, there is great interest in developing semiconductor-based optoelectronic materials for the mid-infrared (mid-IR) wavelength range, and there could be significant advantages to be gained by utilizing patterned QD material as the active region in mid-IR emitter devices. The mid-IR range is an important wavelength range for a variety of applications, including thermal imaging, thermo-photovoltaics, thermal signature control, and perhaps most importantly, molecular sensing [20]. A wide range of molecules have strong fundamental vibrational resonances in the mid-IR range. The ability to develop detectors and light sources at these wavelengths could enable a new generation of compact, wavelength flexible sensors. However, traditional interband transitions in semiconductors cannot reach these wavelengths.
1.2 Intersublevel Transitions

An intersublevel transition is defined as a dipole allowed optical transition between the quantized electronic energy states within the conduction (or valence) band of semiconductor heterostructures. Here we focus on intersub-level (ISL) transitions in the conduction band. Perhaps the most impressive demonstration of an ISL mid-IR optoelectronic device is the quantum cascade laser (QCL) [21]. The QCL emits light via electron transitions between conduction band states in complex semiconductor heterostructures, providing a wavelength flexible, high power, and compact semiconductor light source for a wide range of wavelengths across the mid-IR range (and now the terahertz). While the initial demonstration of the QCL (in 1994 [21]) operated at 10 K, and only produced 8 mW (in pulsed operation) of light, the rapid development of QCLs has led to 5.1 W output powers, continuous wave, at room temperature [22]. Currently, QCLs are commercially available from a number of vendors (Daylight Solutions, Hamamatsu, and Thorlabs).

Other notable devices based on intersubband transitions have been demonstrated, such as quantum well infrared photodetectors (QWIPs), along with QCLs, providing superior performance for many applications, i.e. biomedical sensing, thermal imaging and spectroscopy. In the past decade, research interest in devices and structures based on intersublevel transitions has been expanded to ISLs in QD structures, due to the 3D confined characteristic which brings advantages over traditional structures such as quantum wells. Recent work has demonstrated room temperature infrared emitters and high detectivity photo-detectors taking advantages of ISL transitions in QD structures [23], [24]. Taking the quantum dot infrared photo-detector (QDIP) as an example, the advantages of the QD structure applied in such devices are discussed as follows. Consider the intersubband transition between QD state a and state b, of which the wavefunctions are:

\[\Psi_a = u_c(r)\phi_1(x, y, z)\]  \hspace{1cm} (1.1)

\[\Psi_b = u_c(r)\phi_2(x, y, z)\]  \hspace{1cm} (1.2)

Here \(u_c\) refers to the periodic parts of the Bloch functions, \(\phi_1\) and \(\phi_2\) are the wavefunctions of electrons in QDs states. The optical dipole moment is
given by:

$$\mu_{ba} = \langle \psi_b \mid e\vec{r} \mid \psi_a \rangle = \langle \phi_2 \mid ex \mid \phi_1 \rangle + \langle \phi_2 \mid ey \mid \phi_1 \rangle + \langle \phi_2 \mid ez \mid \phi_1 \rangle$$  \hspace{1cm} (1.3)

Due to equation (1.3), the dipole moment is non-zero in all three directions. Therefore, the absorption coefficient $\alpha(\hbar\omega)$ is not zero for both TE polarization (x, y direction) and TM polarization (z direction). Its advantage over QW is that for infrared photodetector, QDIP is able to detect light at any polarization while QWIP is only able to detect TM-polarized light, therefore, a grating coupler is needed in order to couple incident light into a QWIP during the fabrication. Furthermore, in terms of making an infrared detector, QDIPs have lower dark current than QWIPs. In general, dark current can be estimated as:

$$J_{\text{dark}} = qvn_{3D}$$  \hspace{1cm} (1.4)

where $v$ is the drift velocity and $n_{3D}$ is the electron density in the barrier, which is given by:

$$n_{3D} \approx \exp\left(-\frac{E_a}{k_BT}\right)$$  \hspace{1cm} (1.5)

where $E_a$ is the thermal activation energy, which is equal to the energy difference between the top of the barrier and the Fermi level in the QW or QD. Considering the same barrier material for both QDIP and QWIP, the thermal activation energy related to the cut-off wavelength is given as:

$$E_{aQWIP} = \frac{hc}{\lambda_c} - E_f$$  \hspace{1cm} (1.6)

for QWIP and $E_f$ is the Fermi level in the QW

$$E_{aQDIP} = \frac{hc}{\lambda_c}$$  \hspace{1cm} (1.7)

for QDIP. Thus, for the same cut-off wavelength ($\lambda_c$), the thermal activation energy for QDIP is bigger so that the $n_{3D}$ is smaller in the barrier as well as the dark current $J_{\text{dark}}$.

QDs and QWs are also predicted to have very different carrier dynamics, which can significantly affect ISL-based devices fabricated from these heterostructures. Scattering by optical phonons is the primary cause of the ex-
tremely short excited state lifetimes in QW devices. The fast phonon-assisted non-radiative recombination is the primary cause of the poor luminescence and large threshold current densities for QCLs. However, electron phonon coupling in QDs could be reduced since the energy spacing can be easily tuned by band engineering to be larger than the longitudinal optical phonon energy (less than 40 meV). This reduction of electron phonon interaction in QDs materials, named as phonon bottleneck, results in a longer electron lifetime so that the photo-conductive gain is increased for detectors [25], [26].

It is conceivable that replacing the QW active region of the QCL with a QD active region could allow for improved laser performance. This quantum dot cascade laser (QDCL) would benefit from lower threshold current densities, better temperature performance, and potentially, surface emission. Since the working principle of the QDCL, injecting electrons into device excited states and light emission by ISL transitions from these higher energy states to lower energy QD states, is effectively the reverse of the QDIP operation, the advantages discussed above for QDIP also apply for QDCL. Therefore, the ability to form large-area, uniform and high-quality QDs in a time- and cost-efficient way could lead to a new class of mid-IR sources.

In this chapter, the fundamental theory as well as the advantage of semiconductor quantum dots is discussed, including the intersublevel transition using QDIP as an example. In Chapter 2, the fabrication of our quantum dot will be discussed in detail.
2.1 Nanosphere Deposition

In order to use nanosphere (NS) as an etching mask, a single monolayer of uniformly distributed NS needs to be deposited on top of the semiconductor substrate. Usually, the NS monolayer is deposited by the spin coating method, for which the deposition quality is mainly affected by sample surface (hydrophilic or not), the spin speed and the size of the NS. The sample surface needs to be highly hydrophilic, otherwise the NS will not coat the surface in a uniform manner. Figure 2.1 shows a hydrophilic GaAs sample with 500 nm NS spin-coated onto the surface. Figure 2.2 shows the one with a hydrophobic surface. As can be seen, the surface in Figure 2.2 only has NS on a small portion of the surface while the one with a hydrophilic surface has a well-ordered monolayer of NS on top. In order to make the surface hydrophilic, the samples need to be treated in oxygen plasma for 1-2 mins.

For spin coating, the NS deposition is limited by the size of NS. Usually only large size NS can be deposited as the monolayer on semiconductor sam-

Figure 2.1: 500 nm diameter NS spin-coated on the hydrophilic GaAs sample surface.
For small size NS, for example, 200 nm and 100 nm NS, nanosphere deposition requires a more complicated spin process, which is not efficient. Efforts have been put into how to deposit small size NS on different sample surfaces, and a new method, called dip-coating, has been developed by Weiss’ group [27]. The dip-coating method is shown in Figure 2.3. First, a certain amount (0.1 mmol/l) of sodium dodecyl sulfate (SDS) is added into DI water to increase surface tension which enables the NS to form a monolayer on the water surface. Then, polystyrene (PS) NS (Bang Laboratories, Inc.) is slowly dropped along the surface of a glass slide, such that the ML slide onto the water surface, forming a single layer. Once the monolayer is formed, one can gently slide the substrate into the water and then pull it out of the water, and the substrate becomes coated with the NS. It is important to note that following removal from the water, the sample must be allowed to dry naturally. One cannot blow the sample dry with a Nitrogen gun, lest the water and NS are blown off of the sample surface.

There are some important parameters which have significant effects on the NS dip-coating deposition process, such as the surface property of the semiconductor material, the concentration of NS solution, the surface tension of the water solution. In order to form uniform monolayer NS, the sample surface needs to be flat and smooth. However, as mentioned earlier, the big advantage of the dip-coating method is that the surface does not need to be hydrophilic, unlike the spin-coating method. Also, the concentration of NS solution is important because if it is too low, it can be hard to form a large area of uniformly well-ordered monolayer, yet, if it is too high, one can get multilayer NS formation on the sample surface. The NS solution used here is 8% by weight, which is perfect for NS deposition. In addition, the
Surface tension of the water is another critical factor. Pure DI water does not have high enough surface tension to pack polystyrene NS closely together (as shown in Figure 2.4 a), so SDS is used to increase the surface tension. According to Vogel’s result [27], 0.1 mmol/l is the best SDS concentration for single NS layer deposition (as shown in Figure 2.4 b). Further increasing the SDS concentration can cause multilayer NS deposition to occur, as shown in Figure 2.4 c, the second layer starts to form at 0.5 mmol/l. Once the SDS concentration goes too high (Figure 2.4 d), the surface tension is too high, which prevents the formation of a completed layer of NS, so small patches of either multilayer or NSs form randomly on the water surface.

2.2 Nanopillar Fabrication

2.2.1 Nanosphere Resizing

Once an ordered, closely packed NS monolayer is deposited upon the surface, the NS diameter must be decreased for two primary reasons. First, with touching nanospheres, there is little space to etch down through the semiconductor to form individual QDs. Second, the large NS diameters will not provide substantial lateral quantization, thus resizing the nanospheres will allow us to observe size quantization effects. A master-slave reactive ion
etching (RIE) is used to resize the nanosphere. The recipe used here is:

\[ O_2 = 10 \text{ sccm} \]
\[ \text{Power} = 100 \text{ W} \]
\[ \text{Chamber Pressure} = 150 \text{ mTor} \]

By controlling the time used to etch the NS, the size can be controlled accurately. Taking 200 nm diameter NS as an example, Figure 2.5 shows the resized nanosphere diameter as a function of dry etching time, from which it can be seen that the etching rate is slightly nonlinear because as the diameter gets smaller, less material needs to be etched to further shrink the size.

Figure 2.6 shows the NS diameter resized from 200 nm to about 145 nm diameter. (The etching time is 40 s.) Figure 2.6 shows the reduced NS size has good uniformity, of which the variation is less than 5%.

### 2.2.2 Nanopillar Etching

After having resized the NS to an appropriate diameter, the resized NS are used as a dry etching mask for the nanopillar etch. In order to have high-quality nanopillars, inductively coupled plasma (ICP) RIE is used for nanopillar fabrication. Dry etching is a physical and chemical process meaning that a relatively nonreactive atom (usually Ar) is needed to physically
Figure 2.5: Resized NS diameter as a function of dry etching time.

Figure 2.6: Resized NS from 200 nm to 145 nm diameter with a variation less than 5%.
bombard the atoms out of the semiconductor material and then a reactive molecule or atom is needed to react with the bombarded atom from the material to form a molecule with high volatility which can be easily pumped away from the reaction chamber. The most popular etchant for GaAs/AlGaAs material is a chloride-based molecule such as $BCl_3$ and $SiCl_4$ since both the $GaCl_3$ and $AlCl_3$ formed in the process have a relatively low boiling point (201°C for $GaCl_3$ and 120°C for $AlCl_3$) meaning that they can be easily pumped away from the high vacuum chamber. But for Indium, a chloride-based etchant is no longer suitable, given that the boiling point of $InCl_3$ is 800°C, making it exceedingly difficult to achieve gas phase, which prevents pumping and removal of the $InCl_3$. So $InCl_3$ will just redeposit on the surface of the sample and prevent further etching. In order to etch through the InGaAs quantum well layer, a bromide-based etchant must be used. The boiling point of $InBr_3$ is 420°C, which is almost half of that of $InCl_3$. The etchant used here is a combination of Ar and HBr:

$Ar = 2$ sccm
$HBr = 10$ sccm
$RF1 = 65$ W
$RF2 = 90$ W

The Ar to HBr ratio is very important. If the Ar/HBr ratio is too high, then the physical bombardment is faster than the chemical reaction so that the extra In atoms which cannot be turned into $InBr_3$ can redeposit on the sample surface to prevent further etching. If the Ar/HBr ratio is too low, the HBr molecule can also physically attack the sample surface and make the sample surface very rough. So a balance between the physical and chemical reaction is necessary for getting reasonable etching quality. The RF1 power determines the power of the inductor, which is the key factor determining the plasma density. The higher the plasma density is, the faster the resulting etching rate. This is the advantage of ICP-RIE over traditional RIE: the plasma density can be tuned separately by controlling RF1 power. The RF2 power controls the voltage added between the capacitor plates, which also determines the etching rate. RF2 = 90 W gives a voltage added on the capacitor about 250 V. Figure 2.7 shows the SEM of a nanopillar etched by HBr and Ar, as can be seen from the SEM, well-ordered nanopillars have been formed on the surface of the sample.

After the pillars are etched, one has essentially formed quantum dots in
the nanopillars. In these structures, the lateral confinement is provided by the nanopillar walls, and the vertical confinement comes from the original quantum well. The next step is to remove the NS left on top of the nanopillars. The same O$_2$ RIE is used to remove the NS as to resize the NS. At least 2 mins are necessary to completely remove the polystyrene residue on top of the nanopillar. This step is critical because if the polystyrene is not completely removed, the subsequent overgrowth can suffer. An SEM of the nanopillar array after the NS removal is shown in Figure 2.8. Now an array of well-ordered nanopillars, each of which contains an InGaAs quantum well, is left on the sample surface. Following the NS removal, an InGaAs selective etch is used to further resize the quantum dot diameter. The selective etching recipe is citric acid: $H_2O_2 = 2:1$. SEM of nanopillars after selective etching is shown in Figure 2.9.
2.3 Device Fabrication

At this point, QDs have already formed, and ideally, quantization should be visible in the PL test. However, the dry etching induced damage makes the PL signal very weak to observe. Further, in order to make devices, contact must be made so that current can be run through the QDs. Thus, the etched quantum dot samples are sent back to overgrow after the removal of the residual nanosphere material. The samples are returned to the MBE chamber and annealed for 20 mins at 640°C. The samples experience a mass reflow process, during which GaAs can encapsulate the InGaAs quantum dots, resulting
in an improvement of optical properties. Following the annealing process, a layer of 500 nm beryllium-doped (Be-doped) GaAs ($N_A = 5 \times 10^{17} \text{ cm}^{-3}$) is overgrown and a 50 nm of highly Be-doped GaAs ($N_A = 1 \times 10^{19} \text{ cm}^{-3}$) is capped on the very top of the samples to allow for an ohmic p-type contact. The overgrown material does not fill up the gap between nanopillars, (as shown in Figure 2.10) which can be explained by the fast overgrowth rate. The overgrown material deposits on both the top of nanopillars and the sample surface, but it starts to connect and form a complete layer before the gaps are filled up. After overgrowth, samples are tested by PL and then fabricated into emitters. Figure 2.11 shows the process flow chart (top) and the final device (bottom). Standard photo-lithography is used to pattern mesas (1350 um × 2050 um) and wet etching is used to define the mesas which are etched through the two epilayers to the GaAs below the InGaAs QW/QD layer. After the mesa etch, another photo-lithography is applied to define the top contact pattern. Then a Cooke e-beam evaporator is used to deposit Ti/Au (20 nm/200 nm) contact on the sample surface. Following lift-off, the samples’ current-voltage (IV) curve is measured and the devices with the best IVs (those which look the most like diodes) are wire-bonded to gold pads. A metal grid with 70 um × 70 um openings is designed so that the surface emission is allowed from the underlying diode.

In this chapter, the fabrication process of the quantum dot has been discussed, including two main parts: nanosphere lithography and nanopillar fabrication. The problems and solutions found in the process have been discussed in detail. In Chapter 3, the characterization of QD will be discussed.
Figure 2.10: Cross-section SEM of 150 nm QDs sample. The overgrown material is on top of the nanopillars.

Figure 2.11: Process flow chart of the emitter fabrication.

Once the device is fabricated, EL emission is tested under both 77 K and 300 K, which will be discussed in Chapter 3.
CHAPTER 3
QUANTUM DOTS CHARACTERIZATION

3.1 Photoluminescence

The PL data for both before and after annealing of the 160 nm diameter pillars (at 77 K) is shown in Figure 3.1. Due to extensive damage induced by dry etching, no PL signal from the nanopillars is seen before the annealing and overgrowth. However, following annealing and overgrowth, the optical properties of the QD array is significantly improved, and a clear PL peak is observed from the nanopillar array. PL from the five fabricated samples with

![Figure 3.1: PL emission from 160 nm diameter nanopillars before (dot) and after overgrowth (line). The inset shows a higher resolution of QDs emission (1.32 eV at 77 K).](image)

Figure 3.1: PL emission from 160 nm diameter nanopillars before (dot) and after overgrowth (line). The inset shows a higher resolution of QDs emission (1.32 eV at 77 K).

different pillar size after annealing and overgrowth is shown in Figure 3.2. The figure shows clear PL blue-shifts, with the blue shift energy increasing with decreasing pillar size. The observed size dependence of the PL peak
can be explained by the increase in lateral confinement of the nanopillars with a smaller diameter. For the smallest diameter pillars fabricated (90 nm), a peak blue-shift of 37 meV is observed, indicating a significant lateral confinement in the QDs.

3.2 IV-Test

After overgrowth, the samples are made into emitters then the electrical properties of each diode is tested. Current density-voltage (JV) data taken from the diode emitter fabricated from 90 nm diameter QDs and shown in Figure 3.2. As can be seen from the J-V test, the pn junction quality is reasonably good at both 77 K and 300 K. At 77 K, the turn-on voltage is about 1.8 V and at 300 K, the turn-on voltage is about 1.5 V.
3.3 Electroluminescence

Temperature-dependent EL data taken of the 90 nm diameter nanopillar diode is shown in Figure 3.4 for a current of 12 mA. The EL spectrum at 77 K shows a remarkably narrow QD peak with a full width half maximum (FWHM) of 18 meV, which suggests a better uniformity of dots than standard self-assembled InAs quantum dots [28]. As expected, the emission energy red shifts and the peak intensity decreases as the temperature increases. In order to further increase the emission intensity, a three GaAs/InGaAs quantum well sample is grown and fabricated into an emitter with the same process. Figure 3.5 shows the temperature-dependent EL of a diode emitter made from a 150 nm diameter nanopillar, from which an enhancement of EL intensity can be observed. However, the FWHM of this three-dot emitter is larger than the single quantum dot sample. This is probably caused by the thickness variation of those three quantum wells during the growth.
Figure 3.4: EL spectra from the 90 nm QD diode (I = 12 mA) as a function of temperature, showing narrow linewidth quantum dot electroluminescence up to 200 K. The inset shows an expanded view of the EL spectra for the device at 77 K.

Figure 3.5: EL spectra from a 150 nm QD diode as a function of temperature. This sample is made starting with a 3-QW sample, which shows an enhanced emission intensity.
Figure 3.6: Energy shift data of QD ground state energy as a function of dot diameter. There is clearly a lateral offset between the calculated value (red circular dots) and the experimental value (blue square dots). This offset may be caused by a non-radiative region surrounding the pillar, resulting from defects induced by the fabrication (mainly dry etching) process or surface depletion band-bending.

3.4 Simulation

Our structures are also modeled using the COMSOL multiphysics finite element technique. The modeled results as well as the experimental results, for the quantization of energies in the QDs, are shown in Figure 3.6. From the figure, a clear lateral offset between the experimental (blue square dots) and calculated (red circular dots) data can be observed. This can be explained by the existence of a non-radiative dead layer due to the damage induced by the fabrication process, mainly dry etching. If a dead layer of 35 nm around the nanopillar is taken into consideration, the simulated spectral peak positions align very well with the experimental data.

In this chapter, the characterization as well as the COMSOL model have been discussed, and the experimental results match the simulation results except for the dead layer. In the future, effort will be put into how to simulate the dead layer in COMSOL to better understand the underlying physics principles.
CHAPTER 4

CONCLUSION

The physics of quantum dots and intersublevel transitions in these dots is discussed, demonstrating a potentially promising research future for these nanoscale semiconductor structures. Lateral confinement in NSL QDs with different sizes and electroluminescence from the QD structure have been demonstrated. The nanopillar structures with QD inside are formed by patterning first grown InGaAs quantum wells using NSL, which is cost- and time-efficient. The structures fabricated were modeled using COMSOL, and the simulated results agree well with the experimental results when taking the dead layer into consideration. In the future, even smaller quantum dots can be fabricated using NSL, which will increase the energy spacing between the excited state and the ground state in the QDs. The intersublevel transition, which we hope to push into the mid-IR wavelength range, will be investigated by FTIR spectroscopy. Following the development of highly uniform, high density, and small diameter NSL QDs, an infrared QD emitter with an emission wavelength at about 9.5 um will be designed and fabricated, which may later lead to a QD QCL or QDIP.
REFERENCES


