Low Threshold Lasing in Gallium Nitride Based Microcavities

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Low Threshold Lasing in Gallium Nitride Based Microcavities

A DISSERTATION PRESENTED
BY
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TO
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Abstract

Optical microcavities confine light to small volumes by resonant recirculation. Devices based on optical microcavities have become indispensable in modern optics, finding applications not only in laser devices, optical data recording, fiber optic data transmission, but also as invaluable tools in the realization of many optics experiments in scientific research. Semiconductor microcavities with embedded quantum dots (QDs) or quantum wells (QWs) are excellent platforms for investigating spontaneous emission and cavity lasing. With the right choice of material, microcavities containing optical emitters can offer the possibility of room temperature realization of light-matter interaction.

Gallium nitride (GaN) and its alloys have several exceptional optical and electrical properties, making the material system an outstanding candidate for studying low-threshold lasing in microcavities. Some of the advantages of III-nitride based microcavities include enhanced room temperature performance due to large exciton binding energy, ability to be engineered to emit at any visible wavelength, low surface recombination velocities, and high optical robustness in the presence of defects.
However, many challenges also need to be overcome for us to take advantage of this wonderful material. The main challenge in fabricating high quality GaN based cavities comes from the material’s chemical inertness which brings about great difficulties in the processing of GaN. The practical constraint of the need to grow GaN on lattice mismatched substrates gives rise to large density of strain-induced defects and threading dislocations throughout the material. The intrinsic polarization field present in III-nitrides, coupled with internal field arising from strains in the material, reduces carrier recombination efficiency and hinders efficient lasing. In spite of these difficulties, low-threshold GaN microdisk and photonic crystal lasers containing indium gallium nitride (InGaN) emitters have been realized and examined in recent years, giving us valuable initial insights into the working mechanisms behind cavity-emitter interaction.

The ability to control cavity photon dynamics through efficient cavity-emitter coupling is at the heart of the research into low threshold microcavity lasing. This dissertation builds on previous work and aims to investigate the fundamental limitations to low threshold lasing in GaN/InGaN microcavities, by focusing on the respective roles InGaN quantum dots and fragmented quantum wells (fQWs) play in relation to cavity modes and the photon loss mechanism in laser operation. Microdisks, micro-rings, and photonic crystal nanobeams based on GaN/InGaN are designed and fabricated to aid our understanding of the interaction between cavity and active mediums.
This dissertation is organized into five chapters. Chapter 1 gives an overview of the problem at hand and describes the general approach we take to investigate these questions. Chapter 2 discusses the relevant background knowledge that aids in the understanding of later discussions. In this chapter we give a description of the gallium nitride material, a thorough examination of optical microcavities and its emitters, as well as a review of the fundamental working mechanisms of a laser. Chapter 3 dives into the realization of low-threshold lasing in microdisk cavities containing QDs, fQWs and QWs. This chapter describes in detail the design, growth, fabrication and characterization of microdisk lasers. Additional experiments comparing InGaN QDs and fQWs as gain mediums in a microdisk laser build the foundation for our understanding of the different roles emitters play in relation to gain, capture efficiency, and cavity mode selection. Chapter 4 explores the fundamental limitations to low-threshold lasing through studying micro-ring lasers containing heterogeneous emitters: InGaN QD and fQWs. The chapter walks readers through the process of designing, fabricating and optimizing the micro-ring cavity geometry in the eventual realization of an ultra-low-threshold micro-ring laser with a threshold of 6.2 μJ/cm², an order of magnitude lower compared to previous generation microdisk designs. The chapter highlights the mechanism of photon loss from the low-quality cavity modes, and how we can leverage this by spectrally and spatially overlapping low-quality modes with low-gain fQW emitters, so as to remove undesirable photons from the cavity and drive down the lasing threshold even further. Chapter 5 looks at lowering
lasing thresholds from a different dimension – by altering the cavity design entirely. In this chapter we demonstrate a high-quality factor low-modal-volume photonic crystal nanobeam laser, with only a single mode overlapping the gain region of the emitters. A discussion on the optimal choice of gain material in relation to specific cavity design is also presented.
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Introduction

Gallium nitride (GaN) microcavities with embedded optical emitters have long been sought after as visible light sources as well as platforms for performing cavity quantum electrodynamics (QED) studies. Unlike most other narrow bandgap III-V semiconductors, the large bandgap energy of GaN-based materials offers great potential for
highly efficient blue/UV emitting devices operating at room temperature\textsuperscript{10,11}. Despite fabrication challenges associated with GaN’s chemical inertness and high defect density during material growth\textsuperscript{12}, recent research in GaN-based light emitting devices has made tremendous progress, demonstrating strong coupling and polariton lasing in microcavities featuring distributed Bragg reflectors\textsuperscript{13}, low threshold lasing in microdisk\textsuperscript{14,5} and photonic crystal nanobeam cavities\textsuperscript{8}, as well as single photon emission\textsuperscript{15}. Among the diverse range of applications, our research interest lies in building the most efficient GaN microcavity lasers with ultra-low lasing threshold. These devices can find application in serving as the light source for on-chip optical integrated circuits\textsuperscript{16}, platforms for conducting experiments in cavity quantum electrodynamics\textsuperscript{1,17,18,19}, light-emitting trackers in biological systems\textsuperscript{20}, as well as in any other technology that requires a micro-scale coherent light source which conventional lasers are incapable of.

The approach we have taken in this work is to fabricate GaN based microcavities of various geometries, containing different types or combinations of indium gallium nitride (InGaN) emitters, such as quantum dots (QDs), quantum wells (QWs), and fragmented quantum wells (QWs). These cavities serve as an excellent instrument for studying cavity-emitter interaction and allows for the realization of ultra-low threshold lasing. This work builds on previous findings and offers new insight to the fundamental limitations of low threshold lasing in GaN microcavities.
Optical resonators play an indispensable role in modern optics. The need for a small and efficient light source in on-chip integrated photonic circuits and other scientific experiments motivates our study on building a low-threshold laser in the GaN material system. Before diving into the details of how to build a microcavity laser, let us first
take a look at some fundamental theory knowledge that will aid in the understanding of constructing such a system. This chapter is divided into three main parts, where we systematically introduce the basic theory and background knowledge on (1) the gallium nitride material, (2) optical microcavities, and (3) lasing.

2.1 The gallium nitride material

2.1.1 Basic properties

Gallium nitride (GaN) and its alloys have attracted a tremendous amount of research interest in recent years due to their superior optical and electrical properties\(^{11}\). Its large, direct bandgap, high binding energy, and exceptional optical robustness in the presence high defect density, all contribute towards GaN’s success as an outstanding candidate material for making optical devices\(^{21}\). With the advancement in epitaxial growth and nano-fabrication techniques, there have been numerous demonstrations of GaN based solid-state devices, both commercially and in research. Well-known examples of such include light emitting diodes (LEDs) and lasers which can be engineered to emit in wavelengths across the entire visible spectrum\(^{22,23,24,25,26}\), blue laser diodes (LDs) used to read Blue-ray Discs\(^{27,28}\), transistors used for high frequency, high voltage, and high temperature applications\(^{29,30}\), as well as sensors used in bio-chemical sensing applications\(^{31,32}\), among many others. In this section, we take a look at some basic material properties of this interesting semiconductor material.
Figure 2.1: Schematic of the III-nitride wurtzite unit cell.

Figure 2.2: Band structure of GaN showing the direct band gap at the $\Gamma$ valley.
The zinc-blende (ZB) and wurtzite (W) crystal structures are the most common crystal structures adopted by III-V semiconductor compounds, they differ structurally only in their third nearest neighbor atomic arrangement. However, only the wurtzite crystal phase is thermodynamically stable in III-nitrides such as GaN, AlN, and InN under ambient conditions\(^\text{33}\). Figure 2.1 shows the crystal lattice of a Wurtzite unit cell\(^\text{34}\). The unit cell is generated by two equal length lattice vectors \(a\) with a 120° angle separation, and an unequal third lattice vector \(c\) perpendicular to \(a\). The wurtzite unit consists of tetrahedrally coordinated atoms and can be described as an array of corner-linked tetrahedra, resulting in the formation of alternating hexagonally-packed layers\(^\text{33}\). For an ideal wurtzite structure the tetrahedra are un-deformed, however within III-nitrides, they are slightly stretched or compressed in the \(c\) direction by the ratio \(u\), and for a perfect tetrahedron \(u = 0.375\)^\text{35}.

GaN has a wide bandgap energy of 3.4 eV, and a highly desirable large exciton binding energies of up to 34 meV, giving it enhanced stability at room temperature compared to other III-V semiconductors\(^\text{21}\). It is an efficient light emitter due to the direct bandgap at the \(\Gamma\) valley, compared to indirect bandgap in Si\(^\text{36}\). GaN can also form ternary alloys in the form of \(\text{In}_x\text{Ga}_{1-x}\text{N}\), with bandgap energy spanning across the entire visible spectrum\(^\text{21}\), as shown in Figure 2.3 This gives the material enormous opportunities as a light source as it can be engineered to emit at any wavelength in the visible spectrum.
2.1.2 Problems and Challenges

However, there are also several challenges and complications working with GaN. Due to the lack of symmetry in the [0001] direction in Wurtzite crystals and the partial ionic nature of its bonding, there exists an internal field in the material along the c-axis\textsuperscript{34}. To be specific, this is due to the non-centrosymmetry of the crystal structure, as well as the higher electronegativity of nitrogen atoms, causing more electrons to be attracted towards them. This gives rise to a spontaneous polarization and an internal field along the c-axis\textsuperscript{37,38}. This internal field can have an adverse effect on emitters and device performance, and is especially strong in epitaxially grown heterolayers in the c-direction. In a confined system such as a quantum well, the internal field separates electrons and holes in opposite directions due to their opposite charge, reducing the spatial overlap of
their wavefunctions and thereby reduces the probability of a recombination event and lowers the spontaneous emission rate\textsuperscript{39}. This effect due to internal field is known as the quantum confined Stark Effect (QCSE)\textsuperscript{40,41,42,43}, as illustrated in Figure 2.4. All materials used in this thesis are epitaxially grown along the c-direction and therefore suffers from such an effect.

In addition to the intrinsic polarization field, growth of GaN and its alloys on a lattice-mismatched substrate further aggravate this effect. The technique of growing a material on a substrate different from itself is called heteroepitaxy, and is common for the growth of GaN and its alloys due to the lack of large bulk nitride substrates. Up to 16\% lattice mismatch can be present in the growth of GaN depending on the choice of substrates\textsuperscript{42}. The most widely used substrate for GaN growth is sapphire\textsuperscript{44,45}, and this is the substrate
of choice for materials used in this dissertation. The lattice constants for GaN alloys span a wide range, from 3.1 to 3.5 angstroms. The lattice mismatch and different thermal expansion coefficients between the growth material and its substrate introduce strain and piezoelectric polarization in the material. This piezoelectric polarization is large in III-nitrides, an order of magnitude larger than in typical III-V semiconductors.

The difference in lattice constants and thermal coefficient of GaN alloys and the sapphire substrate also gives rise to threading dislocations, which are lines of crystallographic defects running through the material\(^{46,47}\). These defects originate within the GaN material, and propagate through layers to terminate as pits at the material surface. Threading dislocations cause increased electron scattering and reduce carrier mobility, they also act as non-radiative recombination centers, resulting in carrier loss and reduced optical efficiency\(^{48,49,50}\). The large lattice mismatch between GaN and sapphire gives rise to a considerable amount of threading dislocations in the GaN growth process, with defect density as high as \(10^{10}/\text{cm}^2\)\(^{44}\). This defect density can be characterized by measuring the density of pits on the material surface using an atomic force microscope (AFM). The presence of large amount of threading dislocations not only affects the optical performance of a material but also introduces great difficulties in further processing of the material.

Despite the presence of internal fields, large dislocation density, and difficulty in fabrication, the GaN material exhibits a surprisingly high optical efficiency\(^{38,51,4}\). The typical magnitude of dislocation density in GaN can render conventional III-V semi-
conductors optically inactive, but has much less an effect on GaN. Because of this exceptional optical property, there has been much recent progress in the demonstration of light matter coupling within GaN based solid state system through the development of micro- and nano- scale optical resonators.

2.2 Optical microcavities

2.2.1 The cavity

An optical microcavity, at its most basic definition, is a structure with a set of mirrors arranged in a way that allows for the creation of standing electromagnetic waves, known as resonant modes\textsuperscript{52}. Such standing wave cavities enhance a resonant field through creating enhanced spatially localized interference peaks. The mirrors used for such cavities may either be single interfaces or periodic regions formed by wrapping a waveguide in a circular fashion so that light is trapped within the structure through total internal reflection\textsuperscript{1}. The name microcavity stems from the fact that the size of the structure is usually on the order of micrometer or smaller. The resonance frequency spectrum of an microcavity depends on its size and geometry. There are usually fewer resonance frequencies within a particular frequency range in a microcavity compared to a ‘macro-cavity’ of similar design. We will demonstrate the motivation for making optical cavities small and resonance modes few as we proceed along this thesis.

One property commonly used to characterize optical cavities is the quality factor, $Q$,
which describes how well the resonator traps light. $Q$ is defined as $2\pi$ times the ratio of the total energy stored divided by the energy lost in a single cycle, or equivalently, the ratio of the stored energy to the energy dissipated over one radian of the oscillation. A higher $Q$ indicates a lower rate of energy loss relative to the stored energy of the resonator. A high-Q cavity simply means that light is confined for a longer time before it is lost from the cavity. Common types of microcavities include the Fabry-Perot cavities, micropillars, microdisks, microsphere, photonic crystals, etc. Figure 2.5 organizes the different types of microcavities according to their confinement methods and quality factor.

We briefly discuss each of the three different types of confinement methods. The left

<table>
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<tr>
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<th>Fabry-Perot</th>
<th>Whispering gallery</th>
<th>Photonic crystal</th>
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</thead>
<tbody>
<tr>
<td><strong>High $Q$</strong></td>
<td></td>
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</tr>
<tr>
<td>$Q$: 2,000</td>
<td></td>
<td>12,000</td>
<td>7,000</td>
</tr>
<tr>
<td>$V$: 5 (\mu m)$^3$</td>
<td></td>
<td>$Q_{\text{PG}}$: 1.3x10$^5$</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>$Q$: 13,000</td>
<td></td>
</tr>
<tr>
<td>$V$: 6 (\mu m)$^3$</td>
<td></td>
<td>1.2 (\mu m)$^3$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Ultrahigh $Q$</strong></td>
<td></td>
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<tr>
<td>$F$: 4.8x10$^5$</td>
<td></td>
<td>8x10$^9$</td>
<td>10$^8$</td>
</tr>
<tr>
<td>$V$: 1.690 \mu m$^3</td>
<td></td>
<td>3,000 \mu m$^3$</td>
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**Figure 2.5:** Examples of microcavities organized according to their quality factors and confinement methods used.¹
upper cell shows a micropost - this is a Fabry-Perot type of cavity, where alternating layers of two different materials with different refractive index are stacked on top of one another to form an one dimensional cavity confinement. Most commercial vertical-cavity surface-emission lasers (VCSELs) adopt such a cavity structure. A light emitter is usually embedded within the structure as photon source. We will discuss this further in the next section.

The center column shows a microdisk, a semiconductor add/drop filter, a microsphere, and a microtoroid. These structures confine light differently from the vertical one-dimensional confinement in the Fabry-Perot cavities. We can think of using the ray-optics picture: light propagating along the periphery of the dielectric disks are confined through total internal reflection, because the optical medium has a higher refractive index compared to its surrounding air. The air-dielectric guiding offer both lateral and vertical confinement, yielding higher Q factors than in Fabry-Perot cavities.

The right most column shows the photonic crystal cavity, a periodic nanostructure containing regularly repeating regions of high and low dielectric constants. A photonic crystal affects light propagation in the same way that the periodic potential in a semiconductor crystal affects electron motion by defining allowed and forbidden energy bands. Defects are introduced in photonic crystals intentionally to break the symmetry and form defect modes.

Semiconductor devices based on optical microcavities can be found in a wide range of applications. For example, microcavities made of III–V semiconductor materials can
function as tiny coherent light sources that enable long-distance transmission of data over optical fibers with limited loss⁵⁹; they can also be easily integrated with other semiconductor based electronic and photonic components. Microcavity lasers also enable narrow spot-size laser read/write beams in CD and DVD players¹. Applications of these remarkable devices are vast and diverse, just like their many geometrical and resonant properties. This dissertation in particular is focused on the discussion of microcavity lasing enabled by the GaN material system.

2.2.1.1 THE MICRODISK CAVITY

A microdisk is a simple cavity structure that confines light propagating along its periphery by total internal reflection. It is a small, thin dielectric disk surrounded by a lower index material such as air⁵³. The large index difference between the microdisk material and the surrounding medium allows for strong optical confinement. The highest quality standing waves, or eigenmodes, of a microdisk are called the whispering gallery modes (WGMs)⁶⁰. These modes can be thought of as closed-trajectory rays confined within the cavity by total reflections from the curved surface of the resonator. The WGM is analogous with the sound waves first discovered in the whispering gallery of London’s St. Paul’s Cathedral by Lord Rayleigh.
2.2.1.2 Mathematical definition of the WGM

Whispering gallery modes (WGMs) in a microdisk consist of two degenerate waves propagating in the clockwise and counterclockwise directions. WGMs are classified in terms of their polarization (TE or TM), radial order (p), and azimuthal number (m)\(^61\). The first order WGM is located near the outer periphery of the disk, while high order WGMs are spatially localized further inside the microdisk. Mathematically, computing the resonant modes of a microdisk with radius \(R\) requires solving Maxwell’s Equations for a cylindrical coordinate system\(^62\). To derive this\(^63\), we start with Maxwell’s equations in a linear non-dispersive medium free of charge and current:

![Diagram showing whispering gallery modes](image)

**Figure 2.6:** FDTD\(^2\) simulation showing the whispering gallery modes (WGMs) of resonances of order 1 (left) and 2 (right).
\[ \nabla \times \mathbf{E} = -i\omega \mu_0 \mathbf{H} \]
\[ \nabla \times \mathbf{H} = +i\omega n^2 \epsilon_0 \mathbf{E} \]
\[ \nabla \cdot (n^2 \epsilon_0 \mathbf{E}) = 0 \]
\[ \nabla \cdot \mu_0 \mathbf{H} = 0 \] (2.1)

where \( \mathbf{E}(r, t) \) is the electric field, \( \mathbf{H}(r, t) = \frac{1}{\mu_0} \mathbf{B}(r, t) \) the magnetic field, \( \omega \) the angular frequency, \( \mu_0 \) the free space permeability, \( \epsilon_0 \) the free space permittivity and \( n^2(r) = \frac{\epsilon(\mathbf{f})}{\epsilon_0} \).

Wave equations are derived as:

\[ \nabla^2 \mathbf{E} + \frac{n^2 \omega^2}{c^2} \mathbf{E} = 0 \]
\[ \nabla^2 \mathbf{H} + \frac{n^2 \omega^2}{c^2} \mathbf{H} = 0 \] (2.2)
where \( c^2 = \frac{1}{\mu_0 \epsilon_0} \).

Since the two equations are equivalent, we use \( F \) to represent either \( E \) or \( H \) and write the wave equations in cylindrical coordinates:

\[
\left( \frac{\partial^2}{\partial \rho^2} + \frac{1}{\rho} \frac{\partial}{\partial \rho} + \frac{1}{\rho^2} \frac{\partial^2}{\partial \phi^2} + \frac{\partial^2}{\partial z^2} + \left( \frac{n \omega}{c} \right)^2 \right) F = 0
\]  

(2.3)

By applying a major approximation to separate the modes into TE and TM polarizations, \( F \) has the field components \( (E_\rho, E_\phi, H_z) \) and \( (H_\rho, H_\phi, E_z) \) respectively. Thus \( F_z \) is \( H_z \) (\( E_z \)) for TE (TM) modes. We separate variables with \( F_z = \phi(\phi) \Omega(\phi) Z(z) \) in equation 2.3 as:

\[
\frac{\partial^2 \Omega}{\partial \phi^2} + m^2 \Omega = 0
\]

\[
\frac{\partial^2 Z}{\partial z^2} + \frac{\omega^2}{c^2} (n^2 n_{\text{eff}}^2) Z = 0
\]

(2.4)

\[
\frac{\partial^2 \Phi}{\partial \rho^2} + \frac{1}{\rho} \frac{\partial \Phi}{\partial \rho} + \left( \frac{\omega^2 n_{\text{eff}}^2}{c^2} - \frac{m^2}{\rho^2} \Phi \right) = 0
\]

where \( n_{\text{eff}} \) is the effective refractive index, \( m \) the azimuthal number. The first equation has the solution \( \Omega(\phi) = \exp \left( i m \phi \right) \). The second equation is the standard wave equation for a slab waveguide. The third equation governs the radial dependence of the cavity mode and has solutions of Bessel functions within the disk, and Hankel functions outside of it. The radial solution \( \Phi(\rho) \) has the form:
\[ \Phi(\phi) = \begin{cases} J_m(\frac{\omega}{c} n_{eff} \rho) & \rho \leq R \\
 J_m(\frac{\omega}{c} n_{eff} R) \exp(-\alpha(\rho - R)) & \rho \geq R \end{cases} \] (2.5)

where \( \alpha \) is the decay constant, \( \alpha = \frac{\omega}{c} (n_{eff}^2 n_0^2)^{\frac{1}{2}}, \) \( (n_0 = 1 \text{ for air clad disks}) \), azimuthal number \( m \) is determined by the boundary conditions on the field at \( \rho = R \). This gives the transcendental equation:

\[ \frac{\omega}{c} n_{eff} J_{m+1}(\frac{\omega}{c} n_{eff} R) = (\frac{\omega}{R} + \eta \alpha) J_m(\frac{\omega}{c} n_{eff} R) \] (2.6)

where \( \eta = \frac{n_{eff}^2}{n_0^2} \) for a TE mode and \( \eta = 1 \) for a TM mode.

### 2.2.1.3 Quality Factor, Mode Volume, and the Free Spectral Range, etc.

An optical cavity is conventionally parameterized by its quality factor \( Q \), its free spectral range (FSR) and the effective volume of the cavity resonant mode fields \( V_{eff} \), usually given in units of the resonant mode wavelength \( (\frac{\lambda}{n})^3 \).

WGM resonators can have extremely high quality factors which makes them promising candidates for applications in optoelectronics and experimental physics. The first microdisk, also called the “pill-box” as illustrated in Figure 2.8, was devised by Marcatili in 1969 \(^3 \). Marcatili suggested the use of a microdisk as a passive filter in a photonic circuit, in particular because of the high quality factors that can be achieved in these
Figure 2.8: The ‘pill-box’ devised by Marcatili is the first microdisk proposed\(^3\).

structures. As mentioned earlier, the quality factor of a cavity mode can be expressed as the ratio between the wavelength of the resonant mode and its linewidth at half its maximum (FWHM):

\[
Q = \frac{\lambda}{\Delta\lambda}
\]  

(2.7)

where \(\lambda\) is the wavelength at which a resonance occurs and \(\Delta\lambda\) the linewidth of the resonant wavelength. \(Q\) may be understood as a measure of the rate of energy decay the resonant mode experiences within the cavity. Cavities do not have infinitely high \(Q\) because of both intrinsic losses and energy dissipation due to real world imperfections. There are several mechanisms through which resonance photons are dissipated from the cavity\(^63\). These losses can be due to the intrinsic tunnel coupling of the confined mode to a continuum of propagating modes, or through absorption by the active layer, or due to scattering by defects within the material or imperfection at the surfaces. The total
loss from the cavity can equivalently be written as the follows:

\[ Q^{-1} = Q_{\text{abs}}^{-1} + Q_{\text{scatt}}^{-1} + Q_{\text{tunnel}}^{-1} \]  

(2.8)

where \( Q^{-1} \) is the fraction of energy lost during a single round-trip of the cavity. The tunneling losses are usually negligible. The absorption term \( Q_{\text{abs}} \) depends on the active layer and on the excitation power, it is often dominating when the active layer contains quantum wells. In experiments published thus far, it is clear that scattering by imperfections of the structure is the dominating factor that limits the cavity quality factor. Researchers\(^{64,61,65}\) intentionally introduced a corrugation on the edges of microdisks. Their study showed that the corrugation degrades the optical quality of the disk, and that light leaves the cavity preferentially where surface defects were introduced.

The wavelength or frequency spacing between adjacent WGMs (\( m \) and \( m + 1 \)) of the
same radial order \( p \) is called the free spectral range (FSR), and is defined as

\[
\Delta \lambda = \frac{\lambda^2}{2\pi R n_{\text{eff}}}
\]  

(2.9)

where \( \lambda \) is the mode wavelength, \( R \) the radius of the microdisk cavity, and \( n_{\text{eff}} \) the effective refractive index. The number of modes and free spectral range are determined by the size of the microdisk. The larger the microdisk size, radius, or thickness, the higher the number of WGMs and the shorter the free spectral range. Because of its high quality factor and small modal volume, a microdisk is a great test bed for the sensitive assessment of materials quality and for realization of light-matter interactions.

2.2.2 The emitters

Optical microcavities such as the microdisk provide an environment for light to propagate in and form standing waves. To create photons, we need to embed optical emitters inside the cavity. These emitters are often in the form of material defects, or quantum structures such as the quantum dots (QDs) or the quantum wells (QWs). In this section, we focus our discussion on the QDs and the QWs.

2.2.2.1 Quantum dots and quantum wells

QDs are atom-like, tiny semiconductor particles with size typically on the order of nanometers. Their optical and electronic properties are vastly different from their bulk
Figure 2.10: Schematics of the density of states in bulk, quantum well and quantum dot materials.

By reducing all three dimensions of a system to lengths comparable to the wavelength of its electron wavefunction, or the effective Bohr radius, the continuous density of states associated with the band structure becomes discrete. Transitions between such discrete energy levels result in sharp spectral lines resembling delta-functions, which is a signature of QD emissions. This is a result of the recombination of electrons in the conduction band and holes in the topmost valence band. The reduction in Bohr radius due to additional confinement in the QDs in turn increases the binding energy of InGaN QDs to up to 67 meV, making it stable at room temperature. The electronic structure of a QD can be modified by the number of carriers it traps, due to their Coulomb interaction enforced by the confinement. An attractive Coulomb attraction between an electron and a hole leads to a slight decrease in energy.
by an amount known as the binding energy. Such an electron-hole pair is called a bound exciton, in analogy to free excitons found in bulk semiconductors. However, unlike the bulk excitons, the bound nature of the electron and hole pair is enforced by their confinement potential. The binding energy of the exciton is determined by the separation of the confined carriers, which in turn depends on the size of the QD and the internal electric field. As the QD becomes smaller, the decreasing separation between the electron and holes increases the Coulomb interaction and as a result increases the exciton binding energy. Such a separation has a dominant impact on the time taken for radiative recombination $\tau_{\text{rad}}$. The larger the region an exciton spans, the less likely the carriers will recombine in a given timeframe, and the overall radiative recombination lifetime $\tau_{\text{rad}}$ therefore increases. We compare this to a quantum well which spans a much larger region, excitons a QW are less confined and naturally have radiative recombination lifetime much longer compared to that in a QD.

QWs are structures formed in semiconductors by having a material sandwiched between two layers of another material with a wider bandgap. Carriers are confined in-plane instead of in all three spatial dimensions like in a QD. The presence of internal field in QWs also contribute to the delocalization of carriers, leading to a reduced overlap between the wavefunctions of electrons and holes and an increased probability of non-radiative recombination. Although it lacks superior carrier confinement property and as a result has a longer radiative recombination lifetime compared to a QD, the QW has a much larger capture cross section. When optically pumped by an-
other energy source, there is a much higher probability of carrier capture into the QWs because of the larger areal coverage. Most earlier works published on microcavities use QWs as the active medium\textsuperscript{71,72,73,74}. In recent years, there has been a growing interest in using QDs as the gain material in microcavities\textsuperscript{75,76,14,76}.

2.2.2.2 The growth of InGaN quantum dots

The semiconductor material used for studies in this thesis is the GaN/InGaN material system. The advantage of nitrides over other III-V semiconductor materials is the nitride’s high exciton binding energy. The binding energy $E_b$ is given by

$$E_b(n) = \frac{m^*_e}{m_e} \frac{1}{\epsilon_r^2} \frac{13.6eV}{n^2}$$ \hspace{1cm} (2.10)

where $m^*_e$ is the effective mass of electron. We compare two III-V semiconductors GaAs ($\epsilon_r = 12.9$, $\frac{m^*_e}{m_e} = 0.063$) and GaN ($\epsilon_r = 8.9$, $\frac{m^*_e}{m_e} = 0.2$) and obtain the binding energy of GaAs and GaN to be 4 meV and 34 meV respectively\textsuperscript{77}. The thermal energy, $kT$, at room temperature is approximately 25 meV, much lower than the binding energy of GaN at 34 meV. GaN and its alloys have much superior stability at room temperature compared to other III-V materials\textsuperscript{78}. In addition to this, as mentioned earlier, the additional confinement potential imposed by a QD or a QW can further reduce the Bohr radius which in turn increases the binding energy, giving values as high as 50 meV and 67 meV for non-polar QWs and QDs, respectively\textsuperscript{79,80}. A high exciton binding
energy is desirable as it reduces the chance of thermal decomposition of the electron-hole pair, and hence leads to improved performance at room temperature. However, note that the presence of internal polarization fields may result in bent band edges, which in turn causes asymmetric spatial separation of the electron and hole wavefunctions. This reduces the electron-hole wavefunction overlap and increases the binding energy.

InGaN QD growth is a very involved and challenging process. Although a variety of epitaxial growth techniques have been proposed and studied, most of the methods reported only provide the electron-microscopic detection of InGaN clusters within thin QW regions of the material, rather than the strict detection of isolated nanocrystals of QDs. They also fail to provide spectral evidence of delta-like discrete transitions characteristic of the QDs. These growth procedures rely mainly on self-assembly methods, which are based on the energetically favorable driving force of 3D nano-island formation.

One method to grow InGaN QDs is the well-known Stranski-Krastanov (SK) growth. It is one of the three primary modes by which thin films grow epitaxially at a crystal surface. SK growth rely on the lattice mismatch between the substrate and the deposited layer. Initially, complete films up to several monolayers thick grow layer by layer on a crystal substrate. Beyond a critical layer thickness, the accumulated strain relaxes to form little 3D ‘islands’ on the underlying layer, which is then referred to as the wetting layer. Growth of InGaN QDs using SK-growth has been reported (Adelmann et al., 2000; Pretorius et al., 2008) using molecular beam epitaxy (MBE). However, the standard SK growth method is more often used in the growth of arsenide and phosphide
Figure 2.11: Flowchart of the modified droplet epitaxy (MDE) process. 

QDs, as the strain due to lattice mismatch between InGaN, GaN and the sapphire substrate, as well as the many defects incorporated into the material during growth, make the environment non-ideal for InGaN QD formation.

Another possible InGaN QD growth method involves the initial patterning and processing of substrates to form isolated InGaN regions, with spatial dimensions that bring about a discreet density of states. This technique allows for a greater degree of precision in areal density control and spatial positioning, but requires too much pre-processing from the device fabrication point of view.

The InGaN QDs fabricated in this study utilize a metalorganic vapor-phase epitaxy (MOVPE) based method called the modified droplet epitaxy (MDE), developed by...
our collaborators in Rachel Oliver’s group at Cambridge University, UK. This method to a great extent avoids the aforementioned growth difficulties. The growth process is illustrated in Figure 2.11.

The MDE process involves the initial growth of a $\text{In}_x\text{Ga}_{1-x}\text{N}$ layer with a set composition for approximately 3 nm in thickness. During this process, In rich regions are expected to form at step edges and dislocations throughout the epilayer. In the next step, the layer is annealed under nitrogen environment at the epilayer growth temperature for a fixed amount of time, usually around 30 seconds. This encourages the decomposition of In rich regions within the layer into nitrogen gas and metal In/Ga, causing the formation of a pitted surface covered in an In-rich metal layer. Some of the metal evaporates, while a significant amount of the decomposed metal accumulates and forms nanoscopic droplets due to surface tension. Figure 2.11 (d,ii) shows an atomic force microscope image of an uncapped annealed InGaN layer, the scattered white dots and islands are the metallic droplets$^4$. Following this, a capping GaN layer is grown on top of the material. Re-nitridation of the In/Ga metallic droplets happens during this process, resulting in the formation of InGaN QDs within the GaN matrix. The In composition in the InGaN QDs formed through this process is estimated to be between 20$\%$- 30$\%$.

The areal density of QDs and their size distribution can be controlled to a certain extent by adjusting the temperature and anneal time during the growth process. InGaN QDs grown for experiments presented in this thesis have a broad emission spectrum
spanning from 400 nm to 480 nm in wavelength. Although the QD size distribution can be somewhat controlled, the precise control of the spatial position of each QD cannot be achieved. Because of this lack of precise control during growth, QDs located at different parts of the same wafer may behave differently. The areal density and size distribution of QDs grown under the same condition in different growth cycles may also differ by as much as an order of magnitude. This inhomogeneity in QD quality may lead to variations in performance of devices made from these QDs.

2.2.2.3 Fragmented Quantum Wells

We take a closer look at an AFM image of the uncapped layer during MDE growth. From Figure 2.11 (d, ii), we observe a spread of QDs of different sizes (white in color) over a network of gaping holes and raised ridges (light gray in color). We call this layer
Figure 2.13: Atom probe pictures showing (a) InGaN distribution (marked pink) in 3 layers of InGaN QDs + fQWs and (b) isosurfaces of the 3 emitter layers.

The fragmented quantum wells (fQWs). These fQWs are analogous to broken quantum wells and exhibit 2-dimensional in-plane quantum confinement. Some of the QDs sit on top of the fragmented quantum wells while others are in the pits in direct contact with the GaN layer (dark gray in color) underneath. The fQW layer also exhibits significant variations in width, thickness, and In composition, which varies with anneal temperature. Figure 2.12 shows an AFM image of an uncapped GaN epilayer with strips of InGaN fQWs aligned roughly along the [11-20] direction. The average width of the InGaN fQW strips is approximately 70 nm. The inset to Figure 2.12 shows an AFM line profiling of a selected region on the uncapped InGaN epilayer having a height variation of approximately 2.5 nm. The center of each fQW strip has a greater In concentration.
compared to the edges, creating a graded electronic potential that allows carrier to be confined within the strip. 2.13 shows the 3D atom probe pictures of a sample containing 3 InGaN QD + fQW layers. I would like to thank Austin Akey for taking these pictures.

The presence of the InGaN fQW layer, intrinsic to the MDE process, brings complexity to the gain layer of the material, as the emission spectra of the MDE grown InGaN QD samples would contain both the emission signatures of the InGaN QDs and the fQWs. Figure 2.14 shows the room temperature emission from a GaN/InGaN fQWs wafer optically excited by a 380 nm Ti-Sapphire frequency doubled laser spanning between 420 nm and 490 nm. In general, fQW materials emit with stronger intensity compared to QD materials because of their larger optical density of states. The center of the fQWs emission spectra is experimentally measured to be slightly red-shifted from the center of the QDs emission, as we will discuss in details in later chapters.

The heterogeneous nature of the gain layer makes it difficult to delineate the unique
role of the QD in its optical behavior, but at the same time provides an interesting opportunity to explore the different effects of QDs and fQWs on a range of cavity activities, such as lasing and photon dynamics. The optical microcavity, together with the emitters, form an excellent platform to study the fundamental properties of GaN/InGaN optical devices.

2.3 Lasing Theory

2.3.1 Basic Laser Operations

A laser is a device that emits light through a process of optical amplification called stimulated emission. It is unique from other types of light sources because of its spatial and temporal coherence. Spatial coherence implies that light emitted from a laser is able to remain relatively collimated over a large distance, while temporal coherence means the emitted light is of a single phase and wavelength.
To understand the process of optical amplification in a laser cavity\textsuperscript{86}, let’s consider a two-level system with energy $E_1$ in the lower energy state and $E_2$ in the higher energy state, separated by a bandgap energy of $E_2 - E_1 = \Delta E$. Electrons can undergo transition from one level to another by absorbing or releasing energy. The electron in the higher energy state can only remain in the state for a finite period of time, before it couples to the vacuum fluctuation field and decays to the lower level with the release of the bandgap energy $\Delta E$, usually in the form of a photon. This process is called spontaneous emission, and the average length of time it takes for an electron to relax into the lower energy state is called the spontaneous emission lifetime. Conversely, an electron can also transit from the lower energy state $E_1$ to the higher energy state $E_2$ by absorbing a photon with energy $\Delta E$, and this process is called absorption\textsuperscript{87}.

In the presence of an external stimulus, the probability of electron transition from $E_2$ to $E_1$ can be dramatically increased. An incident photon with frequency equivalent to the bandgap energy can trigger the transition of an electron from $E_2$ to $E_1$, producing an additional photon with the same frequency and phase as the incident one. This process is called stimulated emission. The transition probability of stimulated emission is the same as that of absorption. It is therefore necessary to prepare the system with more electrons in the higher energy level to produce a net gain for stimulated events to happen. This process is called population inversion. Once population inversion is achieved, a spontaneous emission event will trigger stimulated emission, leading to the onset of lasing\textsuperscript{87}. 

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In an ideal two-level system, only radiative transitions are considered. However, non-radiative recombination can also happen in which excited electrons relax to the lower energy state without emitting a photon. The average time it takes for a non-radiative recombination event to happen is called the non-radiative recombination lifetime. Examples of non-radiative processes include carrier recombination at defect sites or with surface states, leading to a loss of carriers and decrease in spontaneous emission. Because of this, it is essential that great care be taken during the material growth process in order to minimize defect density. It is also important that the non-radiative lifetime is significantly longer than the radiative lifetime in any efficient light emitting system.

The different stages of lasing can be better understood through a photon density

Figure 2.16: Plot of photon density against excitation power in (a) linear and (b) log-log scale. The three regimes of lasing operation: spontaneous emission, amplified spontaneous emission (ASE), and stimulated emission are clearly indicated in the plots.
plot, where the three different regimes of lasing, namely spontaneous emission, amplified spontaneous emission, and stimulated emission, are clearly delineated. Figure 2.16(a) shows a typical lasing curve in linear scale and Figure 2.16(b) shows the same curve in log scale. The x-axis indicates the excitation power incident on the laser and the y-axis represents the photon emission intensity. As we pump the laser with excitation energy, the process is first dominated by spontaneous emission, exhibited in the linear increase in overall photon density within the cavity. As carrier population in the excited state increases with increasing pump power, the rate of stimulated emission becomes comparable to spontaneous emission, and we enter the regime of amplified spontaneous emission (ASE). In the ASE region, photons of all frequencies and phases are amplified, leading to an exponential increase in the total population of photon inside the cavity. However, due to the large spontaneous emission events involved, the overall photons emitted are still incoherent, with random phases and a spread in wavelength, although there may exist some local groups of coherent photons. Elimination of incoherent photons from the cavity at this stage will shorten the ASE process and make the lasing process more efficient. As excitation power is further increased, the rate of stimulated emission takes over spontaneous emission at the lasing threshold, and lasing is achieved. Lasing threshold is defined as the pump power at which the linear fit to the post-threshold emissions intersects the x-axis. The three regimes of laser operation are clearly indicated on Figure 2.16.
2.3.2 Mathematical description of laser parameters

The lasing process can be described mathematically by the coupled laser rate equations. In this section, we use the steady-state solution\textsuperscript{90} of the rate equations for microcavity semiconductor lasers to investigate the roles various parameters play on the threshold and other behaviors of a laser.

The coupled laser rate equations describe the change in carrier and photon densities inside a cavity throughout the lasing process:

\[
\begin{align*}
\frac{dN}{dt} &= \frac{I}{qV} - \left(\frac{1 - \beta}{\tau_{sp}} + \frac{\beta}{\tau_{sp}}\right) N - \frac{N}{\tau_{nr}} - \frac{gp}{V} \\
\frac{dp}{dt} &= (\gamma g) p - \frac{\beta NV}{\tau_{sp}}
\end{align*}
\] (2.11)

and the steady state solution takes the form:

\[
I = \frac{q\gamma}{\beta} \left[ \frac{p}{1+p} (1 + F) \left( 1 + \beta p + \frac{\tau_{sp}}{\tau_{nr}} \right) - F \beta p \right]
\] (2.12)

where \(N\) is the carrier population, \(I\) the injection current, \(q\) the charge of an electron, \(V\) the volume of active material, \(g\) the active material gain, \(\beta\) the spontaneous emission factor, \(p\) the photon number, \(F(N_0, V, \beta, \gamma, \tau_{sp})\) the photon number in the lasing mode, \(\gamma = \frac{1}{\tau_{cav}}\) the cavity loss rate, \(\tau_{cav}\) the cavity lifetime, \(\tau_{sp}\) the spontaneous emission lifetime, and \(\tau_{nr}\) the non-radiative recombination lifetime.
In the following, we study the effect of changing spontaneous emission factor, spontaneous emission lifetime, non-radiative recombination lifetime, active material volume, and cavity decay rate, on the lasing threshold and post-threshold slope efficiency through simulations.

\section*{Spontaneous emission factor, $\beta$}

The spontaneous emission factor ($\beta$) refers to the fraction of spontaneous emission that is coupled to a single discrete mode of interest, usually the lasing mode, versus all other channels in a laser cavity. It takes on the value between 0 and 1. Here, we vary $\beta$ between $1 \times 10^{-4}$ and 1 and plot the corresponding LI-LO curves in Figure 2.17. We also perform a linear fit on the linear part of the lasing curve beyond threshold to obtain...

**Figure 2.17:** Light in – light out curves of photon population plotted against the injection current in log scale (LEFT) and linear scale (RIGHT) with varying values of the spontaneous emission factor $\beta$. 

![L-L curve plotted on a log scale](image1)

![L-L curve plotted on a linear scale](image2)
Figure 2.18: Table and plots showing the effects of changing the spontaneous emission rate $\beta$ on the lasing threshold and slope of the post-threshold lasing curve.

<table>
<thead>
<tr>
<th>$\beta$</th>
<th>Threshold (mA)</th>
<th>Slope (mA$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.60E-04</td>
<td>6.25E+03</td>
</tr>
<tr>
<td>0.1</td>
<td>2.46E-03</td>
<td>6.25E+03</td>
</tr>
<tr>
<td>0.01</td>
<td>2.41E-02</td>
<td>6.25E+03</td>
</tr>
<tr>
<td>0.001</td>
<td>2.40E-01</td>
<td>6.25E+03</td>
</tr>
<tr>
<td>0.0001</td>
<td>2.40E+00</td>
<td>6.25E+03</td>
</tr>
</tbody>
</table>

The lasing threshold and post-threshold slope. The values to these quantities and the plots are presented in Figure 2.18. From the plots, we see that a larger spontaneous emission factor leads to a lower lasing threshold, but does not have an effect on the post-threshold lasing efficiency. Physically, the spontaneous emission factor dictates the percentage of emitted photons into the lasing mode, it thus makes sense that with larger $\beta$, more photons are going into the lasing mode, and lasing is achieved at a lower threshold.

**SPONTANEOUS EMISSION LIFETIME, $\tau_{sp}$**

$\tau_{sp}$ is the spontaneous emission lifetime, which is the average amount of time it takes for a spontaneous emission event to happen in the laser cavity. We vary $\tau_{sp}$ between the value of $1 \times 10^{-9}$ s and $5 \times 10^{-7}$ s and plot the corresponding lasing curves in Figure 2.19. The lasing threshold and slope efficiencies are shown in Figure 2.20. There is a rapid increase in lasing threshold with decreasing $\tau_{sp}$, but the lasing curve slope efficiency stays largely constant across different values of $\tau_{sp}$ once the onset of lasing is
Figure 2.19: Light in – light out curves of photon population plotted against the injection current in log scale (LEFT) and linear scale (RIGHT) with varying values of the spontaneous emission lifetime $\tau_{sp}$.

Figure 2.20: Table and plots showing the effects of changing the spontaneous emission lifetime $\tau_{sp}$ on the lasing threshold and slope of the post-threshold lasing curve.
Figure 2.21: Light in – light out curves of photon population plotted against the injection current in log scale (LEFT) and linear scale (RIGHT) with varying values of the non-radiative recombination lifetime $\tau_{nr}$.

<table>
<thead>
<tr>
<th>$\tau_{nr}$ (s)</th>
<th>Threshold (mA)</th>
<th>Slope (mA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.00E-09</td>
<td>2.24E-02</td>
<td>6.23E+05</td>
</tr>
<tr>
<td>3.00E-09</td>
<td>1.97E-02</td>
<td>6.24E+05</td>
</tr>
<tr>
<td>4.00E-09</td>
<td>1.84E-02</td>
<td>6.24E+05</td>
</tr>
<tr>
<td>5.00E-09</td>
<td>1.76E-02</td>
<td>6.24E+05</td>
</tr>
<tr>
<td>6.00E-09</td>
<td>1.71E-02</td>
<td>6.24E+05</td>
</tr>
</tbody>
</table>

Figure 2.22: Table and plots showing the effects of changing the non-radiative recombination lifetime $\tau_{nr}$ on the lasing threshold and slope of the post-threshold lasing curve.

Non-radiative recombination lifetime, $\tau_{nr}$

We vary the non-radiative recombination lifetime $\tau_{nr}$ between $2 \times 10^{-9}$ s and $6 \times 10^{-9}$ s, and plot the corresponding lasing curves in Figure 2.21. Values of the lasing threshold and post-threshold slope efficiency are presented in Figure 2.22. Again, a non-linear
Figure 2.23: Light in – light out curves of photon population plotted against the injection current in log scale (LEFT) and linear scale (RIGHT) with varying values of the active material volume \( V \).

Figure 2.24: Table and plots showing the effects of changing the active material volume \( V \) on the lasing threshold and slope of the post-threshold lasing curve.

decrease in lasing threshold with increasing \( \tau_{nr} \) is observed, while there is no significant change in the slope of the lasing curves after the device begins to lase.

**Active material volume, \( V \)**

The cavity volume for our 1 m microdisk is approximately \( 1.57 \times 10^{-3} \) cm\(^3\). Here, we vary \( V \) between \( 1 \times 10^{-15} \) cm\(^3\) and \( 1 \times 10^{-13} \) cm\(^3\) and plot the corresponding lasing
Figure 2.25: Light in – light out curves of photon population plotted against the injection current in log scale (LEFT) and linear scale (RIGHT) with varying values of cavity loss rate $\gamma$.

<table>
<thead>
<tr>
<th>$\gamma$ (s$^{-1}$)</th>
<th>Threshold (mA)</th>
<th>Slope (mA$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.00E+10</td>
<td>2.24E-02</td>
<td>6.25E+05</td>
</tr>
<tr>
<td>2.00E+10</td>
<td>2.24E-02</td>
<td>3.13E+05</td>
</tr>
<tr>
<td>3.00E+10</td>
<td>2.25E-02</td>
<td>2.08E+05</td>
</tr>
<tr>
<td>4.00E+10</td>
<td>2.25E-02</td>
<td>1.53E+05</td>
</tr>
<tr>
<td>5.00E+10</td>
<td>2.25E-02</td>
<td>1.25E+05</td>
</tr>
</tbody>
</table>

Figure 2.26: Table and plots showing the effects of changing the cavity loss rate $\gamma$ on the lasing threshold and slope of the post-threshold lasing curve.

curves in Figure 2.23. We observe an increase in the lasing threshold with increasing volume, but no change in post-threshold slope efficiency.

**Cavity loss rate, $\gamma$**

Cavity loss rate $\gamma = \frac{1}{\tau_{cav}}$ describes the rate at which photons are lost from the cavity, where $\tau_{cav}$ is the cavity photon lifetime. We vary $\gamma$ between $1 \times 10^{10}$ s$^{-1}$ and $5 \times 10^{10}$ s$^{-1}$.
and plot the corresponding lasing curves in Figure 2.25. The lasing threshold and post-threshold slope efficiencies are shown in Figure 2.26. Note here that with larger values of \( \gamma \), the lasing threshold increases, and the post-threshold slope efficiency decreases. The cavity loss rate \( \gamma \) thus plays a crucial role in controlling the total number of photons inside the cavity, and consequently affects the lasing threshold and post-threshold lasing efficiency. Conversely, by looking at the post-threshold slope efficiency of lasing curves, we can gain important insight into the process of photon loss and cavity lifetime of any cavity laser of our interest.

2.3.3 **Purcell effect**

The Purcell effect is the enhancement of spontaneous emission rates of atoms or emitters when they are incorporated into a resonant cavity versus being in free space\(^9\). When a photon emitter is properly coupled to a cavity: spectrally on resonance and spatially located at the antinode of the vacuum field, the spontaneous emission rate is enhanced by a Purcell factor given by:

\[
F_p = \frac{3}{4\pi^2} \left(\frac{\lambda}{n}\right)^3 \frac{Q}{V_{\text{eff}}}
\]

(2.13)

where \( \lambda \) is the wavelength of the cavity mode, \( n \) the index of refraction of the cavity, \( Q \) the quality factor of the mode, and \( V_{\text{eff}} \) the cavity modal volume.

Optical cavities with high \( Q \) factors and small mode volumes have high Purcell factors
and consequently a higher spontaneous emission rate. Large Purcell factors are desirable for low threshold lasers, for it increases the spontaneous emission rate of the lasing mode\textsuperscript{92}. In addition, in order to maximize the light-matter interaction, the cavity resonance should overlap the emitters both spatially and spectrally. The desire for high Q and low V cavities serves as the guiding principle for cavity design in this work.
This chapter focuses on the fabrication and analysis of the microdisk laser. The chapter is divided into four sections. We begin by introducing the design philosophies behind the microdisk laser. We then elaborate on the fabrication process in detail, this is the fabrication method used throughout most part of this dissertation, unless
otherwise stated. Following that, we analyze a first set of low-threshold microdisk lasers made in the GaN/InGaN material system, and finally discuss the role different types of emitters play in low threshold cavity lasing.

3.1 Design of the microdisk

3.1.1 Mode selection

To design a microdisk cavity suitable for our material system, we perform simulations using finite difference time domain (FDTD) methods to study the theoretical limitations and emission patterns of the WGMs in microdisks. FDTD is a numerical technique using Yee cells to compute the electrodynamics of a system by finding approximate solutions associated with the Maxwell’s equations. Maxwell’s differential equations tell us the change in E-field in time is dependent on the change in H-field in space, while the change in H-field in time is dependent on the E-field in space. This forms the basic FDTD time-stepping relation: at any point in space, the updated value of the E-field in time is dependent on the stored value of the E-field and the numerical curl of the local distribution of the H-field in space. The H-field is time-stepped in a similar manner: at any point in space, the updated value of the H-field in time is dependent on the stored value of the H-field and the numerical curl of the local distribution of the E-field in space. The FDTD method iterates the E-field and H-field values in a time-stepped process where the electromagnetic waves under consideration propagate
in a numerical grid stored in the computer memory. Implementing this process helps us to understand with ease the steady-state field distribution of electromagnetic waves in a system and provides a picture to the spectral resonances of the cavity. Simulations in this dissertation are performed using the commercially available software Lumerical FDTD solutions\(^2\).

We simulate GaN microdisks with either 1 \(\mu\text{m}\) diameter or 2 \(\mu\text{m}\) diameter each with a thickness of 200 nm using Lumerical FDTD solutions. The resultant cavity emission spectrum is shown in Figure 3.1. There is a greater number of modes in a 2 \(\mu\text{m}\) diameter disk compared to a 1 \(\mu\text{m}\) meter one. The free spectral range of the first order WGM in the 2 \(\mu\text{m}\) microdisk is approximately 12 nm, smaller than that of the 1 \(\mu\text{m}\) disk at approximately 25 nm. The number of modes and the free spectral range are determined by the size of the microdisk. An increase in microdisk diameter or thickness will lead to an increase in the number of WGMs and a decrease in the free spectral range. A
3.1.2 Optical isolation

As with every cavity system, perfect isolation of the cavity from its surrounding medium is critical in reducing photon loss due to evanescent coupling to the surrounding environment in order to obtain the highest Q factor. To optically isolate the microdisk, we suspend the cavity atop of a supporting post so that the periphery of the disk where first order WGMs are located at are sandwiched between air. Unlike most III-V materials such as GaAs/AlGaAs, the creation of such a post in the GaN/InGaN material...
system is a great fabrication challenge due to the presence of QCSE\textsuperscript{94}. It requires the carefully controlled growth of a material stack consisting a sacrificial super lattice (SSL) layer sandwiched between two layers of GaN material. The SSL is made of alternating InGaN layers with different In composition, and is selectively removed during a photo-electrochemical etch process to form the supporting pedestal. Much work was done in optimizing the structure of this superlattice for optimal photoelectrochemical selective etching\textsuperscript{95,96}. On the one hand, the SSL layer has to be thick enough so that the air gap created provides enough isolation to the suspended disk to prevent a severe degradation in Q. On the other hand, we also do not want to make the SSL unnecessarily thick as it contributes to lattice strain and increased internal field. To determine the thickness of the airgap, we simulate 2 $\mu$m microdisks with GaN substrate ($n = 2.5$) located beneath the disk at various separation distances $d$ ranging from 50 nm to 350 nm. The resultant Q values are plotted in Figure 3.2. The plot displays Q values of two different first order modes near 413 nm and 436 nm, with the horizontal lines indicating Q of the respective modes when the microdisk is suspended in air with no substrate ($d = \infty$). We observe that at a small separation distance of $d = 50$ nm, the Q degrades by more than two orders of magnitude, whereas Q values are generally on the same order of magnitude as a disk with no substrate for $d \geq 200$ nm. Disks with small distances of separation do not provide sufficient optical isolation for the cavities.

As with any microcavity designed for low threshold lasing, high quality factors of its modes are desirable. Microdisks that include imperfections such as surface roughness,
Figure 3.3: Scanning electron microscope image of a 1 µm diameter, 200 nm thick GaN microdisk with a visible whisker attached to the bottom surface of the top GaN membrane.

material defects, and whiskers as a result of fabrication imperfection are susceptible to absorption and scattering which leads to a lower Q factor. Whiskers are undesirable cone-shaped structures attached to the under-surface of a cavity, formed sometimes during the photoelectrochemical etching process necessary to create the supporting post for a suspended cavity in GaN/InGaN. The working mechanism of this process will be discussed in greater details in Section 3.2.3. The formation of whiskers stems from the loss of carriers, especially holes, near threading dislocations running through the material. An example of a microdisk with one whisker is showns in 3.3. In a microdisk, due to the slight variation in localization, WGMs can have different quality factors and different susceptibility to defects and imperfections. First order WGMs are located near the periphery of the disks and may be susceptible to whiskers formed directly underneath the higher field region causing a degradation in $Q$. Higher order WGMs
are spatially localized further inside the microdisk and have stronger tendencies to couple to the post of the microdisk. They require greater undercut to become spectrally visible. We simulate the effect of whiskers by placing cone-shape GaN structures 20 nm in diameter and 100 nm in height on the under-sufface of a microdisk at field maxima and calculate the change in Q. We also include the GaN substrate at d = 200 nm below the undersurface of the GaN microdisk cavity. For a mode near 402 nm, the Q of the microdisks changes from $9.67 \times 10^6$ to $9.61 \times 10^6$ with one whisker and $2.67 \times 10^6$ with five whiskers, which are both within the same order of magnitude as Q of a micodisk without whiskers. Therefore, a few whiskers at a substrate separation distance of $d = 200$ nm have little effect on the cavity Q, but substantial amount of whiskers will result in poorer optical isolation and a decrease in quality factor of the cavity.

We also optimize for the diameter of the post so understand how much undercut we need to provide enough optical isolation to the disk without introducing additional modes. As shown in Figure 3.4, a 2 µm diameter GaN microdisk cavity with a post

Figure 3.4
with the same diameter effectively creates a much larger cavity, which increases the number of modes overlapping the gain spectrum. A post with 1 µm diameter gives the microdisk similar amount of high-Q cavity modes to a disk without any post.

3.2 Materials and fabrication

3.2.1 Material growth parameters

The material used in this dissertation consist of GaN grown on sapphire substrate using metalorganic vapor-phase epitaxy MOVPE. It contains InGaN QWs or QDs made from the MDE method mentioned in the previous chapter. These materials are grown
by our collaborators in Rachel Oliver’s group at Cambridge, UK. The general structure of the GaN/InGaN wafer is shown in the schematics in Figure 3.5 and contains 1, 3, 5 or 7 layers of InGaN QW or In$_{0.2}$Ga$_{0.8}$N QDs gain layer(s) in the middle of a 200 nm membrane of intrinsic GaN. The exact number of layers of active material may vary for devices used in different experiments. Below the 200 nm cavity membrane is a 200 nm layer of undoped In$_{0.051}$Ga$_{0.949}$Mn$_{0.065}$Ga$_{0.935}$N sacrificial superlattice which rests on top of an n-GaN pseudo substrate overlying the sapphire substrate. The 20 nm Al$_{0.2}$Ga$_{0.8}$N layer serves as an electron blocking layer that prevents the breakdown of the gain material during the photoelectrochemical etching process$^{99,100}$.

The growth starts with a standard Si-doped LDD GaN template on sapphire$^{101}$. The sacrificial superlattice was then grown and capped by 10 nm of uid-GaN. The 20 nm of Al$_{0.2}$Ga$_{0.8}$N was grown at 1050°C, followed by the growth of 60 nm of uid-GaN on top of which 3 layers of InGaN active medium (QW, fQW, or QD) were then grown. After the final InGaN active medium layer was grown, a 10 nm GaN capping layer was grown at the same temperature as the InGaN in a N$_2$ environment, followed by a further 80 nm of uid-GaN grown at 1000°C using H$_2$ as the carrier gas. The final structures are shown in Figure 3.5.

To grow the InGaN QDs, an initial 2.5 nm InGaN epilayer was grown at 710 °C followed by 30 seconds of post-growth N$_2$ anneal causing the formation of In rich metallic droplets. When the capping layer is grown, these droplets re-react with ammonia leading to the formation of InGaN QDs. GaN barrier layers were then grown at 710 °C.
AFM image of the uncapped QD and fQW epilayer is shown in Figure 3.6. The areal density of the QDs is estimated to be approximately $1 \times 10^{10} \text{ cm}^{-2}$.

To better understand the distribution of the QDs position, whether they sit on fQWs or bare GaN, we performed image analysis using the AFM image of an uncapped layer as shown in Figure 3.6. We do this through identifying the grayscale range (between 1 and 255) each type of emitter is associated with, and then performing a classification of regions over the entire image. To generate data, we randomly sampled 32 points each for the bare GaN layer, the QDs, and the fQWs from the AFM image, and recorded their grayscale values. Figure 3.7 shows the distribution of emitters along grayscale value ranges. From the histogram, it looks like differentiating between QD and fQW is not very straight forward. Our strategy is to identify points on the image as regions of...
either bare GaN or fQWs. Since the distribution of QDs is fairly uniform as observed from the AFM image, we are able to approximate the percentage of QDs standing alone on bare GaN and the percentage of QDs that have underlying fQWs as the percentage areal coverage of GaN and fQWs, respectively. Our classification algorithm calculates a 79.4% areal coverage of fQWs and 20.1% of bare GaN. We also note that the areal density of fQW can vary between different locations on the sample sample, and between samples grown in different growth cycles. A different sample grown using the same process was estimated to have a fQW density of 64

InGaN QWs are grown using the same technique as above. To minimize the indium loss from the QW during barrier growth, GaN barriers were grown, at the same temperature as the InGaN QWs, at 740°C. The nominal thickness for the QWs is 2.5 nm. This method resulted in continuous QWs with no visible well width fluctuation measured
Figure 3.8: AFM image of uncapped InGaN QW layer during growth.

using transmission electron microscopy. An AFM image of the uncapped QW layer is shown in Figure 3.8.

3.2.2 Fabrication flow

The general fabrication process of a microdisk involves 3 major steps: creating a hard mask of the microdisks; transferring the mask pattern into the material using reactive ion etching (RIE); and finally creating a post under the microdisk cavity by selectively removing parts of the material beneath the cavity through a process called photoelectrochemical etching, so as to achieve optical isolation.

The latter two steps are common in all fabrication processes used to create GaN/InGaN microdisks in this study, but the first step can be achieved through either of the two following techniques: 1) with a direct deposition of silica beads as the hard masks; 2) using electron-beam (e-beam) lithography to create disk patterns. Both methods can produce tens of thousands of microdisks on the same wafer in one fabrication cycle,
which is extremely useful in getting statistically significant information about the microdisks, in the presence of material inhomogeneity inherent to the gain layer. When the precise location and identity of an individual microdisk is not important, the simpler and more straight-forward silica beads method is often used in preference to e-beam writing. However, if an experiment involves repeated measurements of the same device such that the identity and location of individual microdisks are important, we employ the second method of fabrication. We present the fabrication process of each method in details below.

(1) Using silica beads

We begin by cleaning a fresh GaN wafer thoroughly with piranha solution made from a 3:1 mixture of concentrated sulfuric acid (H₂SO₄) and hydrogen peroxide (H₂O₂) remove any organic residues from the wafer, followed by soaking it in acetone and IPA solutions in an ultrasonic sonicator for 2 minutes each. Next, we deposit a diluted solution containing silica beads of the desired size onto the cleaned sample surface using a micropipette. The sample is then left to dry on a hotplate so that any solvent can be evaporated rapidly and completely. At the end of this process, most of the silica beads aggregate to form clusters, while a fraction of them are present on the sample surface as individual beads, which are useful in creating isolated single microdisks. The amount of individual beads present can be controlled by adjusting the concentration of silica bead solution before deposition. Microdisks of various diameters can be fabricated with
Figure 3.9: Overview of the microdisk fabrication process using silica beads, which includes patterning using the silica beads, dry etching for pattern transfer into the material, and an selective wet etching undercut to optically isolate the microdisk cavities.

silica beads of the corresponding sizes as the hard masks.

The deposited silica beads serve as hard masks during the inductively coupled plasma etching process, which operates at 500 W in a nitrogen/chlorine environment with a flow rate of 25/25 sccm. By controlling the etch duration, we transfer the pattern down into the material and remove approximately 500 nm of GaN. We then evaporate a Ti/Pt metal grid onto our sample which serves as the cathode during photoelectrochemical (PEC) etching, a bandgap-selective process that preferentially etches the sacrificial superlattice into a post, creating an air gap between the microdisk cavity and the wafer below so as to obtain optical isolation. An optical microscope image of microdisks made using silica spheres as hard mask is showns in Figure 3.10

Using silica spheres as hard masks provides us with an easy and fast way to make
microdisks. However, this method is limited by the available dimensions of the silica beads, which do not run continuously in size. It also does not allow the precise control over the positioning of each microdisk we write. Furthermore, re-sputtering of silicon dioxide onto the sidewall of the microdisk cavity during dry etch can be difficult to remove sometimes, even chemically, and this lowers the quality of the microdisks. To circumvent these problems, we use electron-beam lithography to accurately define the size and position of the microdisks.

(2) Using ebeam lithography

We first deposit onto a cleaned GaN wafer a 5 nm layer of SiO$_2$, followed by a thin metal conductive layer consisting of Ti / Au / Ti (2 nm / 5 nm / 3 nm) to prevent charging
during the subsequent e-beam lithography. The role of the SiO$_2$ layer is to prevent the diffusion of metal into the GaN membrane. Approximately 500 nm of FOX-16 negative e-beam resist is then spun evenly onto the sample. We use e-beam lithography to pattern the FOX-16 into 1 \( \mu m \) diameter microdisks. Upon development in TMAH, the exposed parts of FOX-16 form disk-shaped SiO$_2$ which serve as the hard masks during inductively coupled plasma etching. The hard mask, Ti/Au/Ti metal layer, and the 5nm of SiO$_2$ can be removed chemically after pattern transfer with dry etching. The rest of the fabrication process is similar to that described in the section above. Figure 3.3 shows the scanning electron microscope (SEM) image of a fabricated 1 \( \mu m \) diameter microdisk.
3.2.3 Photoelectrochemical etching (PEC etching)

GaN is a chemically inert material that was largely processed using dry etching methods in the past. However, creating a photonic cavity in GaN requires the removal of materials immediately below the cavity so as to create a suspended cavity and air gap necessary for optical isolation, without compromising the integrity of the cavity. This is difficult to achieve with dry etching alone. Instead, selective wet chemical etching is required to create a suspended cavity structure. However, the unusual chemical stability of III-nitride materials makes it difficult to identify a reliable and controlled wet etchant at room temperature. Wet-etching of III-nitrides in KOH at room temperature occurs at a relatively slow, on the order of tens of angstroms per minute\(^94\). Etching at elevated temperature increases the etch rates, but does not allow an isotropic etch as only the N-face of the III-nitride material is attacked.

A rapid, room-temperature, bandgap-selective, photo-assisted wet etching technique has been demonstrated in the successful etching of III-nitride materials, this is known as the photoelectrochemical (PEC) etch\(^94\). It is a critical process in the fabrication of microdisks and deserves special attention. We dedicate this section to explaining the working principles behind PEC etching.

In short, PEC is a photo-assisted oxidation process that selectively removes In\(_x\)Ga\(_{1-x}\)N in preference to GaN. The PEC set-up consist of an above bandgap 1000W Xe lamp and an electrolyte cell containing 0.004M diluted hydrochloric acid. A GaN filter is placed
Figure 3.12: A standard PEC set-up consisting of a Xe lamp, a GaN filter, the sample with a metal cathode, and the electrolyte.

below the light source and above the electrolyte cell and serves the purpose of filtering off wavelengths above the GaN bandgap.

During the PEC process, the semiconductor sample serves as the anode and a metal grid patterned on the GaN surface serves as the cathode. The metal contact is made of e-beam evaporated Ti (5 nm) and Pt (50 nm) in the form of a grid placed on top of the n-doped GaN surface underneath the sacrificial superlattice. Careful photolithography work and thorough cleaning ensure good contact between the metal grid and the GaN. Incident light from the Xe lamp with wavelengths below the GaN bandgap but above the InGaN bandgap is absorbed by the sacrificial superlattice, generating electron-hole pairs within the layers. The electrons are extracted through the metal cathode while the holes diffuse towards the semiconductor-electrolyte interface. Oxidation of the semiconductor material happens here and the oxide formed is dissolved in the electrolyte,
resulting in material etching. An AlGaN electron blocking layer is grown to prevent the cathode extraction of electrons formed in the InGaN gain layer (consisting of QDs or QWs). Electrons in the gain layer are thus much more likely to recombine with the holes, preventing the diffusion of holes to the semiconductor/electrolyte interface where oxidation could happen. This is necessary since any etching of the gain layer is undesirable.

Due to the internal fields in GaN and InGaN, photo-generated carriers, especially holes, are confined at the interfaces between layers, leading to uneven etch profiles when the InGaN layer is thick. Since a 200 nm post is required to provide enough optical isolation for the cavity, a superlattice made up of alternating thin InGaN layers of different In composition (5.1% and 6.5%) is developed in place of one thick InGaN layer of single composition. This creates a greater number of interfaces in a periodic fashion, trapping holes at each interface so as to create a uniform etch profile within the entire SSL. The optimization of InGaN layer thickness and composition is done through a series of experiments by Elaine Haberer.

The N-face of InGaN can also be etched in HCl or KOH without a light source in a chemically driven process. However, this is a non-crystallographic etch and results in high surface roughness. For the sake of understanding the difference between a photon-assisted process and a chemically driven one, we conducted a side experiment to examine their etch rates. This part of the experiment is done using a different set of GaN/InGaN material that has a similar superlattice structure to the materials used in the rest of
Figure 3.13: GaN/InGaN material structure used in the PEC side experiment. It has a similar layer structure to that in Figure 3.5, the sacrificial super lattice (SSL) also has the same composition as that in Figure 3.5.

The material used in this side-experiment has the structure illustrated in Figure 3.13. 1.3 \( \mu \text{m} \) diameter microdisks are etched with a 100 W Xe lamp in the set-up described in Figure 3.12, using 0.5 M, 0.1M, and 0.005 M of aqueous KOH as the electrolyte in a series of experiments over various amount of times. Figure 3.14 (a – c) are SEM images of the etched sample after 7 minutes of PEC in (a) 0.5 M, (b) 0.1 M, and (c) 0.005 M of KOH, respectively. The higher the concentration of KOH, the more chemically driven the process, and the lower the selectivity for the preferential etch of the InGaN superlattice compared to the top GaN layer. We can see from the Figure 3.14 (a) that a mere 7 minute etch in 0.5 M KOH results in both the GaN layer and the InGaN layer being etched at almost the same rate. Comparing that to Figure 3.14 (c), where a 100
Figure 3.14: SEM images of etched sample in (a) 0.5 M KOH for 7 minutes, (b) 0.1 M KOH for 7 minutes, (C) 0.005 M KOH for 7 minutes, and (d) 0.005 M KOH for 25 minutes.

x dilution of KOH solution is used, we observe a much higher selectivity of InGaN etch. However, we note that the etch rate of InGaN is reduced significantly when using a lower concentration of KOH. Figure 3.14 (d) shows a 25 minute etch of the material in 0.005 M of KOH. The InGaN superlattice etches preferentially at a faster rate compared to GaN, but the N-face of the GaN membrane layer is also attacked, resulting in a rough surface. The important lesson here is that a photo-driven process may have a lower rate of reaction, but it provides a higher InGaN/GaN etch selectivity, which is important in keeping the integrity of the GaN cavity.
3.2.4 Photoluminescence (PL) Measurements

The optical characterization of microdisks and other microcavities discussed in this dissertation is performed at room temperature using a frequency-doubled titanium sapphire laser emitting at 380 nm. This is below the bandgap of GaN but above the bandgap of the InGaN QDs, so that the pump photos are captured and electron-hole pairs are produced in the gain layers only. The pump laser is routed through a series of free space mirrors and an optical fiber, and finally passes through a long working distance objective (×100, numerical aperture (NA) = 0.9) before hitting the sample. The sample absorbs a portion of the excitation laser and subsequently emits photons with principal wavelengths intrinsic to the active material. Parts of the emission from the microdisks is collected from above and through the same objective lens and directed
into a spectrometer for analysis. The PL spectrum is generated by guiding the photons into a grating-coupled monochromator with a silicon charge-coupled device (CCD) camera. We are interested in the wavelength range of 400 nm to 480 nm, which is the emission range of the InGaN QDs and QWs embedded in the material. For life-time measurements, a photon counter measures the difference in photon numbers between the arrival of the laser pulse and the incident photons, generating the lifetime of the emitters. A full schematic of the PL set-up is illustrated in Figure 3.15.

### 3.3 The First Microdisk Lasers

High Q, small volume microcavities in GaN-based materials offer the prospect of low threshold lasers in the UV to visible range. Using the fabrication process outlined in the previous section, we have successfully fabricated 1 μm diameter microdisk lasers containing various types of InGaN emitters. This section summarizes some of this work and the important lessons we have learned.

The first demonstration of low-threshold GaN-based microdisk lasers containing InGaN QDs is realized by Igor Aharonovich et al.\(^5\), with a lasing threshold as low as 0.28 mJ/cm\(^2\) for a cavity encapsulating 3 layers of QDs. In this work, GaN microdisks 1 μm in diameter, with a membrane thickness of either 120 nm or 200 nm, containing either a single layer or 3 layers of QDs are fabricated and characterized for their lasing
Figure 3.16: (a) Material structure used in the fabrication of the first microdisks containing either single layer or 3 layers of QDs. (b) Fabrication flow of the micordisks using silica beads as hard mask. (c) Material parameters of the four investigated samples. (d) Scanning electron microscope image of a 1 μm diameter, 120 nm thick microdisk cavity.

<table>
<thead>
<tr>
<th>Sample</th>
<th>QDs layers</th>
<th>Membrane thickness (nm)</th>
<th>Peak emission wavelength (nm)</th>
<th>Surface pit density (cm⁻²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>3</td>
<td>200</td>
<td>439 ± 2 nm</td>
<td>(5 ± 0.4) × 10⁹</td>
</tr>
<tr>
<td>B</td>
<td>3</td>
<td>120</td>
<td>447 ± 8 nm</td>
<td>(5 ± 0.6) × 10⁹</td>
</tr>
<tr>
<td>C</td>
<td>1</td>
<td>200</td>
<td>454 ± 5 nm</td>
<td>(4 ± 0.6) × 10⁹</td>
</tr>
<tr>
<td>D</td>
<td>1</td>
<td>120</td>
<td>467 ± 9 nm</td>
<td>(4 ± 0.5) × 10⁹</td>
</tr>
</tbody>
</table>

Figure 3.17: (a) Optical characterization of a 1μm diameter, 200 nm thick microdisk containing 3 QD layers showing WGMs decorating the broad QD gain layer emission. (b) PL spectrum of a high Q mode with Q = 6600. Green and red lines are fits to Lorentzian functions.
behavior using photoluminescence measurement with a pulsed laser excitation. The microdisks are fabricated using silica beads as hard masks. The fabrication process, a summary of the different samples, and the SEM image of one of the disks are presented in Figure 3.16. Figure 3.17(a) shows the PL spectra of one of the microdisks, where WGMs in resonance with the cavity are shown modulating the broad emission from the QD-containing layers. The quality factors of cavity modes are fitted from the emission spectra using a Lorentzian. Figure 3.17(b) shows an example of such a fit for a cavity mode with Q of approximately 6000. This particular mode exhibits splitting between the usually-degenerate clockwise and counterclockwise propagating modes. This break in degeneracy is likely the result of fabrication imperfection that destroyed the rotational symmetry of the microdisk. The red and green curves are both fitted to Lorentzian functions, and quality factors are calculated from their respective FWHMs as discussed in Chapter 2.

A comparison among the four different samples gives us a first idea at the most important factors affecting lasing behavior in these devices – there is a lower limit to the amount of gain material required for lasing. As we have observed, all microdisks in these four samples (A – D) exhibited pronounced modes in the PL spectra. However, only microdisks from sample A and B, comprising of 3 layers of gain material, achieved lasing, while none of the microdisks with a single layer of QDs lased.

Figure 3.18(a) shows the power-dependent PL emission from a Sample A microdisk, where lasing is observed at 432 nm. The non-linear change in emission intensity in
Figure 3.18: (a) PL spectra as a function of excitation power recorded from a 1 lm size microdisk cavity (Sample A). (b) Optical output power of the microdisk laser as a function of excitation power for sample A (blue triangles) and B (red circles). A clear lasing threshold is observed at 0.28 mJ/cm² and 0.63 mJ/cm² for samples A and B, respectively. The lines are a linear fit to the data above threshold. (c) Linewidth of the lasing mode plotted as a function of excitation power for sample A. The reduction of the linewidth is in accord with lasing behavior. Inset top right, same data as in (b) replotted on a logarithmic scale. Inset bottom left, an optical image of the microdisk laser above threshold recorded using a CCD camera.

Figure 3.19: Lasing threshold plotted as a function of maximum Q recorded from the same microdisk for sample A (blue triangles) and sample B (red circles).
3.18(b) further confirms that the device is lasing. This is also apparent in the linewidth narrowing of the 432 nm emission peak as power increases as shown in 3.18(c).

Another observation made is the difference in Q and device yield between microdisks of different thicknesses. In sample A where the disks have a membrane thickness of 200 nm, approximately 60% of the microdisks achieved lasing, with a threshold between 0.28 mJ/cm² and 0.92 mJ/cm². Microdisks in Sample B have membrane thicknesses of 120 nm, and approximately 30% of such disks reached lasing, with thresholds ranging between 0.4 and 1.1 mJ/cm². The average Q of modes from the microdisks in sample A is higher than that in sample B, which is consistent with our FDTD simulations, although the measured Qs are an order of magnitude lower than the values obtained in simulation, due to imperfections in the material or in the fabrication process. Because of the higher Q and better yield devices in sample A, all cavities for further lasing experiments employed a 200 nm thick cavity structure.

However, it is also noted that there is no clear relationship between the Q and the lasing threshold of the microdisks. A plot of lasing threshold against cavity Q across a number of Sample A and Sample B devices in Figure 3.19 illustrates this. Microdisks in samples C and D did not achieve lasing, and their measured cavity Qs are comparable to or lower than the microdisks in sample A and B. This suggests that re-absorption within the InGaN layers themselves is not the dominant factor limiting Q in these structures, and multiple layers of QDs are necessary to supply enough gain for lasing under current pulsed excitation pumping.
To further understand the roles emitters play in microdisk lasing, another set of experiments were conducted by Alex Woolf et al.\textsuperscript{14} focusing on studying the lasing dynamics and correlation between lasing wavelength and lasing threshold of microdisks whose active areas comprise either InGaN QDs + fQWs, fQWs, or QWs. Since we previously learnt that a sufficient amount of gain material is necessary to achieve lasing, wafers used for this set of experiments contain 3 layers of gain material. 1.2 $\mu$m diameter microdisks are fabricated from four wafers with identical material structure except for the aforementioned three layers of gain materials embedded in $c$-plane GaN. The active material of Sample A and Sample B each contains three layers of InGaN QDs + InGaN fQWs, they defer in QD density, estimated to be $2.8 \pm 0.1 \times 10^{10}$ cm$^{-2}$ and $2.5 \pm 0.1 \times 10^{9}$ cm$^{2}$, respectively. Sample C contains three layers of InGaN fQWs. Sample D contains three layers of InGaN QWs. AFM image analysis shows the QW coverage for each sample is as the follows: Sample A: 75.3\% fQW, Sample B: 63.9\% fQW, Sample C: 78.3\% fQW, Sample D: 100\% QW.

To understand the respective emission characteristics of QD and fQW in the heterogeneous gain layer, low-power (1.4 $\mu$W) and low-temperature (4 K) PL measurements on microdisks with InGaN QDs + fQWs gain layers were performed. The results show that the QDs pre-dominantly emit light on the short-wavelength side of the gain spectrum. The same measurement was also taken at a higher power of 43 $\mu$W. The emission spectrum is shown in Figure 3.20. The QD emission modes are visible at the shorter wavelength side of the emission spectrum at both high and low pump powers. The wave-
length of QD emission is believed to be a consequence of the MDE growth technique. The QD excitons are only visible at the lowest incident power of 1.4 $\mu$W. Dominant modes of emission do not appreciably change as the excitation power is raised from 1.4 W to 43 W, but the broad gain emission spectrum is blue shifted by approximately 10 nm as fitted using a Gaussian equation.

Room temperature lasing is observed in all four samples. Figure 3.21 shows the statistical distribution of lasing wavelengths in each of the measured devices in the four samples. The histograms are overlaid with the average broad background emission in each of the samples and is denoted in black. This emission is contributed by all emitters present in the sample. For samples A and B, containing both QDs and fQWs, the distribution of QD emission, determined by taking the average wavelength and

Figure 3.20: Low temperature (4 K) normalized PL spectra from a microdisk in Sample A, containing both InGaN QDs and fQWs. The QD exciton peaks are visible at low pump powers only while cavity modes are visible at all pump powers. Gaussian fits to the data points are shown as well.
Figure 3.21: Histogram of the lasing mode wavelength for each of the four samples: (a) QD + fQW(A), (b) fQW+QD(B), (c) fQW, and (d) QW. The normalized board background emission in each sample is overlaid on the histograms in black. Broad emission from QDs are overlaid in gray in (a) and (b). The average lasing threshold of microdisks in each histogram bar is represented by the color map, with yellow and red corresponding to low and high thresholds, respectively.

Figure 3.22: Power dependent emission spectra of microdisks containing (a) QWs, (b) fQWs, and (c) QDs + fQWs. Log-scale light in light out curves are shown as insets.
standard deviation of QD exciton peaks at low temperature, is also denoted in light gray. We note here that the average broad background emission in Samples A and B are mostly consistent with the broad emission by the fQWs in Figure 3.21(c). This suggests that the wavelength range of emissions from the QDs and fQWs are different, with emission from QDs centered at a lower wavelength. Related to this, we also observe that the lasing wavelengths for the QW and fQW devices are fairly equally distributed about the center-emission wavelengths for these materials, but the lasing wavelengths of the QDs + fQWs materials are substantially blue-shifted by about 15 nm from the broadband gain emission, and are centered on the QD emission spectrum. This key insight into the difference in wavelength distribution between the broad emission of QDs vs fQWs is important, and offers us the capability to tailor cavity designs to the preferential selection of photons from one emitter over another. This, as we will see later, forms the foundation for many of our later experiments.

In fact, the consequence of the difference in wavelength distribution between QD and fQW emissions is already apparent in this experiment. Figure 3.22(a)-(c) show the typical LI-LO curves of microdisks containing QWs, fQWs, and QDs + fQWs, respectively, at different pump powers. Multiple WGMs are visible in each device at low pump powers, as the pump power increases, pronounced narrowing of the lasing mode occurs, signifying increased temporal coherence of emission as the device enters the lasing regime. The insets to Figure 3.22(a)-(c) show the LI-LO curves in log-log scale, where the S-shaped curves are clear indications that the devices have achieved
lasing. One should note that in Figure 3.22(a), the dominant mode of emission at low pump power at 451 nm is consistent with the dominant emission mode at high pump power and remains its spectral position through lasing. This mode is located near the center of the broad QW luminescence. In the fQW microdisks in Figure 3.22(b), the initial wavelengths of emission have the highest intensity mode located near the right tail of the background luminescence at 471 nm. However, as the pump power increases, the dominant mode of emission hops to a much shorter wavelength of 452 nm and this mode subsequently reaches lasing. In Figure 3.22(c), the low pump power dominant mode initially appears at around 436 nm, but a distinctive blue-transition to 421 nm occurs as the pump power increases and the device crosses into the lasing regime. This change in lasing mode indicates a transition of dominant emission from fQWs to QDs. This is likely due to an interplay between and relative importance of the carrier capture cross-section versus the radiative emission efficiency of the fQW regions and QDs of varying sizes, as we will discuss in more details in the next section through a series of experiments.

Table 3.1 summarizes the center of background emission spectrum, average lasing wavelength, average lasing threshold, and lasing threshold range, averaged over 20 microdisks measured from each of the four samples. Microdisks with 3 QW layers have the lowest average lasing threshold among all gain materials, due to their larger electronic density of states, larger areal coverage, and larger capture cross-section. The QW microdisks also have a lower variance in lasing threshold among all devices because
Table 3.1: Table showing the center wavelength of gain emission, average wavelength of lasing, average lasing threshold, and lasing threshold range for each of the four active layer materials.

<table>
<thead>
<tr>
<th>Samples</th>
<th>Average background emission, nm</th>
<th>Average lasing mode, nm</th>
<th>Average lasing threshold, $\mu$W</th>
<th>Threshold range, $\mu$W</th>
</tr>
</thead>
<tbody>
<tr>
<td>QW</td>
<td>446 ± 2.3</td>
<td>448 ± 6.7</td>
<td>184</td>
<td>88-375</td>
</tr>
<tr>
<td>fQW</td>
<td>457 ± 3.5</td>
<td>451 ± 6.7</td>
<td>253</td>
<td>83-3600</td>
</tr>
<tr>
<td>QD+fQW A</td>
<td>441 ± 4.8</td>
<td>428 ± 3.8</td>
<td>303</td>
<td>118-815</td>
</tr>
<tr>
<td>QD+fQW B</td>
<td>437 ± 4.4</td>
<td>429 ± 6.3</td>
<td>2029</td>
<td>350-6175</td>
</tr>
</tbody>
</table>

of their gain layer homogeneity and a more uniform material quality in general. In comparison, microdisks with fQW gain layers have a wider range of lasing thresholds due to the inhomogeneity and randomness in fQW locations within the gain layers and their spatial overlap with the microdisks. Microdisks with QDs + fQWs as the active material exhibited more consistent lasing threshold with a lower average threshold compared to the fQW samples. Even though the number of QDs in spatial and spectral overlap with the high Q WGMs of the microdisks are limited, devices containing QDs still achieved significantly lower average lasing threshold than those containing QWs.

This could be related to the lower threshold carrier density required for QDs compared to conventional QWs. Overall, microdisks comprising QW gain layers achieved lasing with greater consistency and lower threshold, making InGaN QWs a promising choice of emitters for GaN based microdisk lasers.
3.4 Role of the emitters

The two important components of a microcavity laser are the cavity structure and the emitters embedded within. Previously, we have successfully fabricated low threshold GaN based microlasers with the microdisks as the cavity and either InGaN QDs + fQWs or InGaN QWs as the emitters. In this section, we will take a closer look at the roles of the different types of emitters.

To further understand what are the dominant limitations to low threshold lasing in this material system, we systematically modify the number of QD and QW gain layers (3, 5, 7) within the same cavity structure, and compare the resulting emission spectra and lasing thresholds. 1 \mu m diameter with 200 nm in thickness microdisks are fabricated using silica beads as hard masks, and according to the fabrication procedure as described in Chapter 2. The microdisk structure, with its small number of discrete modes overlapping the gain region, allows us to delineate the difference in interaction between photons and different cavity modes.

We identified single microdisks on each sample and performed room-temperature photoluminescence (PL) measurements using a pulsed laser source with frequency 76 MHz and wavelength at 380 nm. Lasing was observed in almost all our QW cavities, and the quality factors range between 1200 and 2800. Figure 3.23 shows the light in – light out curve of one of the 3QW layer devices in both linear and log scales. The nonlinear increase in intensity as we increase the pump power and the characteristic
Figure 3.23: Light in light out curve of an 1 µm diameter microdisk with 3 QW gain layers in (a) linear and (b) scale. The vertical dotted line indicate the lasing threshold.

Figure 3.24: Power dependent PL spectrum of a 3QW layer microdisk optically excited at increasing pump powers of (93, 163, 283) µW. These powers are taken with a power meter in the optical path of the measurement set up before the objective lens.
S-shaped curve in log-scale show that the devices are clearly lasing. Figure 3.24 shows the emission spectrum of a 3QW layers microdisk at increasing pump powers of 93 $\mu$W, 163 $\mu$W, and 283 $\mu$W. Note that these power values are measured with a continuous wave power meter placed in the optical path of the measurement set-up right before the objective lens. A conversion to units of mJ/cm$^2$ is done when calculating the threshold lasing power. In this calculation, we take into consideration the fraction of excitation beam that is intercepted by the devices, the reflection at air-GaN interfaces, the material absorption coefficient, as well as the thickness of the gain layers. Details of this calculation are presented in Appendix A.

Table 3.2: Mean lasing threshold of microdisks containing 3, 5, or 7 layers of QWs averaged over 10-15 devices.

<table>
<thead>
<tr>
<th>Number of QW layers</th>
<th>Average lasing threshold (mJ/cm$^2$)</th>
<th>Standard deviation of threshold (mJ/cm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>0.101</td>
<td>0.010</td>
</tr>
<tr>
<td>5</td>
<td>0.075</td>
<td>0.012</td>
</tr>
<tr>
<td>7</td>
<td>0.056</td>
<td>0.010</td>
</tr>
</tbody>
</table>

We average the lasing threshold of each type of the QW microdisks over 10 to 15 devices and observe a decrease in the average lasing threshold as we increase the number of gain layers. Table 3.2 tabulates the average lasing threshold and standard deviation of each type of QW microdisks. The reason for the decrease in lasing threshold is attributed to the increase in the number of gain layers in the disk cavity, resulting in an increase in the capture cross section of the gain material. Increased capture generates
Figure 3.25: Light in light out curve of an 1 µm diameter microdisk with 3 QW gain layers in (a) linear and (b) scale. The vertical dotted line indicate the lasing threshold.

A greater number of electron-hole pairs per unit time and consequently increases the rate of photons produced. This is an intuitive process and generally agrees with our expectation.

Table 3.3: Mean lasing threshold of microdisks containing 3, 5, or 7 layers of QWs averaged over 10-15 devices.

<table>
<thead>
<tr>
<th>Number of QD layers</th>
<th>Average lasing threshold (mJ/cm²)</th>
<th>Standard deviation of threshold (mJ/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>0.111</td>
<td>0.016</td>
</tr>
<tr>
<td>5</td>
<td>0.115</td>
<td>0.013</td>
</tr>
<tr>
<td>7</td>
<td>0.103</td>
<td>0.006</td>
</tr>
</tbody>
</table>

However, for our QD microdisks, we did not observe a significant decrease in lasing threshold as we increase the number of gain layers. Instead, the lasing threshold stays relatively constant regardless of the amount of gain materials present, as tabulated in Table 3.3. This is counter intuitive since the addition of gain material, which would theoretically produce a greater number of electron-hole pairs and consequently more photons, did not lead to a decrease in the lasing threshold. In addition, we also note
that the average lasing threshold of a microdisk containing 3, 5, or 7 QD layers is lower than the threshold of microdisks containing the same number of QW layers, as is consistent with our previous experiments.

To understand what is going on, let us first take a look at the PL emission spectra of these microdisks. Figure 3.26(a) plots the output intensities of a microdisk containing 3 layers of InGaN QWs at various pump powers. We note that the dominant emission peak around 445 nm wavelength at low pump power stays the same when the pump power increases, and this subsequently becomes the lasing mode as the device transition into the lasing regime. Figure 3.26(b) shows the output intensities of a microdisk containing 3QD layers. From the plots, we can see that at low pump power of 9 µW and 173 µW, the dominant emission wavelength is at the center of the gain spectrum, at approximately 450 nm. However, as the pump power increases to 260 µW, the dominant emission blue-
shifts to around 431 nm, and eventually lases in this mode. This blue-shift in dominant emission wavelength with increased power is consistent with our observation in earlier experiments described in Section 3.3, and occurs only in microdisks containing both InGaN QD and fQWs.

The reason for the shift in wavelength and the eventual lasing at lower wavelength can be explained by the differing carrier capture efficiencies and carrier confinement abilities of the QDs and the fQWs. At low pump powers, there is a much higher probability of carrier capture into the fQWs because of the larger areal coverage of the fQWs. The percentage of fQW is estimated at around 64 ± 3% based on four 2 µm × 2 µm AFM images of uncapped QD samples. As the pump power increases, the carrier capture probability into the QDs also increases. The QDs offer superior carrier confinement compared to the fQWs, favoring radiative recombination, leading to the blue-shift in the dominant emission wavelength. The cavity mode, resonant with the QD emission wavelength, further augments the spontaneous emission rate of QDs in good spatial overlap with the WGMs, leading to lasing eventually at QD wavelengths. The shift from fQW wavelength to QD wavelength of emission indicates the presence of a greater
We also performed room temperature lifetime measurements on the QD and fQWs. By using a 434 nm bandpass filter with a 17 nm window, we selectively filter out emission from the QD wavelengths. The two spectra in Figure 3.28 are taken at the same spot on the sample containing both InGaN QDs and fQWs. The blue curve is taken with the bandpass filter in path, while the green curve is taken without the bandpass filter. We fit the exponential curves for radiative lifetimes of the emitters. The average radiative lifetime of the QDs are 1.79 ns, while the lifetime of the fQWs is 15.05 ns, 14 times that of the QDs. The shorter spontaneous emission lifetime of the QDs means greater amount of spontaneous emission events happening per unit time, which leads to higher photon density in the cavity. Once we are able to increase the pump power sufficiently to increase the capture rate into the QDs, the short radiative lifetime of the QDs ultimately...
helps the disk to lase at the shorter wavelengths characteristic of the QDs.

Going back to Table 3.3, the addition of QD layers did not appreciably reduce the lasing threshold exactly because the gain layers contains both the QDs and fQWs. Without the parasitic fQWs as energy sinks, a microdisk containing only QDs would likely go into lasing at a much lower threshold. The increase in the number of gain layers here increases both the amount of QDs and parasitic fQWs. However, since fQWs constitute a larger percentage of the gain material for a given layer, it is reasonable that the lasing threshold stays relatively constant.
In this chapter we investigate the feasibility of building a low threshold laser in a micro-ring cavity system. The chapter is divided into four parts: 1. The design and motivation for building a micro-ring laser; 2. Fabrication challenges; 3. Building the first low-threshold GaN micro-ring laser; and 4. Modifying the micro-ring laser with
dielectric coatings to further explore cavity-gain interactions.

4.1 Motivation and Design

In the last chapter, we have demonstrated low threshold GaN based microdisk lasers with either InGaN QDs + fQWs, fQWs, or QWs as gain layers. One of the distinct advantages of the microdisk cavity lies in the high-Q factors of the WGMs, with only a few modes that overlap with the gain region. Having few distinct modes is extremely desirable as it allows us to take a closer look at cavity photon dynamics specific to a particular mode, and also helps to reduce mode-mode competition for pump power in the lasing process. The high-Q WGMs of a microdisk are confined to the periphery of the cavity; with little if any overlap with the inner volume of the microdisk. This inner disk region is therefore a less efficient contributor to the lasing process, yet we have been pumping energy into it whenever we pump the microdisk to lasing, making the process inefficient. In addition to that, the less efficient inner volume also contains a mixture of different gain materials, some of which may act as energy sinks and absorb part of the pump power in competition with the lasing process. Ideally, we would like to work with a cavity that removes this unnecessary volume, but at the same time retains the desirable property of having only a few discrete modes that overlap the gain region. The micro-ring structures, where the inner volume of the microdisk is removed, is likely to have such properties and should exhibit lower lasing thresholds. In addition to that, the
removal of the inner volume also disproportionally removes fQWs, which are competing with the QDs for lasing.

Using FDTD methods, we simulated the cavity resonance spectra of a 1 \( \mu m \) GaN microdisk and a 1 \( \mu m \) diameter micro-ring with 500 nm of inner diameter. The resonance spectra of the two look similar, each with 4 first order WGMs overlapping the gain region between 400 nm and 480 nm. In both structures, the WGMs are near the periphery of the microdisk and the micro-ring. Figure 4.1 shows the comparison between the two. The WGMs of the microdisk and micro-ring with the same outer diameter also look similar for the same mode, as shown in Figure 4.2.

For the purpose of comparison, we fabricated micro-ring laser structures with different geometries, using an active medium comprising three layers of InGaN QDs, as well as
Figure 4.2: WGMs of the mode near 425 nm in a (a) 1 µm diameter microdisk and a (b) micro-ring with 1 µm outer diameter and 500 nm inner diameter.

Figure 4.3: Schematic showing the geometry of four different microdisk/micro-ring designs. Each structure has an outer diameter $d_o$ of 1 µm, and inner diameters $d_i$ of 0 nm (microdisk), 200 nm, and 400 nm, respectively.
Figure 4.4: Schematic on removing the center of a microdisk to form a micro-ring using the Focused Ion Beam (FIB).

microdisks of the same gain layer composition. The geometries are chosen so that the peripheral modes are not affected by the removal of central volume. The outer diameter \((d_o)\) of the microdisk and all micro-rings are 1 \(\mu m\) in size, while the micro-rings have an inner diameter \((d_i)\) of either 200 nm, 400 nm, or 500 nm. A schematic illustrating the dimension of each type of micro-ring design is shown in Figure 4.3.

4.2 Fabrication

We tried several methods of fabrication to realize these micro-ring structures. In the following, we outline two of these attempts.

4.2.1 Focused Ion Beam

To fabricate the desired ring-shaped cavities, we started off with the method of first fabricating a complete 1 \(\mu m\) diameter microdisk using the e-beam lithography method
Figure 4.5: SEM image showing the damaged micordisk in forming a micro-ring.

as outlined in Chapter 2, followed by doing a controlled damage to the center of each micordisk using the focused-ion-beam (FIB) tool. Since we already have a set of readily available microdisk 1 \( \mu \text{m} \) diameter microdisks, producing the micro-rings simply involves an additional step of damaging the centers of the disks with the FIB tool. The advantage of this method is that we can quickly produce some micro-rings and evaluate their feasibility in serving as low-threshold lasers. However, the obvious disadvantage of using the FIB is that we need to remove the center of the microdisk one at a time, making the entire process less efficient compared to a batch process. In addition, it is uncertain how FIB damage may affect the performance of the microdisk.

Figure 4.4 gives an illustration of this process, where as an example we remove a 300 nm diameter of materials from the center of the micordisk. Since the microdisks are
orderly aligned in an array, we are able to damage the center of each disk with great precision. Using FIB, we modified approximately 20 1 μm microdisks containing 3 layers of quantum dots, using a 30 kV beam at 7.7 pA, with a diameter of damage of 300 nm and a depth of 200 nm. Figure 4.5 shows the resultant micro-ring structure. We took PL measurements on the micro-rings but observed negligible emission – the spectrum is more or less flat. This shows that all of the active material is damaged during the FIB process, giving no emission between 400 nm and 480 nm at all. Although only a 300 nm diameter hole is created at the center of the disk, there is likely some lateral straggle of the ions that had damaged emitters near the periphery of the disks, where the whispering gallery modes are. In addition to that, the ions used in the FIB are gallium ions, which might interact with our InGaN emitters and change the emitter properties. There could also be some damage across the top surface of the disk during the FIB process, since locating the disk centers involves looking at the disk in the SEM, which damages the disk to a small extent. A possible way to avoid this is to deposit a thin layer of SiO2 prior to doing FIB, and then removing it with HF acid afterwards.

As we can see from the above experience, successfully fabricating micro-rings using the FIB method would involve a highly precise control over the precision of ion beam power and damage diameter used, so as to minimize damage to the active layer in the cavity. These restrictions make the process a more tedious one than we have initially projected. In addition to that, the lack of ability to damage all disks at the same time makes the method inefficient and introduces variance among disks in the fabrication
process. In the following section, we explore a different method of fabrication where we attempt to batch process all micro-rings at the same time using the e-beam lithography method.

4.2.2 E-beam and reactive ion etch

Instead of modifying existing microdisks and creating a hole by removing the center, we can fabricate micro-rings by defining a ring-shaped mask using e-beam lithography. The ring pattern will be transferred down into the GaN/SSL layers with coupled plasma etching, after which, further PEC etch will be conducted to chemically remove part of the SSL layer below the GaN membrane. With a cylindrical ring structure, the SSL layer will be etched from both the inside and outside during PEC etching, since the electrolyte now also has access to inside of the SSL through the center opening of the ring. Because the ring is only 1 \( \mu m \) in diameter, and at least 150 nm of SSL material needs to be removed laterally inward from the periphery of the disk, the electrolyte having access to both the inside and outside of the SSL layer means oxidation can take place at both interfaces, and the SSL layer is removed at twice the rate of normal PEC processes. This creates a problem as the supporting SSL layer may become too thin to support the cavity structure above, or too thin to remove heat efficiently as we pump the cavity with an excitation laser.

To circumvent this problem, we want to create a structure does not give electrolyte access to the inner surface of the ring during PEC. To do this, we expose the micro-ring
Figure 4.6: Schematic illustrating the exposure of the outer ring and inner circle of the micro-rings at different dosages. Here, we write a $7 \times 7$ dose array with 49 different combinations of dosages for each device design, so as to find the best dose combination to achieve our intended geometry.

Figure 4.7: Flow chart of fabrication process where the outer ring and inner circle of the micro-ring are exposed in different steps with different dosage.
pattern in a two-step process, where the outer ring is exposed at a higher electron beam dosage, and the inner circle is exposed at a lower electron beam dosage, so that e-beam resists in the two different regions can later be developed at different rates. We write a 7 x 7 dose array with 49 different combinations of dosages for each device design, so as to find the best dose combination to achieve our intended geometry. Figure 4.7 illustrates the fabrication process. In Step 1a, we spin a layer of negative FOX-16 e-beam resist onto the sample wafer, and first expose the outer ring shape at a high e-beam dosage. We then expose the inner circle pattern at a lower dose in Step 1b. Exposed FOX-16 forms a SiO$_2$ layer after resist development in tetramethylammonium hydroxide (TMAH). The two-step expose creates a thinner layer of SiO$_2$ at the center of the disk and a thicker layer of SiO$_2$ on the outer ring region after developing the exposed resist in TMAH. In the next step of reactive ion etch, the ring region under the thicker SiO$_2$ area is fully protected from the dry etch, while exposed areas outside of the micro-ring regions get etched down for approximately 500 nm in depth. The center region under the thinner SiO$_2$ layer will get protected at the start of the reactive ion etch, but eventually get etched away rapidly as the thin layer of SiO$_2$ is fully removed by the bombarding ions. Careful calibration of the etch rate will allow us to etch only the 200 nm GaN membrane layer without etching into the SSL layer below. This creates a structure as shown in Step 2 of Figure 4.7. Following this, we deposit a metal contact made up of Ti and Pt onto the wafer, which acts as a cathode which aids in electron extraction during the PEC process in Step 4. This two-step exposure method creates
Figure 4.8: SEM image of the developed FOX-16 pattern of a 400 nm inner diameter, 1 \( \mu m \) outer diameter micro-ring. The ring is over-exposed in the micro-ring region and under-exposed in the inner circle region, giving both a smaller inner diameter and outer diameter than intended.

The SEM image in Figure 4.8 shows the FOX-16 e-beam resist after resist development in TMAH. We can clearly see the difference in the outer ring region and the inner circle region. We intended the inner circle diameter to be 400 nm and the outer ring diameter to be 1 \( \mu m \) in this case, but the actual measured device has both a smaller inner and outer diameter, indicating that this micro-ring region is under-exposed while the inner circle is over-exposed.

Figure 4.9 shows the top view of the cavity after the reactive ion etch. We notice that a microdisk is formed instead of a micro-ring, as no part of the center circle is etched. This is probably due to too thick a layer of SiO\(_2\) on top of the center circle during the e-beam write, since the part is under-exposed, which led to reactive ion etch unable to
Figure 4.9: SEM image of the etched pattern of a 400 nm inner diameter, 1 µm outer diameter micro-ring. However, no part of the inner circle is actually etched in this device. The inset shows the same disk with FOX-16 on top.

punch through the SiO₂ layer at the center, and therefore unable to transfer this part of the pattern down into the substrate.

Instead of doing a two-step exposure, we modify the process into a simple step of e-beam-exposure of just the outer ring region, followed by reactive ion etch to transfer the pattern into the substrate. Figure 4.10 outlines this process. This process proves to be efficient and created micro-rings of intended geometries, without pattern transfer problems. Figure 4.11 shows the SEM images of some of these fabricated micro-rings. We have also fabricated a microdisk without removing any of the materials at the center for the purpose of comparison with the micro-rings.

To better understand the cross-sectional structure of the micro-rings, especially the
Figure 4.10: Flow chart of fabrication process where only the outer ring is exposed in the e-beam process.

Figure 4.11: SEM images of (a) microdisk and (b-d) micro-rings fabricated using one-step e-beam lithography, with an outer ring diameter of 1 µm and inner ring diameter of (b) 200 nm, (c) 400 nm, and (d) 500 nm.
Figure 4.12: Cross section of a micro-ring with (a) 200 nm inner diameter and (b) 400 nm inner diameter. Lighter gray area surrounding the micro-rings are Pt used during the FIB process in removing part of the disk.

width of the supporting post after the PEC etch, we removed half of the micro-ring using FIB for each of the four micro-ring geometries. Figure 4.12(a) shows the cross sectional SEM image of a micro-ring with 200 nm inner diameter, and (b) shows that of a micro-ring with a 400 nm inner diameter. The cross section of the micro-ring with 500 nm inner diameter is similar to the 400 nm inner diameter ring. The lighter gray area surrounding the micro-rings in the SEM images is Pt, a coating used to protect the devices from damage during the FIB process. The outline of the micro-ring is clear from the contrast between the GaN material and the Pt. Inspecting the images, we observe that the rings have different cross sectional profiles depending on how large their inner diameters are. For a micro-ring with a smaller inner diameter, the reactive ion etch did not fully puncture through the entire GaN membrane at the center, leaving
a thin sheet of GaN at the bottom of the micro-ring cavity. This is probably due to the high aspect ratio between the approximately 500 nm thick FOX-16 resist layer and the small opening of 200 nm at the center of the ring, which results in a slower etch rate in this region of the device compared to outside of the ring. The thin layer of GaN at the bottom of the GaN membrane layer prevents electrolyte from gaining access to SSL directly below the center hole during PEC, and therefore protects the SSL from getting oxidized or etched away at the center. In contrast, micro-rings with a larger opening of 400 nm or 500 nm inner diameter have the entire GaN membrane layer etched through, giving the SSL layer at the center access to electrolyte during PEC. This led to the SSL layer getting etched laterally from both the outside and from the inside, leaving a much thinner sheet as the supporting post to the cavity above. The narrow width of the post requires us to be extremely careful when optically pumping the device during PL measurements, since the cavity is likely to overheat due to poor heat dissipation through the narrow supporting post.

4.3 DEMONSTRATION OF A LOW-THRESHOLD MICRO-RING LASER

The mirodisk and micro-rings are optically pumped at room temperature using a frequency doubled, pulsed, titanium-sapphire laser emitting at 380 nm with a 76 MHz repetition rate and 200 ps pulse duration through a high numerical aperture objective (NA = 0.90) as described in Chapter 2. We measure the Q values of lasing modes using
Figure 4.13: Spread of lasing thresholds in microdisks and micro-rings of different geometries. The mean threshold in each geometry group, averaged over eight data points, is marked off with a cross. Inset: I-O curves of selected microdisk and micro-rings with 1 µm outer diameter, and different inner diameters of \( d_i = 200 \) nm, 400 nm, and 500 nm. The lasing threshold and post-threshold slope efficiency both decrease as more volume is removed.

\[
\frac{\lambda}{\Delta \lambda},
\]

where \( \lambda \) is the emission wavelength and \( \Delta \lambda \) is the full width half maximum at \( \lambda \).

The typical measured Q measured for these devices range between 2,000 and 3,000. All of the microdisk and micro-ring cavities achieved lasing, though at different thresholds and with different lasing characteristics. We proceed to discuss some of these interesting results in detail in the following section.

In Figure 4.13, we plot the LI-LO curves of selected microdisk and micro-rings from each geometry design. The four devices presented here have lasing behaviors representative of the geometry groups they each belong to. By performing linear fits to the lasing
curves, we identify lasing threshold as the pump power at which the fitted line intersects the x-axis. Our threshold value calculation takes into consideration the reflections at layer interfaces as well as material absorption coefficients. Greater details can be found in Appendix A. From the graphs, we observe two clear correlations in laser performance with the geometry of the micro-cavity: (1) a decrease in lasing threshold as the central volume is removed, and (2) a concomitant decrease in post-threshold slope efficiency.

As observed from the four devices in Figure 4.13, when more of the central volume is removed the lasing threshold decreases from 12 $\mu J/cm^2$ in the microdisk ($d_i = 0$ nm) to 9.9 $\mu J/cm^2$ in a micro-ring with $d_i = 200$ nm, 8.2 $\mu J/cm^2$ in a micro-ring with $d_i = 400$ nm, and 6.2 $\mu J/cm^2$ in a micro-ring with $d_i = 500$ nm. The inset to Figure 4.13 shows the consistency in decreased threshold with the removal of the central volume for a set of eight devices. The mean threshold of each micro-ring geometry, averaged over eight data points, is marked off on the plot with a cross. Thus, the removal of the center region, where the active layer material does not spatially overlap with the WGMs, has indeed lead to a lowering of the lasing thresholds, as we have hoped.

To better understand the difference in lasing mechanism between the microdisk and the micro-rings, we plot the pump-power-dependent PL emission spectra of a microdisk and a micro-ring ($d_i = 500$ nm) in Figure 4.14. For both structures, the spectra at low pump power reveal two dominant high-Q WGMs that overlap with the emission region of our heterogeneous InGaN gain material. The shorter wavelength mode of 440 nm is attributed to emission from QDs and the longer wavelength mode of 460 nm
is attributed to emission from the fQWs, as we have discussed in Chapter 3. In both the microdisk and the micro-ring, the highest intensity mode at low pump power is at the longer wavelength, although lasing ultimately occurs at the shorter, QD wavelength. The blue shift in wavelength with increased power is consistent with differing carrier capture efficiencies and hence photon emission of the QDs and fQWs in our material, as pointed out in Section 3.4. At low pump powers, there is a much higher probability of carrier capture into the fQWs because of the larger areal coverage of the fQWs. The percentage of fQW is estimated at around 64±3% based on four 2µm × 2µm AFM images of uncapped QD samples. As the pump power increases, the carrier capture probability into the QDs also increases. QDs offer superior carrier confinement in comparison to the fQWs, favoring radiative recombination. They also have a 10x shorter characteristic spontaneous lifetime, between 1 and 5 ns, compared to the fQWs. Furthermore, the cavity mode, resonant with the QD emission wavelength, further augments the spontaneous emission rate of QDs in good spatial overlap with the WGMs, ultimately producing lasing at the shorter wavelengths characteristic of the QDs. A comparison of Figure 4.14(a) and Figure 4.14(b) highlights the differences in PL spectra at low pump power. The intensity of both WGMs is dramatically reduced in the micro-ring structure, with a greater reduction in the intensity of the longer wavelength (fQW) modes. The reduced “competition” of the longer wavelength mode also contributes to the QD lasing in the micro-ring structures.

To understand the decreasing post-threshold slope efficiency for the micro-ring struc-
tures as more center volume is removed, we fit our experimental data to the laser rate equations. Our simulations using the theoretical rate equations show that post-threshold slope efficiency shows greatest sensitivity to variations in the value of $\gamma$, the decay rate of photons from the cavity. Higher values of $\gamma$ result in lower slope efficiencies. If, indeed, there is an increase in $\gamma$, or loss of photons associated with the micro-ring geometry, we expect to observe some degradation of the Q of the modes of the device. However, the mode widths shown in Figure 4.14 (related to Q values) show no degradation, and this is the case in all of our measured devices. In addition to that, one would also imagine that greater photon loss would result in increased lasing thresholds, which is contrary to what we observe experimentally.

We believe that the resolution to these issues relates to the role of the higher-order modes of the micro-ring structures, illustrated in the FDTD simulations shown in Fig-
Figure 4.15: FDTD simulation showing the field profile of the first- and higher-order modes of a micro-ring with (a) $d_i = 200$ nm and (b) $d_i = 500$ nm, as well as the cavity resonance wavelengths and simulated Q values for different first order WGMs. Red circles representing the inner and outer boundaries of the micro-rings are marked off on the diagrams. Slight broadening of the second order mode at $\lambda = 452$ nm is observed in the $d_i = 500$ nm micro-ring. First order mode at $\lambda = 436$ nm corresponds to the experimental lasing mode.

The field profiles of first-order (WGM) and higher-order modes and the corresponding spectra are modeled for two micro-rings with $d_i = 200$ nm and $d_i = 500$ nm, respectively. While the WGMs in both micro-ring structures have simulated Q values on the order of 100,000, the higher-order modes at $\lambda = 452$ nm are broadened (reduced Q, greater photon loss). For the disk with $d_i = 500$ nm, there is substantial overlap of the evanescent field of the higher-order mode with the inner boundary of the disk, indicated schematically by the solid red line in Figure 4.15, providing an easy visualization of the loss mechanism. Photons are lost from the higher-order modes at wavelengths that do not overlap with the QD emission wavelength responsible for lasing. This also explains why the changing micro-ring geometry does not affect the Q of the WGMs.

To determine values of $\gamma$ that correspond to our devices, we fit our lasing data to
Figure 4.16: (a) Fitted microdisk log-log lasing curves with $\beta = 0.85$ and $\gamma = 310^{11}$, and (b) the fitted slope and height of the ASE region.

Table 4.1: Table of Fitted Values of the Cavity Decay Rate $\gamma$ and ASE Height in Microdisk and Micro-Rings of Various Geometries

<table>
<thead>
<tr>
<th></th>
<th>Microdisk</th>
<th>400 nm micro-ring</th>
<th>200 nm micro-ring</th>
<th>500 nm micro-ring</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Volume</td>
<td>100</td>
<td>84</td>
<td>96</td>
<td>75</td>
</tr>
<tr>
<td>Fitted $\gamma$ ($10^{12}$ s$^{-1}$)</td>
<td>0.30</td>
<td>0.70</td>
<td>1.20</td>
<td>1.60</td>
</tr>
<tr>
<td>ASE Height</td>
<td>3.44</td>
<td>3.15</td>
<td>3.01</td>
<td>2.89</td>
</tr>
</tbody>
</table>

the characteristic “S-shape” curves of input versus output to more clearly delineate regions of sub-threshold operation, amplified spontaneous emission (ASE), and lasing. $\gamma$ was used as the fitting parameter. The value of spontaneous emission lifetime of QDs used in our calculation is 1.9 ns, within the range of QD lifetimes from our experimental measurements, and the transparency carrier concentration is between $1.0 \times 10^{26} m^{-3}$ and $1.1 \times 10^{26} m^3$. Figure 4.16 shows an example of such a fit on a microdisk with a $R^2$ value of 0.97. All our fits have $R^2$ values ranging between 0.95 and 0.97, showing an excellent
fit to the empirical data. The results are shown in Table 4.1, which indeed shows an increase in cavity decay rate, \( \gamma \), with increased removal of the center volume. Table 4.1 also shows a correlation of cavity geometry with details of the fitted ASE region. As more material is removed from the enter, the total contribution of ASE is reduced, likely reflecting the loss of incoherent photons from the cavity. ASE arises from the amplification of spontaneously emitted photons, which copy themselves by triggering stimulated emission events. The ASE region amplifies the intensity of photons from all phases and wavelengths, leading to an overall increase in the cavity incoherence, although there may exist local groups of coherent photons. Excess ASE is an undesirable effect in lasers as it can limit the maximum gain that can be achieved in the gain medium. The rather distinctive effect we observe here relate to lowering lasing threshold accompanied by lowered slope efficiency and reduced ASE contribution may be related to the heterogeneous nature of our gain layer, with both the fQWs and QDs that influence different regions of the spectrum. Hence, we believe that photon emissions from the fQWs dominates the ASE, and those photons overlap the more lossy higher-order modes in the micro-ring structures. The selective loss of fQW photons during ASE, together with the reduced competition from fQW emission into a mode, produce the dramatically reduced threshold for lasing that we observe in the micro-rings.
4.4 Modified micro-ring lasers

We have learned from the experiments so far that lasing in a micro-ring cavity containing a mixture of InGaN QDs and InGaN fQWs always takes place in the shorter QD wavelengths, largely due to the better carrier confinement ability of QDs, while fQWs act as an undesirable energy sink that competes with the QDs in the lasing process. The decrease in lasing threshold in the micro-rings is attributed to the loss of cavity volume at the center of the micro-ring, which removes large amount of competing fQWs. We also learned that the post-lasing-threshold slope efficiency is dependent on the photon decay rate and the amount of photon loss from the higher order modes. Increase in leakage of incoherent fQW photons that spectrally overlaps the higher order modes reduces the ASE region and allows the device to reach lasing at a lower threshold.

Having a heterogenous gain layer makes it challenging to delineate the difference in photon activities contributed by the QDs vs. the fQWs. However, one great property about our mixed gain layer is that the distribution of broad background emission from the QDs does not overlap with the fQW broad emission completely, with the QD emission blue-shifted by approximately 15 nm, as we recall from Figure 3.21. This allows us to distinguish between the QDs and fQWs, and empowers us with the ability to deliberately engineer the amount of contribution by each emitter towards cavity photon activity.

We want to answer the question if we can deliberately modify the cavity geometry so
that it preferentially encourages spontaneous emission from high-Q first order WGMs, and removes photons from low-Q higher order modes. We can engineer the cavity modes to have the high-Q first order WGMs spectrally overlap with the center of the QD emission, while having the low-Q higher order cavity modes overlap the center of the fQW emission. By doing so, we can deliberately modify photon contributions by balancing the QD emission with leakage from the fQWs.

We modify the existing $d_i = 500$ nm micro-ring cavity by strategically coating the micro-ring with different thicknesses of SiO$_2$ layers, which has a lower refractive index of 1.5 compared to the refractive index of 2.5 in GaN. In doing so, we will be able to shift the cavity resonance. We may be able to coat the disk in a way such that we can separately control the number of photons lost from cavity due to evanescence decay from the higher order mode vs. from the first order WGMs. By doing so, we will decouple the in-cavity photon dynamics between the high Q first order WGMs and the lower Q higher order modes.

Using FDTD methods, we performed simulations on a micro-ring with 1 $\mu$m outer diameter and 500 nm inner diameter, by coating either (a) the inner and outer walls of the micro-ring, or (b) the top and bottom surfaces of the micro-ring, with different thicknesses of SiO$_2$ layers. This is illustrated in Figure 4.17 for clarity. For each type of coating, we look at the evanescence field of the first order WGMs and the higher order modes separately, by integrating the total field outside of the micro-ring, or inside the center hole of the micro-ring, respectively.
Figure 4.17: Illustrations showing the coating of SiO$_2$ around a micro-ring with 1 $\mu m$ outer diameter and 500 nm inner diameter. Orange area represents SiO$_2$ while the dotted area represents GaN. (a) SiO$_2$ is coated evenly on the inner and outer walls of the micro-ring. (b) SiO$_2$ is coated evenly on the top and bottom sides of the micro-ring.

Figure 4.18: Simulated Q values of the first order WGM at 426 nm, for micro-rings coated with SiO$_2$ on the inner and outer walls for different thicknesses of SiO$_2$. 
Figure 4.19: Graph showing the integrated total field vs SiO\textsubscript{2} deposition thickness for a micro-ring that is coated with SiO\textsubscript{2} on the inner and outer walls as illustrated in Figure 4.17(a), for a first order WGM near 426 nm. LEFT: Total field outside of the micro-ring (region indicated by orange shaded area) against SiO\textsubscript{2} thickness. RIGHT: Total field inside of the micro-ring (region indicated by orange shaded area) against SiO\textsubscript{2} thickness.

Figure 4.19 plots the total integrated field of a first order mode near 426 nm in a micro-ring that is coated on the inner and outer walls with SiO\textsubscript{2} layers between 0 and 80 nm thick with 10 nm intervals. On the left, we integrate over the area immediately outside of the micro-ring for each SiO\textsubscript{2} thickness. We observe that the total field outside of the disk is the lowest when the thickness is 70 nm. Since the first order WGMs is located near the periphery of the micro-ring, the field present in the area immediately outside of the ring is attributed to loss from the first order WGMs. It is notable that there is an increase in the total field, and therefore total amount of photon loss, whenever the SiO\textsubscript{2} layer is non-zero in thickness, with an exception when the thickness is 70 nm. This is because 70 nm is approximately a quarter wavelength of the 426 nm mode in SiO\textsubscript{2} medium (n = 1.5). At 70 nm of SiO\textsubscript{2}, the layer acts as a mirrored cavity that reflects at its interfaces with adjacent media (GaN and air), this helps to trap and reflect some
Figure 4.20: Graph showing the integrated total field vs SiO$_2$ deposition thickness for a micro-ring that is coated with SiO$_2$ on the inner and outer walls as illustrated in Figure 4.17(a), for a higher order mode near 411 nm. LEFT: Total field outside of the micro-ring (region indicated by orange shaded area) against SiO$_2$ thickness. RIGHT: Total field inside of the micro-ring (region indicated by orange shaded area) against SiO$_2$ thickness.

of the 426 nm light at resonance with the first order WGM mode back into the ring, thereby reducing photon loss to outside of the cavity. In fact, the photon loss in this case is actually lower compared to without any SiO$_2$ coating. On the right side of Figure 4.19, we examine the total field inside the center hole of the micro-ring, illustrated in the figure as shaded orange region. There is an increase in photon loss to the center void of the ring when there exists a SiO$_2$ layer. Even though the relative total field in this region at 70 nm of coating is higher compared to that at other SiO$_2$ thicknesses, the absolute amount of photon loss here is negligible compared to the loss at the outer periphery of the ring. From these two graphs, we see that a SiO$_2$ coating thickness of 70 nm on the inner and outer wall of the micro-ring is highly desirable, as photon loss is reduced and more light in resonance with the first order WGM is kept within the cavity.
Next, we take a look at a higher order mode near 411 nm for the same ring that is coated on the inner and outer walls with various thicknesses of SiO$_2$. Since the higher order modes are usually competing with the lasing mode, a greater loss of photons from the higher order mode is desirable. As shown in Figure 4.20, the total field within the central void of the ring is the highest when thickness = 70 nm, indicating a larger amount of photon loss from the higher order mode into the center void due to increased evanescent coupling, as the higher order mode is spatially situated closer to the SiO$_2$/air inner interface. Second order modes of even lower quality factors located at other parts of the emission spectrum behave similarly to the second order mode at 411 nm. We studied the 411 nm mode for ease of comparison of quality factors between the coated and uncoated micro-rings. From the simulations, it looks like coating the micro-ring on the inner and outer walls with 70 nm of SiO$_2$ best helps us in trapping more photons specific to high-Q WGMs inside the cavity, while leaking undesirable higher order mode photons out of the cavity. We proceed to fabricate such a device and compare its performance with an uncoated micro-ring in the following.
1 µm diameter micro-rings with 500 nm inner diameter are coated with 70 nm of SiO\textsubscript{2} through atomic layer deposition. The thickness of the deposited SiO\textsubscript{2} is checked to be at 70 ± 5 nm using an ellipsometer with precision of 5 nm. The top surface of the coated micro-ring is then removed with reactive ion etching, leaving the inner, outer, and under surfaces of the ring covered with 70 nm of SiO\textsubscript{2}. This process is described in Figure 4.21. We compare the micro-rings before and after SiO\textsubscript{2} deposition with SEM images in Figure 4.22 and measure the various diameters of the micro-rings using these SEM images carefully.

Using values from the SEM measurements, we run FDTD simulations and compare the simulation results against experimentally measured PL spectra. The left plot of
Figure 4.23: A 1 µm outer diameter micro-ring with 500 nm inner diameter opening prior to coating with SiO₂. Left plot shows the simulated emission, with high-Q first order WGMs highlighted in different colors. The insets show the field distribution of each mode. Right plot shows the experimentally obtained PL emission from a micro-ring.

Figure 4.24: A 1 µm outer diameter micro-ring with 500 nm inner diameter opening coated on the inner and outer walls with 70 nm of SiO₂. Left plot shows the simulated emission, with high-Q first order WGMs highlighted in colors corresponding to the same modes as in Figure 4.23. The insets show the field distribution of each mode. Right plot shows the experimentally obtained PL emission from a micro-ring.
**Figure 4.25:** Comparison between simulated emission spectra of micro-ring before and after depositing 70 nm of SiO$_2$. Cavity modes are red-shifted by approximately 10 nm after coating.

Figure 4.23 shows the simulated emission spectrum of a micro-ring prior to SiO$_2$ deposition. The three highlighted modes near 415 nm, 436 nm, and 460 nm are high-Q first order WGMs, with Q values of 190,648, 76,637, and 138,571, respectively. The field distributions of the modes are also shown as insets above their respective wavelengths. On the right of Figure 4.23, we show the PL emission of the micro-ring at low excitation power, with two high-Q cavity modes at 436 nm and 460 nm getting picked out among a broad background of gain emission. The simulated emission spectrum and experimental PL emission for a micro-ring coated with 70 nm of SiO$_2$ are shown in Figure 4.24. The high-Q first order WGMs are highlighted and color-coded correspondingly as in Figure 4.23. The simulated Q values of the three first order modes near 424 nm, 446 nm, and 472 nm are 110,165, 122,878, and 93,801, respectively. We note that the addition of 70
Figure 4.26: Light In – Light Out (LI-LO) curve of a micro-ring prior to SiO$_2$ deposition. The inset shows the LI-LO plot in log scale, with the S-shape curve characteristic to lasing behavior.

nm of SiO$_2$ red-shifts the cavity modes by approximately 10 nm, as shown in Figure 4.25.

In the following, we compare the lasing behaviors of the micro-rings before and after the deposition of 70 nm SiO$_2$. Figure 4.26 shows the lasing curves of the first order mode near 436 nm for a micro-ring prior to SiO$_2$ deposition, with the inset in log-scale showing the characteristic S-shape of the device indicating lasing behavior. The lasing threshold is measured to be 9.1 $\mu$J/cm$^2$ and the Q of the mode 1980. Figure 4.27 shows the power dependent emission spectra of the micro-ring. At low pump power, both modes near 436 nm and near 457 nm are dominant against the broad gain background. These are first order high-Q modes as indicated in our simulation. As the pump power increases, emission from the 436 nm mode gets more intense and lasing is eventually
Two types of lasing behaviors are observed for micro-rings coated with 70 nm of SiO$_2$ on the inner and outer walls: either (1) lasing at a single wavelength near 424 nm is observed, or (2) mode hoping between lasing mode near 424 nm and 443 nm are observed. Let’s look at case (1) where there is lasing at a single wavelength. Figure 4.28 plots the pump-power dependent emission spectra of the micro-ring at 424 nm. Both the modes near 424 nm and 443 nm are visible at low pump power, with the 424 nm mode taking over and eventually lasing as pump power increases. The measured
Figure 4.29: Light In – Light Out (LI-LO) curve of a micro-ring after SiO$_2$ deposition. The inset shows the LI-LO plot in log scale, with the S-shape curve characteristic to lasing behavior.

Figure 4.30: PL emission spectra of a micro-ring with SiO$_2$ coating that displays double lasing behavior. The plots show the emission intensity at various pump powers as indicated on the top right hand corner of each graph. The two modes of interests at 424 nm and 443 nm are highlighted in green and blue.

Q value of the two modes are both above 2,000, with the 424 nm mode at a slightly higher Q value of 2,652 and the 443 mode at 2,114. Figure 4.29 shows the LI-LO curve of the 424 nm mode, with the inset showing the log-scale characteristics S-shape curve indicative of lasing behavior.

In case (2), where double lasing at two different wavelengths are observed, we observe mode-hopping happening between the mode near 424 nm and the mode near 443 nm,
Figure 4.31: Light In – Light Out (LI-LO) curves of a micro-ring that displays double lasing behavior after SiO$_2$ deposition. The lasing curves are shown at two different lasing modes of 424 nm and 443 nm.

with the 443 nm mode first achieving lasing at a threshold of 10.4 $\mu$J/cm$^2$, and the 424 nm mode at a higher threshold of 18.0 $\mu$J/cm$^2$. Figure 4.30 shows the pump-power dependent emission spectra of the micro-ring, highlighting the two modes of interests at 424 nm and 443 nm, respectively. At a low pump power of 881 $\mu$W (measured in path before the objective), the mode near 443 nm is the dominant emission, as the pump power increases, the mode goes into lasing at a threshold of 10.4 $\mu$J/cm$^2$. The LI-LO curve of this mode is plotted on the right side of Figure 4.31. As we continue to increase the excitation power beyond the lasing threshold of the 443 nm mode, the first order mode near 424 nm becomes more intense in its emission, and eventually achieves lasing at a threshold power of 18.0 $\mu$J/cm$^2$. The emission from the 443 nm mode plateaus as
The reason that we see single lasing near the 424 nm mode, or double lasing near both the 424 and the 443 nm modes is because these first order WGMs overlaps with the central region of the broad gain emission of the InGaN QDs which spans between 410 nm and 450 nm, with the center of the Gaussian emission at around 435 nm. By coating the micro-ring with SiO$_2$, we have shifted the cavity resonance modes such that both first order modes fall within the span of the broad QD emission. Whereas in the original micro-ring, only one high-Q WGM overlaps with the central region of the QD gain-spectra, other high-Q WGMs spectrally overlap with the central region of the broad emission from InGaN fQWs. The fQWs are not efficient photon generators due to their lower gain and longer spontaneous emission lifetime in comparison to the QDs, thus they eventually lose out to the QDs in competing for the lasing mode. This is
illustrated in Figure 4.32 for clarity, where the gray shaded region denotes the broad emission from the InGaN QDs.

By coating the micro-rings with a dielectric of a different refractive index, we have modified the cavity resonance modes. The relative spectral position of overlap between the cavity resonance modes and the center of the gain region of the QD broad emission, as well as the center of the gain region of the fQW broad emission, will change as a result of this. We can have control over the amount of photon emission we get from each type of emitters by controlling the thickness of the dielectric coating, and hence the spectral position of the emission mode.

This is significant because it allows us to deterministically engineer cavity mode positions to balance QD emission with leakage from the fQWs. By spectrally and spatially overlapping lossy high-order radial modes with the fQW broad emission, we can leak out undesirable fQW photons and reduce the height of the ASE region in the lasing process. As discussed earlier, the ASE region amplifies the intensity of photons from all phases and wavelengths, leading to an overall increase in cavity incoherence. Excess ASE is undesirable in lasers as it can limit the maximum gain that can be achieved in the gain medium. By reducing the total amount of irrelevant fQW photons, the ASE region can be reduced significantly. In addition, designing the high Q first order WGMs to spectrally overlap the broad emission of the QDs allows higher-gain QD to reach lasing faster. Together, separate control of QDs and fQWs is achieved through the careful design of cavity mode positions, giving rise to enhanced QD spontaneous emission.
and reduced ASE contribution, leading to an overall decrease in lasing thresholds.
In this chapter, we shift our attention to a different type of micro-cavity structure – the photonic crystal nanobeam. We begin by motivating the need for investigating such a new cavity geometry and how it enables an increase in the spontaneous emission factor of the lasing mode, leading to a reduction in lasing threshold. Following that,
we discuss the design and fabrication of three different types of nanobeams containing either InGaN QDs + fQWs, fQWs, or QWs and analyze their lasing performances. Part of this work has been discussed by Alex Woolf and Nan Niu in their dissertations.

5.1 Motivation

5.1.1 Spontaneous emission factor, $\beta$

The ability to control the spontaneous emission lifetime by modifying the density of states is critical for the realization of low-threshold lasers. This is because only photons emitted into the lasing mode, as opposed to other cavity modes or extended free space states, contribute to lasing. Recall from Chapter 2 that the spontaneous emission factor ($\beta$) refers to the fraction of spontaneous emission that is coupled to a single discrete mode of interest (lasing mode) versus all other channels. The spontaneous emission factor is given by

$$\beta = \frac{\Gamma_{sp_0}}{\Gamma_{sp_{total}}} = \frac{\tau_0^{-1}}{\tau_{sp}^{-1}} = \frac{F_0}{F_0 + \xi} \quad (5.1)$$

where $0 \leq \beta \leq 1$, $\Gamma_{sp_0}$ is the spontaneous emission rate into the desired mode, $\Gamma_{sp_{total}}$ the total spontaneous emission, $\tau_0$ the spontaneous emission lifetime of the lasing mode, $\tau_{sp}^{-1}$ the spontaneous emission rate in free space, $F_0$ the Purcell factor of the lasing mode, and $\xi$ the ratio of spontaneous emission coupled to radiative modes other than the lasing mode. Lasers with $\beta$ values closer to 1 are desirable because for these lasers
much of the spontaneous emission is radiated into the lasing mode and limited emission is ‘wasted’ into other channels that do not contribute to lasing. There are two ways to maximize $\beta$. $\beta$ approaches unity when $F_0 \gg \xi$ or when $\xi \to 0$. It is desirable to have a high Purcell factor $F_0$ for the lasing mode. Purcell factor of a mode is directly proportional to the quality factor $Q$ of the mode and inversely proportional to the modal volume $V$ of the optical cavity. Hence, designing a high $Q$, low modal volume cavity is important in attaining a low lasing threshold. The other way to maximize the value of $\beta$ is to minimize the value of $\xi$, such that photons can couple to as few optical pathways as possible outside of the lasing mode. We can engineer $\xi$ to be extremely small by carefully designing the cavity geometry and tailoring the cavity mode density of states to be much greater than other emission channels. With this, we may be able to increase the rate of spontaneous emission into the desired cavity mode and lower the laser threshold dramatically.

5.1.2 PHOTONIC CRYSTAL CAVITY

The photonic crystal cavity (PCC) is an optical cavity that utilizes a symmetry breaking inside a periodic dielectric structure in order to localize light within the region of the optical defect so as to guide and manipulate light at the scale of optical wavelength. It affects the movement of photons in much the same way as ionic lattices affect electrons in solids. Photonic crystal cavity is a cavity with one of the highest spontaneous emission factors, it is an ideal system for building a low threshold cavity laser.
**Figure 5.1:** Band structure for a 1D dielectric air stack showing the location of photonic band gaps\(^6\).

**Figure 5.2:** Schematic structures of (a) L4 PCC, (b) H0 PCC, (c) mode-gap PCC, (d) ring PCC, and (e) shoulder-coupled PCC.\(^7\)
To understand the working principle of a photonic crystal cavity\(^6\), we consider a one dimensional periodic lattice with lattice constant \(a\) made up of alternating layers of materials with dielectric constants \(\epsilon_1\) and \(\epsilon_2\), where \(\epsilon_1 > \epsilon_2\). Photons with wave vector \(k\) propagating within the cavity form a standing wave with a back-propagating wave under Bragg scattering when the photon wavelength matches the lattice spacing \((k = \pi/a)\). The energy density is proportional to the dielectric constant multiplied by the square of the magnitude of the electric field. Field energies are localized primarily in the regions of high and low dielectric constants. The band structure of the photonic crystal can be calculated using the photonic analogue of the quantum Kronig-Penny model, and is illustrated in Figure 5.1. A photonic band gap exists if \(\epsilon_1 > \epsilon_2\). In this case, the lower dielectric constant medium where \(\epsilon_2 = 1\) is air. Light is therefore localized in the dielectric and air medium, respectively. To from a photonic crystal cavity, we introduce a break in the periodicity of the dielectric stack by introducing a defect state that exists within the photonic band gap. Since light with frequencies within the photonic band gap is forbidden in the periodic region of the dielectric stack, the light will be spatially confined to the region of the photonic crystal defect. Some examples of photonic crystal cavities are shown in Figure 5.2.

There are three reasons that make a photonic crystal an excellent platform for building a low-threshold laser. Firstly, the break in the periodicity of the photonic crystal needs to be only the size of one element in the periodic array, making the modal volume \(V\) of the optical cavity extremely small, as low as \(0.01\left(\frac{\lambda}{2}\right)^3\). Secondly, the cavity lifetimes
of the photonic crystal cavities are extremely long due to the vanishingly small density of states at frequencies within the photonic band gap in the dielectric stack region of the device. Equivalently, we say the cavity has a high Q factor. The long lifetime greatly enhances the interaction strength between optical field and material in the defect region. The high quality factor of the cavity, combined with the small modal volume, contribute to an extremely high Purcell factor, $F$, for the lasing mode. This in turn leads to a high spontaneous emission factor $\beta$. Thirdly, photonic crystal cavities reduce the rate of spontaneous emission into pathways that are not the lasing mode.

Since the rate of emission is proportional to the density of states, the small density of states at frequencies other than the lasing mode leads to inhibited emission and a low $\xi$, which also contribute to a higher value of $\beta$, desirable for low threshold lasing.

5.1.3 Designing the Nanobeam Cavity

By adjusting the structural parameters of a photonic crystal, the propagation of light can be modified and engineered at will. Using a deterministic method of designing PCC proposed by Qimin Quan et al., we design a photonic crystal nanobeam consisting of a ridge waveguide perforated with gratings of air holes. Using FDTD simulations, we
Table 5.1: Table showing the design parameter of the nanobeams

<table>
<thead>
<tr>
<th>Hole</th>
<th>Design I (453 nm)</th>
<th>Design II (438 nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner hole</td>
<td>36.0</td>
<td>41.0</td>
</tr>
<tr>
<td>Hole 2</td>
<td>35.2</td>
<td>40.2</td>
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<td>33.5</td>
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<td>Hole 13</td>
<td>25.9</td>
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<tr>
<td>Hole 18</td>
<td>21.7</td>
<td>26.7</td>
</tr>
<tr>
<td>Hole 19</td>
<td>20.8</td>
<td>25.8</td>
</tr>
<tr>
<td>Outer hole</td>
<td>20.0</td>
<td>25.0</td>
</tr>
</tbody>
</table>

Come up with two different designs of PCC nanobeams, each with a unique frequency of resonance, quality factor, and modal volume. Nanobeam of design 1 has a resonant mode at 453 nm with a Q factor of ~ 118,000 and a modal volume of $\sim 1.5\left(\frac{\lambda}{n}\right)^3$, where $n = 2.5$ is the refractive index of GaN. Nanobeam of design 2 has a resonant mode at 438 nm with a Q factor of 101,000 and a modal volume of $\sim 1.7\left(\frac{\lambda}{n}\right)^3$. Both designs use the same beam length of 5.2 $\mu$m with the same periodicity of 130 nm between adjacent holes and membrane thickness of 200 nm, the size of the holes are larger near the center.
of the beam and decreases in size outwards from the center. The width of the beam in design 1 is 130 nm whereas the beam width is 125 nm in design 2. Figure 5.3 shows the FDTD simulation of the field profile of the resonant mode at 438 nm for design 2. The optical mode is concentrated and confined within the small volumes of the semiconductor material, between the inner etched holes. Table 5.1 shows the design parameter of the two nanobeams listing the radii of the holes. The design is symmetrical about the line between the two inner most holes at the center, and the inner hole is defined as one of the center holes next to the line of symmetry, and the outer hole is the one nearest to the outer edge of the beam. We have designed a high-Q nanobeam cavity where we use holes to create a modulation of the index of refraction, setting up steady-state modes with high field strengths confined to very small volumes. The cavity has one and only one mode that overlaps with the gain spectrum.

5.2 Fabrication

We fabricate nanobeams using materials containing either 3 layers of QDs + fQWs, 3 layers of fQWs, or 3 layers of QWs. Taking into consideration the cavity resonant wavelength, design 1 is adopted for fabrication of nanobeams with QDs + fQWs as the active media, while design 2 is used for nanobeams containing fQWs and QWs, since the distribution of emission wavelength from the QDs is centered around 435 nm, while that for QWs is centered at a longer wavelength of 450 nm. Figure 5.4 outlines the
Figure 5.4: Fabrication flow chart of a PCC nanobeam showing both the top view and the side view. The process involves two e-beam lithography exposures, one with positive resist XR and another with negative resist FOX-16.

Figure 5.5: SEM images of the (a) side view and (b) top view of a photonic crystal nanobeam cavity.
fabrication process, which involves a two-step e-beam lithography process and critical point drying, which are not necessary in the fabrication of microdisks and micro-rings we have discussed earlier. We start by sonicating the sample wafer in acetone and IPA each for 3 minutes, followed by a 30 minutes cleaning in piranha and a 3 minutes buffer oxide etch to remove any surface oxides. We then deposit a 5 nm SiO\textsubscript{2} diffusion prevention layer and a 10 nm Ti conductive layer onto the wafer surface, before spinning the XR-1541 e-beam resist. E-beam lithography is then used to define the nanobeam and circular pads on each end which serve as masks for the subsequent reactive ion etch in 25 sccm of N\textsubscript{2} and Cl\textsubscript{2} for an approximate depth of 300 nm. Following this, we remove the XR resist, Ti, and SiO\textsubscript{2} layers from the sample, and spin-coat approximately 500 nm of FOX-16 e-beam resist. E-beam lithography is used again to define a large rectangular pad aligned to the dry-etched nanobeam and circular pad. This pattern is subsequently dry-etched with reactive ion etch using the same parameters as described above to a further depth of approximately 200 nm. PEC etching is then carried out to selectively remove the SSL layer below the nanobeam membrane layer, producing a suspended photonic crystal nanobeam structure shown in Figure 5.5.
5.3 Measurements and results

5.3.1 Low-threshold lasing in nanobeams

We performed optical characterization on the nanobeams using the photoluminescence measurement with a frequency doubled Ti-Sapph laser at 380 nm through a long working distance objective with 40x magnification and a numerical aperture of 0.5. The quality factors of the fQWs and QWs beams have Qs ranging between 1300 and 2500, while nanobeams containing QDs + fQWs have Qs in the 4000 range.

Figure 5.6: PL emission spectra of a photonic crystal nanobeam containing InGaN (a) fQWs, (b) QWs, and (c) QDs + fQWs active media at low powers of excitation.
Figure 5.7: PL emission spectra of a photonic crystal nanobeam containing 3 fQW layers at three different pump powers: before lasing, near lasing threshold, and above lasing threshold. The spectra taken with pump power above and at threshold are attenuated 1250 times and 5 times, respectively, with respect to the spectrum taken with below threshold pumping. The inset shows the linewidth narrowing and the slight blue-shift in emission wavelength of the principal mode at above and below threshold.

The dominant mode of emission in the fQW and QW nanobeams are measured at 452 nm and 458 nm, this is over 15 nm red-shifted from the intended design at 438 nm. This deviation is due to the reduced sizes of the etched holes in the actual fabricated devices compared to their designed values, leading to an enlargement of the cavity region and a red-shift in mode positions. At low pump power, the PCC nanobeams exhibit excellent signal to noise ratio compared to microdisks made from the same material. Figure 5.6 shows example emission spectra from nanobeams containing fQW, QW, and QD + fQW gain materials.

Lasing in the nanobeams are demonstrated for devices containing InGaN fQWs as well we InGaN QWs. We have observed lasing through the linewidth narrowing of modes due
Figure 5.8: Log-log plot of the emission intensity vs. pump power of a fQW nanobeam. The blue dots are experimental data points, the red curve shows the best curve fit to data points, giving a spontaneous emission factor of $\beta = 0.94$. The characteristic S-shape curve clearly demonstrates the three regimes of lasing operation: spontaneous emission, amplified spontaneous emission, and stimulated emission.

to increased temporal coherence, as well as the dramatic nonlinear increase in emission intensity as the excitation power increases. A slight blue-shift in emission wavelength of the principal mode is observed as pump power increases, possibly related to the screening of the built-in field. Figure 5.7 shows the emission spectra of a nanobeam containing 3 fQW layers taken at three different pump powers: below threshold, near threshold, and above threshold. At low pump power, we observe the broad background emission signature of the InGaN fQWs coupled to the leaky mode of the cavity. The broad spectrum of frequencies is due to the variation in sizes of fQWs present in the material. As pump power increases, the linewidth of the principal emission mode narrows near the lasing threshold, and a non-linear increase in output power is observed as the device enters the lasing regime. Figure 5.8 shows the log-log plot of the experimental data.
of a fQW nanobeam, the red curve best fits the data with a spontaneous emission factor of $\beta = 0.94$. The curve clearly demonstrates all three regimes of operation: spontaneous emission, amplified spontaneous emission, and stimulated emission. The high value of $\beta$ results from the small modal volume, high Q factor of the mode, and hence a higher Purcell factor. The high value of $\beta$ is also a result of having only one cavity resonant mode that overlaps the broad emission region of the gain material. This reduces energy loss to other pathways so that light can be efficiently channeled into essentially a single mode. In comparison, a microdisk made from the same material has multiple modes that overlap the gain region. The competition between these modes reduces the spontaneous emission rate ($\beta$) into the lasing mode, making the microdisk a less efficient cavity structure for low threshold lasing compared to the nanobeam.

The measured threshold of the fQW nanobeams ranges between 9.1 $\mu J/cm^2$ and 27.2 $\mu J/cm^2$ with an average of 15.6 $\mu J/cm^2$, at a relatively consistent emission wavelength of around 454 nm. Probabilistically speaking, a mode near the center of the broad gain emission is more likely to go into lasing. Despite being on the blue-side of the broad fQW emission spectrum, the principal mode of emission we observe is the only mode that spectrally overlaps the fQW gain emission, and consequently becomes the lasing mode.

Nanobeams fabricated using the same design parameters as above (design 2) but containing 3 layers of InGaN QWs instead of fQWs exhibited lasing in a limited number of devices. While all of the 11 fQW nanobeam lasers measured demonstrated lasing, only
Figure 5.9: LI-LO plots comparing the thresholds of the fQW and QW lasers. The inset shows a zoomed-in version of the plot for the fQW laser with a threshold of 9.1 µJ/cm². The QW laser has a threshold of 198.6 µJ/cm².

Figure 5.10: AFM image of the InGaN fQWs before growing the capping layer. Inset shows a schematic of the side view of the layering structure within the GaN membrane.
3 out of 10 QW nanobeams probed demonstrated lasing behavior, at wavelengths of 451 nm, 455 nm, and 457 nm, respectively. The lasing threshold of the QW nanobeams are significantly higher at an average of 203.6 $\mu$J/cm$^2$, about an order of magnitude higher than the average lasing threshold of the fQW nanobeams (15.6$\mu$J/cm$^2$). An example of the lasing curves is shown in Figure 5.9. This is a particularly interesting finding as our earlier discussion of microdisk cavities in chapter 3 yielded the exact opposite result: microdisk cavities containing 3 layers of fQWs performed worse and have an average lasing threshold approximately four times that of microdisks containing QW active layers.

This different behavior in lasing threshold stems from the discrepancy between the photon loss mechanism in the two different cavity-gain medium systems. The nanobeam cavities provide a small modal volume which allows for stronger cavity-emitter coupling. This also offers enhances the spatial localization of the electron-hole pairs, increasing the amount of carrier radiative recombination. When we pump the nanobeams optically
with an excitation laser, the incident photons are absorbed by the gain layer, producing electron-hole pairs. For a nanobeam containing QW layers as the gain medium, the electrons and holes produced can diffuse freely within the gain layer. They may move to the edge of the etched holes in the nanobeam and recombine non-radiatively with surface states, as illustrated in Figure 5.11. If the average distance of photo-generated carriers to etched-surface is less than the carrier diffusion length, a substantial loss of carriers to non-radiative recombination can happen. The carrier diffusion length of the carriers is estimated to be approximately 1.1 \( \mu m \), much longer than the 130 nm typical distance between holes in the nanobeam. Therefore, a substantial proportion of photo-generated carriers diffuse to the edge of the holes and undergo non-radiative recombination. The reduction in carrier-generated photons due to this loss of carriers will significantly increase the lasing threshold of nanobeams with QW as the active layer. However, a nanobeam containing fQW active material circumvents this problem by providing better localization of carriers with the smaller size of fQWs, and aids in limiting the diffusion of carriers to the surface. This reduces carrier loss to non-radiative recombination, increases the number of photons generated through radiative recombination, and consequently enables a lower lasing threshold.

In a microdisk cavity, high gain regions are located in the WGMs near the periphery of the disk. Carriers generated in the entire interior of the disk may diffuse to the periphery, recombine radiatively and resonate with the WGMs. The radius of the microdisk (500 nm) is smaller than the carrier diffusion length of 1.1 \( \mu m \), which allows a
greater proportion of carriers to recombine radiatively in a useful manner. In this case, a uniform layer of QW aids in the diffusion and radiative recombination of carriers in the vicinity of the WGMs, whereas smaller grained fQWs disrupt that uniformity and hinder the diffusion of carriers to the periphery of the microdisks. This leads to a higher lasing threshold in microdisks containing fQWs compared to QWs. Hence, matching the right type of cavity geometry to the suitable type of emitters is critically important in designing a microcavity laser with low lasing threshold.

5.3.2 Modified nanobeam design for QD emitters

Among the nanobeam cavities fabricated using design 1 and with materials containing 3 layers of QDs, none of the devices we probed achieved lasing, given the maximum

\[ \text{59 } \mu\text{W} \]
\[ \text{343 } \mu\text{W} \]
\[ \text{493 } \mu\text{W} \]
excitation power available to us. This is largely because the particular geometry is designed for a principal emission mode near 453 nm, while the fabricated device has a smaller hole size which led to a red-shift in its resonant frequency of approximately 15 nm, making the actual resonant wavelength to be around 468 nm. This unfortunately falls on the far right side of the broad emission from the QD gain layer. Probabilistically, there are much fewer quantum dots that overlap both spectrally and spatially with the high Q mode of the nanobeam, making the lasing threshold extremely high, if the nanobeam is able to lase at all.

To correct for this, we have re-designed the nanobeam with the geometry parameters listed in Table 5.2 with a beam length of 5.2 $\mu$m and width of 100 nm, that has a simulated emission mode at 426 nm. The actual fabricated nanobeam cavity has a
Table 5.2: Table showing the design parameter of the nanobeams

<table>
<thead>
<tr>
<th>Hole</th>
<th>Design III (426 nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner hole</td>
<td>36.0</td>
</tr>
<tr>
<td>Hole 2</td>
<td>35.2</td>
</tr>
<tr>
<td>Hole 3</td>
<td>34.3</td>
</tr>
<tr>
<td>Hole 4</td>
<td>33.5</td>
</tr>
<tr>
<td>Hole 5</td>
<td>32.6</td>
</tr>
<tr>
<td>Hole 6</td>
<td>31.8</td>
</tr>
<tr>
<td>Hole 7</td>
<td>30.9</td>
</tr>
<tr>
<td>Hole 8</td>
<td>30.1</td>
</tr>
<tr>
<td>Hole 9</td>
<td>29.3</td>
</tr>
<tr>
<td>Hole 10</td>
<td>28.4</td>
</tr>
<tr>
<td>Hole 11</td>
<td>27.6</td>
</tr>
<tr>
<td>Hole 12</td>
<td>26.7</td>
</tr>
<tr>
<td>Hole 13</td>
<td>25.9</td>
</tr>
<tr>
<td>Hole 14</td>
<td>25.1</td>
</tr>
<tr>
<td>Hole 15</td>
<td>24.2</td>
</tr>
<tr>
<td>Hole 16</td>
<td>23.4</td>
</tr>
<tr>
<td>Hole 17</td>
<td>22.5</td>
</tr>
<tr>
<td>Hole 18</td>
<td>21.7</td>
</tr>
<tr>
<td>Hole 19</td>
<td>20.8</td>
</tr>
<tr>
<td>Outer hole</td>
<td>20.0</td>
</tr>
</tbody>
</table>

cavity resonant wavelength at around 440 nm, which is red-shifted for about 14 nm from the intended design due to fabrication discrepancies.

The nanobeams are fabricated using a one-step e-beam lithography method similar to the process discussed in the previous section. However, instead of doing e-beam alignment and exposing the beam and the etch pad in two separate steps, we have combined the processes into one step using a mixture of FOX-16 e-beam resist and MIBK in the ratio of 1:2. This spins to a resist thickness of about 300 nm at 3000 RPM.
With the particular selectivity between the e-beam resist and the GaN substrate, such a thickness is able to allow reactive ion etching of the entire structure for about 500 nm in depth without completely etching away the mask, while allowing for a sufficiently small aspect ratio of the mask resist such that the sub-100 nm diameter holes are all etched thoroughly.

A SEM image of the fabricated nanobeam is shown in Figure 5.13, and the pump power dependent emission spectra is shown in Figure 5.12. Lasing is demonstrated through the clear linewidth narrowing with increased pump power. The lowest lasing threshold observed for the QD nanobeam is 158.8 $\mu$J/cm$^2$. This is higher than the lasing threshold of the fQW nanobeams and lower than that of the QW nanobeams. This is because despite the QD can provide better carrier localization compared to the more lossy QWs, it offers a much smaller capture cross section in comparison, and hence a lower rate of carrier generation. The trade-off between better carrier confinement and higher capture cross section is critical in determining the lasing threshold in a cavity-emitter micro laser system, and is a recurring lesson we have learned from the microdisk, micro-ring as well as the photonic crystal nanobeam system.
Conclusion

In this dissertation work, we took an attempt at answering the question: what are the fundamental mechanisms that limit low threshold lasing in a microcavity laser, through studying GaN microdisk, micro-ring, and photonic crystal nanobeams embedded with InGaN QDs, fQWs, and QWs. Each type of cavity geometry and emitter structure has its own pros and cons, and it is important to place the right kind of emitters into the
most suitable cavity. Cavities with high quality factors, small modal volumes, containing high gain emitters, are most efficient at reducing lasing thresholds. The lowest threshold achieved in this work is 6.2 $\mu$J/cm$^{-2}$, in an 1 $\mu$m diameter GaN micro-ring laser with a 500 nm diameter opening at the center. The micro-ring is embedded with 3 layers of InGaN QDs and fQWs.

The key to building an ultra-low threshold microcavity laser lies in the ability to control cavity photons. Retaining useful photons that contribute towards lasing and removing undesirable ones that hinder lasing makes the overall system more efficient, and allows lasing to take place at a lower threshold. In addition, when designing an efficient microcavity laser, effort should be made to minimize the number of cavity modes that overlap with the gain region, so as to reduce unnecessary energy loss due to mode-mode competition towards stimulated emission.

The most efficient microcavity laser requires the placement of the best performing emitters at the best-performing modes.

From a cavity perspective, every microcavity contains a mixture of high-quality modes (such as the first order WGM in microdisk and micro-rings) and lower quality ones (such as the radial modes in microdisk and micro-rings). A high Q mode is able to trap light better, photons of that particular frequency are more likely to attain coherence and reach stimulated emission at a faster rate, whereas photons in a low Q mode are lossy, and do not reach stimulated emission as likely. They also act as an energy sink that competes with the lasing mode by increasing the total cavity incoherence during
amplified spontaneous emission.

From an emitter perspective, QD offers better carrier localization, and radiative recombination events are more likely to happen with a shorter spontaneous emission lifetime. The drawback of QDs as emitters is that their capture cross section is small, and they are less efficient at capturing pump photons at low excitation powers. QWs and fQWs, on the other hand, have much larger capture cross sections, but are less efficient gain material as they do not localize emitters as well, and the spontaneous emission lifetime in fQWs and QWs are an order of magnitude longer than in QDs.

By strategically placing high-gain QD emitters near high-Q first order cavity modes, and low-gain fQW emitters near low-Q higher order cavity modes, we can deterministically leak out incoherent fQW photons and curtail their contribution in the amplified spontaneous emission (ASE) phase of lasing. This reduces the total incoherence and competition inside the cavity. With a shorter ASE region, photons from higher gain QDs are able to reach stimulated emission faster at a lower lasing threshold.

Our heterogenous gain layer containing both QDs and fQWs allows us to do this exactly. The broad distribution of emission wavelength in QDs is blue-shifted from the fQW broad emission by approximately 15 nm. Taking advantage of this, we can engineer the cavity geometry so that the QD emission is spectrally centered on the high Q first order cavity mode, while fQW emitters are spatially located near, and its emission spectrally centered on, a leakier higher order mode. This allows large amount of undesirable, incoherent fQW photons generated through spontaneous emission at
low pump powers be leaked out of the cavity during ASE. The remarkable ability to separately control photons from each type of emitters and leverage their respective advantages help us to realize the lowest threshold microcavity laser.
Calculation Details

In this section we present the calculation details of the lasing threshold used in this dissertation where careful thoughts are given to the fraction of excitation beam that is intercepted by the devices, the reflection at the air-GaN interfaces, the material absorption coefficient, as well as the thickness of the gain layers.

The actual power absorbed by a micro-cavity can be less than the incident power
applied onto the cavity. In the following, we carry out calculations to estimate the actual power absorbed by each of our micro-cavities.

The amount of excitation laser power absorbed by the cavity can be approximated by

\[ P_{\text{abs}} = \eta P_{\text{in}} \cdot A_{\text{int}} \]  

(A.1)

where \( P_{\text{in}} \) is the incident power from the pump laser, measured directly under the objective lens. \( P_{\text{abs}} \) is the actual power absorbed by the cavity. \( A_{\text{int}} \) is the percentage of the laser beam intercepted by the cavity. \( \eta \) is an effective material absorption factor.

To calculate the percentage of laser beam intercepted by cavity, we assume the diffraction limit and estimate the laser spot diameter to be 515 nm with an objective lens of NA = 0.90 at wavelength of 380 nm. This diameter is smaller than the size of all our micro-cavities. The area of laser beam interception with a microdisk is unambiguous. However, depending on where the laser beam shines on a micro-ring, the area of interception can vary for a micro-ring of a definite geometry. When taking measurements, we scan the laser spot around and take PL measurements at the position with the maximum amount of output light. We assume this position corresponds to the position of maximum overlap between the laser beam and the device. We simulate the maximum area and percentage of overlap for each device geometry below:

A portion of the incident laser beam is reflected at each interface between air and the
Table A.1: Table of percentage area of micro-ring cavities

<table>
<thead>
<tr>
<th>Inner ring radius of microcavity (nm)</th>
<th>Percentage of beam interception, $A_{int}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 (microdisk)</td>
<td>1</td>
</tr>
<tr>
<td>200</td>
<td>0.92</td>
</tr>
<tr>
<td>400</td>
<td>0.74</td>
</tr>
<tr>
<td>500</td>
<td>0.63</td>
</tr>
</tbody>
</table>

Micro-cavities. The effective absorption factor $\eta$ is approximated by

$$\eta = \frac{(1 - R) \cdot (1 - \exp(-\alpha d))}{(1 - Re^{-\alpha d})}$$ \hspace{1cm} (A.2)

where $R = 0.18$ is the percentage of reflected light at air - GaN interface due to the difference in refractive index, $\alpha = 5 \times 10^4$ cm$^{-1}$ is the effective absorption coefficient for 380 nm light by the active material, and $d$ is the total thickness of the active layer(s). Micro-cavities with only 1 layer of InGaN QDs have $d = 2.5$ nm, while micro-cavities with 3 layers of InGaN QDs have $d = 7.5$ nm. Hence, the effective material absorption factor $\eta$ computes to 1.29% for cavities with 1QD layer, and 3.65% for cavities with 3QD layers.

Calculation of $P_{abs}$ in units of energy density (mJ/cm$^2$) We calculate the actual power of absorption by the micro-cavity $P_{abs}$ with Equation A.1. Since measurements of $P_{in}$ are taken in units of power (mW) from a pulse laser at 76 MHz, we convert $P_{abs}$ into units of energy density by dividing $P_{abs}$ by the frequency of the laser pulse, and the area of the micro-cavity:
\[ \frac{P_{\text{obs}}}{76 \text{MHz} \cdot A_{\text{micro-ring}}} \] (A.3)

where the area of the micro-cavities are:

**Table A.2:** Table of area of micro-ring cavities

<table>
<thead>
<tr>
<th>Inner ring radius of microcavity (nm)</th>
<th>Area of micro-cavity (nm(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 (microdisk)</td>
<td>785,400</td>
</tr>
<tr>
<td>200</td>
<td>753,908</td>
</tr>
<tr>
<td>400</td>
<td>659,730</td>
</tr>
<tr>
<td>500</td>
<td>589,050</td>
</tr>
</tbody>
</table>
References


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[63] Xia Li. Evanescent field coupled microdisk cavities. 2007.


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