MICRO- AND NANO-CAVITY LASERS FOR SENSING APPLICATIONS

BY

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DISSERTATION

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ABSTRACT

Lasers can be used for a multitude of sensing applications. This dissertation discusses two types of lasers for sensing applications. The use of an integrated vertical-cavity surface-emitting laser and photodetector as a position sensor is first detailed. Design, fabrication, and simulation of the position sensing capabilities are discussed. The use of a grating as the position gauge ultimately makes the range of measurement very large. Experimental demonstration of position sensing and velocity sensing is shown.

Photonic crystal membrane lasers, a type of nanoscale laser, are advantageous for sensing because of their compactness and ultra-small modal volume. Different aspects and properties of photonic crystal membrane lasers are discussed. The thermal characteristics of a photonic crystal laser are studied using a finite element method. Two new types of photonic crystal membrane cavity lasers are also presented and discussed: the decimated photonic crystal cavity and the heterostructure photonic crystal cavity. The later cavity is analyzed in greater detail via experiment and simulation.

Progress towards creating an electrically injected photonic crystal emitter is also discussed. The materials design and fabrication technique are presented. Here, the devices are fabricated in the InGaAs/GaAs material system. An oxidation layer is used to create a current aperture as well as to provide index contrast to the photonic crystal membrane. Calculations pertaining to the quality factor of the cavities in the diode
configuration are presented. A fabrication sequence and required process development is discussed, as well as progress toward laser diode fabrication.
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CHAPTER 1

Introduction

1.1 Motivation

Since their invention in 1960, lasers have been at the forefront of numerous applications due to their coherent and directed optical emission. Industrial applications that require highly localized beams of energy for tasks such as drilling, welding, and brazing use high-power lasers coupled into flexible optical fibers. Medical applications use similar technologies but at lower powers and with much higher spectral and spatial precision. Fiber optic-coupled semiconductor lasers also provide the large communication bandwidth required for the infrastructure for data communication, Internet, and wireless communication applications.

Lasers are also useful candidates in a number of sensing applications. A multitude of systems use the coherent properties of laser light in order to take measurements. Such systems can perform chemical [1], [2] and biological [3]–[8] sensing. These applications use a laser source to perform Raman spectroscopy, fluorescence measurements, and refractive index-based sensing and detection.
Position sensing is also an application in which lasers have become well incorporated. Laser rangefinders and 3-D scanners (lidar) are commercially available systems used to measure position on the scale of meters. Vertical-cavity surface-emitting lasers (VCSELs) have been suggested for use as position sensors with submicron accuracy [9], [10], and are currently implemented for measuring larger distances in commercially available computer laser mice [11], [12]. On a much larger scale, the distance from the earth to the moon has been measured to extremely high accuracy during the Lunar Laser Ranging Experiment.

This thesis deals with the design, fabrication, and testing of two types of semiconductor lasers for use as optical sensors. First, the use of an integrated VCSEL and photodetector as a position sensor is investigated. The thesis then describes the development of different types of photonic crystal nanolasers and the progress towards manufacture of electrically injected devices.

1.2 Integration of VCSELs with Photodetectors for Position Sensing

Vertical-cavity surface-emitting lasers are an excellent light source for many applications due to their low operating power, low circular beam divergence, and single longitudinal mode operation as well as their ease of manufacturability and array fabrication. They can be used for a number of applications including data communications [13]–[15], optical storage [16], and chemical and biomedical sensing [2], [17]. The ability to monolithically integrate VCSELs with photodetectors also allows for the creation of low-cost optical transceivers and biomedical sensors [18]–[22]. Wafer bonding of VCSEL die to detector die has also been used to create VCSEL-based optical encoders in order to measure translational distance [10].
Monolithically integrated VCSELs and photodetectors can be used for long-range precise position sensing [9]. Lithography systems and other high-precision positioning stages require the implementation of non-interfering, non-contact position sensors that operate over long ranges and with high precision. Within the Center for Nanoscale Chemical-Electrical-Mechanical Manufacturing Systems (NanoCEMMS) Center, sponsored by the National Science Foundation at the University of Illinois, a fluid-based manufacturing system that requires high-resolution position sensing and velocity monitoring is under development [23]. The position sensing system must be very compact and allow for high-precision measurements. Traditionally, capacitance gauges and laser interferometers have been used to achieve high-accuracy position sensing. While both systems provide nano-scale position sensing resolution, laser interferometers are far from being compact, and capacitance gauges typically have a limited range of measurement. More recently, optical encoders have been implemented in position sensing applications, and using data interpolation and interpretation can provide nano-scale position sensing accuracy over a large range of motion. Monolithically integrated VCSELs and PIN photodetectors that monitor a signal reflected off a grating can also be used in position measurement systems [9]. The monolithic integration of the VCSEL with the photodetector results in very compact, low-cost sensors [13]. Since the position sensor in this case uses a periodic position gauge, the range of motion detectable by the integrated VCSEL and photodetector position sensors should be theoretically as long as the position gauge.

### 1.3 Photonic Crystals as Sensors

The progression of fabrication technologies has allowed for the realization of compact and efficient semiconductor lasers. Because of this, micro-cavity semiconductor lasers have been used in a wide variety of applications in communications and sensing, as
well as for experiments in cavity quantum electrodynamics. Recently two-dimensional photonic crystals have been pursued as viable candidates for creating micro- and nanoscale lasers [24]. These types of devices utilize a periodic refractive index variation that enables ultra-small modal volume and low lasing threshold with high fidelity in their lasing spectrum [25]–[28]. While fabrication of photonic crystals in the optical regime can be challenging, it is the ability to modify light sources on the scale of the wavelength of light that makes them so appealing. In a given material system, the optical properties of photonic crystals are determined by their geometry. This means that they are suitable for a wide range of integrated applications because their optical characteristics are lithographically tunable.

The ability to lithographically tailor the dispersion of a photonic crystal has allowed for the possibility of a number of sensing applications. Enhanced molecular fluorescence and biomolecular detection have been demonstrated using a photonic crystal embedded in a plastic substrate [29], [30]. The use of photonic crystals in two dimensions to create an ultra-high quality cavity has allowed for record high sensitivity refractive index sensing in liquids [31]. Another application of the high quality factors obtainable is the use in systems to measure quantum electrodynamics phenomena. The Rabi splitting between a photonic crystal cavity and a single quantum dot has been demonstrated and measured [32].

There still remains much work to be done in the optimization of the thermal and electrical conductivity of photonic crystal membrane lasers, which is critical to diode operation. Since most membrane lasers are suspended in air and perforated with holes, the thermal and electrical conductivity are degraded. This has led to only a limited number of publications in which electrically injected photonic crystal membrane emitters are demonstrated [33]–[36]. Many researchers have utilized wafer-bonding techniques in order to provide heat sinking [37]. This approach generally improves the device performance
and can lead to room temperature continuous wave lasing. However, since the substrates onto which the photonic crystal membranes are transferred are low-index, non-conductive dielectrics, the electrical properties of the devices are, for the most part, unaltered. In order for photonic crystal lasers to become practical tools for use in sensing applications, the present thermal and electrical issues that prevent these devices from functioning as laser diodes must be thoroughly addressed.

1.4 Scope of Thesis

This thesis focuses on two semiconductor laser structures suitable for sensing applications. The first topic is the use of an integrated VCSEL and photodetectors as a position sensor. This is discussed via calculations and experimental measurements. The second part of this thesis describes the progress towards making electrically injected photonic crystal lasers for sensing. Progress toward electrically injected devices is addressed in two ways: novel cavity designs that provide favorable thermal and electrical properties and fabrication techniques that allow for diode operation.

Chapter 2 focuses on position sensing. First, the position sensing scheme is described and the material used is motivated. Then, the fabrication and design of the position sensors is discussed. The position sensing scheme is simulated using an integral method and experimental verification of the position sensing capabilities is shown. Chapter 3 gives a basic introduction to photonic crystals and photonic crystal lasers and describes a means of fabrication of optically pumped photonic crystals. The thermal properties of photonic crystal cavities are discussed, and a novel type of cavity, the decimated photonic crystal cavity is introduced. Chapter 4 focuses on the novel photonic crystal heterostructure cavity laser. Cavity design and experimental results are discussed. Simulation techniques are used to confirm measured phenomena. Chapter 5 describes the progress toward cre-
ating electrically injected photonic crystal lasers. The material design and fabrication techniques are discussed, and some preliminary results are shown.

1.5 References


[23] www.nano-cemms.uiuc.edu


CHAPTER 2

Position Sensing Using an Integrated VCSEL and PIN Photodetector

2.1 Position Sensing Scheme

The position sensing scheme utilizes a monolithically integrated VCSEL and photodetector as the position sensor and a reflective metallic corrugation as a position gauge. The position sensing scheme is shown in Figure 2.1 [1], [2]. The VCSEL and photodetector are positioned in a plane parallel to a metallic corrugation or grating. The optical emission from the VCSEL impinges on the grating and is reflected back to the plane of the photodetector. When the grating is far from the sensor die, the general distribution of the reflected field is mostly independent of small changes in the exact grating position. However, when the grating is brought into closer proximity with the VCSEL and detector die, the exact placement of the grating begins to affect the reflected field. Again, the global distribution of the reflected field is not greatly affected by small changes in grating placement. However, the local amplitude variation of the reflected field does depend on small changes in grating position. While this variation is small, it is still measurable and
Figure 2.1 A sketch of the position sensing scheme using a monolithically integrated VCSEL and photodetectors as a sensor. The position gauge is a metallic corrugation or grating.

can provide information about the relative placement of the grating. Since the grating position gauge is periodic, the measurement range of the sensor is as long as the physical extent of the grating.

The position sensing scheme poses some restrictions on what type of photodetectors can be integrated with the VCSEL. In general three types of detectors lend themselves to monolithic integration with VCSELs: metal-semiconductor-metal (MSM) photodetectors [3], resonant cavity photodetectors (RCPD) [4],[5], and PIN photodetectors [6]–[8]. For the application of position sensing, the photodetector needs to be able to measure small amounts of light that are incident at oblique angles. The MSM photodetectors are undesirable due to their lower detection-area-to-device-size ratio and relatively large dark current. The rapid photoresponse inherent to an MSM detector is also not needed. The RCPDs can have a larger detector area and are very easily integrated with VCSELs, but suffer from inherent spectral and angular sensitivity. They are not desirable because, even though the reflected light can be at the resonant wavelength of the detector, it will likely be directionally mismatched to the resonance of the cavity of the photodetector.
Non-spectrally selective PIN photodetectors are therefore chosen for this work because of their intrinsically broad spectral and angular response along with their high efficiency, low dark current, and compact integration with VCSELs.

2.2 Material, Fabrication, and Sensor Layout

The fabrication technique follows that discussed in [1]. The VCSEL and PIN photodetector material is grown by metal organic chemical vapor deposition. The epitaxial structure is grown on an n-type GaAs substrate. The VCSEL bottom reflector is composed of a 35 period n-type Al$_x$Ga$_{1-x}$As distributed Bragg reflector (DBR). On top of this is a 1λ-thick intrinsic region containing three quantum wells with peak optical emission at 850 nm. The top reflector of the VCSEL is a p-type Al$_x$Ga$_{1-x}$As DBR. The detector is grown on top of the VCSEL and is separated by a thin In$_{0.49}$Ga$_{0.51}$P layer. This layer acts as an etch stop in a chlorine-based reactive ion etch. The p-type side of the detector is comprised of the p-DBR of the VCSEL, the In$_{0.49}$Ga$_{0.51}$P layer, and a 270 nm thick p-type Al$_x$Ga$_{1-x}$As layer. The absorption region of the detector is a 2 μm thick intrinsic GaAs layer. The n-type side of the detector consists of a 300 nm n-type Al$_x$Ga$_{1-x}$As layer capped with a thin layer of GaAs to prevent surface oxidation and allow for ohmic contact deposition. A sketch of the wafer cross-section after device fabrication is complete is given in Figure 2.2

Fabrication begins with the deposition of ohmic contacts to the n-type top layer of the detector and then to the backside of the n-type substrate. This is done by evaporation of AuGe, Ni, and then Au. The detector mesas are defined using a chlorine-based reactive ion etch. Using a 50:1 mixture of BCl$_3$:Cl$_2$ and either SiO$_2$ or photoresist as an etch mask provides a high etch selectivity of AlGaAs/GaAs over In$_{0.49}$Ga$_{0.51}$P. This allows for a uniform etch depth across the entirety of a 3-inch wafer. The etch stop layer is
removed by a mixture of either HCl:water or HCl:H$_3$PO$_4$. Ohmic contacts are then made to the p-type regions of the VCSEL and detectors by deposition of Ti and then Au. A layer of SiO$_2$ is then deposited to act as an etch mask. The VCSEL and detector bottom mesas are defined by photolithography, and a Freon-14-based reactive ion etch is used to transfer the pattern into the SiO$_2$ mask. The VCSEL and detector bottom mesas are defined using an inductively coupled plasma reactive ion etch process. This etch is performed using a mixture of SiCl$_4$ and Ar and allows for a highly anisotropic etch. The current and optical apertures of the VCSEL are defined by subsequent steam oxidation at 410 °C. A photodefínable polyimide is used to create a planar surface in order to facilitate the deposition of Au interconnects and bond pads at the edge of each sensor die. The Au interconnects and the edges of the bond pads are encapsulated in a second layer of polyimide in order to improve the metal adhesion during die packaging. Microscope images of the fabricated integrated VCSEL and detector geometries are shown in Figure 2.3. In each image, the VCSEL is in the center and is 25 µm in diameter.
Figure 2.3 Optical image of three sensing configurations of a VCSEL surrounded by PIN detectors. The VCSEL is in the center of each die.

2.3 Simulation of Position Sensing Capabilities

Simulations in two dimensions were performed to diagnose the sensing capabilities of the integrated laser and detector configuration [2]. An integral method according to [9]–[11] was used to perform the calculation. These simulations focus on calculating the reflected field from the output of a VCSEL impinging on a periodic metallic corrugation. The translation direction considered is along a line that bisects the VCSEL and surrounding detectors, as shown in Figure 2.3. The light output from a VCSEL, with emitted wavelength $\lambda$, was modeled as the lowest-order Gaussian beam, with beam radius of $3\lambda$ ($\sim 5 \mu m$ diameter for the VCSEL emission at $\lambda = 850$ nm). The metallic corrugation was assumed to be a perfect electric conductor. A sawtooth triangular geometry was chosen for the metallic corrugation profile to model a typical commercially available grating. Figure 2.4 shows the backscattered electric field from a sawtooth corrugation of period $4\lambda$, amplitude $2\lambda$, and distance $75\lambda$ from the laser source. The symmetric and antisymmetric corrugation placements correspond to the alignment of the corrugation node relative to the central axis of the VCSEL and a translation of the prior by a quarter of the grating period, respectively. It should be noted that these calculations do not
Figure 2.4 Backscattered field from a triangular corrugation placed $75\lambda$ from the laser source whose center is at $x = 0$.

take into account Fresnel reflection at the detector surfaces. The collected power for the various detector geometries in Figure 2.3 can be found by spatially integrating the field intensities over the appropriate positions on each side of the VCSEL.

The total power incident on the innermost detectors as the corrugation translates to the right through one period is shown in Figure 2.5. Figures 2.5(a), (b), and (c) correspond to the detector geometries shown in Figures 2.3(a), (b), and (c), respectively. Here, the vertical axis is the total power measured in a detector normalized to the total power emitted by the VCSEL. The translation distance of zero corresponds to the central axis of the VCSEL being aligned with a maximum (peak) of the corrugation. Note that approximately 47% of the VCSEL output power is reflected back toward the optical aperture of the VCSEL (in this case 9 $\mu$m diameter) and that this power varies by approximately $\pm$ 3.6% when the grating is linearly translated by one period.

The geometry of the detector pictured in Figure 2.3(a) gives rise to a 58% variation in incident power during corrugation movement. Although this variation is relatively
large, the overall incident power and, therefore, measured signal is small compared to the other two geometries. The detector geometries in Figures 2.3(b) and (c) result in about an order of magnitude larger incident power, but with a smaller overall power variation. The overall variation in the incident power in Figures 2.3(b) and (c) is about 5% and 14%, respectively. For each detector geometry, the incident power changes from its mean value to its maximum or minimum value after the corrugation has traveled approximately one quarter of the corrugation period, which would approximately correspond to the position sensing resolution.

![Graphs showing incident power](image)

**Figure 2.5** The normalized incident power on the detectors as the corrugation moves to the right. The horizontal axis is normalized to the corrugation period. The solid and dashed lines correspond to the detectors to the left and right of the VCSEL, respectively. (a), (b), and (c) correspond to detector geometries shown in Figures 2.3(a), (b), and (c), respectively.

Figure 2.6 shows the amplitude of the measured signal in each of the detector configurations as the grating moves farther from the detectors. More specifically, this corresponds to the difference between the maximum and minimum measured signals when a calculation similar to that presented in Figure 2.5 is performed for different grating to sensor distances. The detector geometry of Figure 2.5(c) works best at smaller detector-to-grating-separation distances, while the other two geometries show better performance.
Figure 2.6 The normalized signal amplitude as a function of the distance from the grating to the sensor. The dashed (a), dotted (b), and solid (c), lines correspond to the detector configurations in Figures 2.3(a), 2.3(b), and 2.3(c), respectively.

at larger distances. At very large distances, none of the detector configurations considered perform very well. This shift to better performance from different detector configurations is due to the variation of which part of the reflected field changes more drastically as the grating-to-sensor distance increases. It is evident, then, that for use in a practical system, the sensor configuration should be chosen with the system design, considering specifically the separation between sensor and position gauge.

2.4 Position Sensing Measurements

In order to provide electrical connections to a packaged sensor die while at the same time leaving the nearby area free from obstructions, a silicon host substrate, or coupon, is fabricated according to the method found in [12]. Deeply etched pockets roughly the same thickness as the sensor die are etched into a Si substrate using an inductively coupled
plasma Bosch etch process. The surface of the host substrate is rendered nonconductive by oxidation, and metal pads are subsequently deposited. Conductive epoxy is used to connect the die to the substrate. After creating polymer ramps on the substrate to fill in the gaps around the sensor die and depositing interconnect metal, connections to the top side of the sensor die are made using a conductive epoxy. To facilitate easy electrical contact to the die, wires are attached to the bond pads using a conductive epoxy.

To demonstrate feasibility of the position sensing scheme and effectiveness of the sensing die, experimental data similar to the calculated data shown in Figure 2.5 are desired. In order to experimentally verify the position sensing capabilities of the sensor die, the sensor configuration shown in Figure 2.3(c) is packaged into a coupon that is integrated into a translational test system. Here, the silicon host substrate is attached to a manually operated translation stage. This allows for electrical connections to be made without interference to the relative motion of the sensor. A commercially available, low-cost replica grating with period of 3.49 µm is used as the position gauge. The grating is attached to a computer-controlled linear translation stage with the grating grooves perpendicular to the direction of motion. The silicon coupon is then raised to be in close proximity to the grating, as judged visually. The VCSEL is biased by an external current supply. The detector leads are connected to an external transimpedance amplifier whose output is monitored by an oscilloscope. A general sketch of the experimental setup is given in Figure 2.7.

The grating is moved at various speeds, and the output of the transimpedance amplifier is recorded over various time scales. Multiple modes of operation of the translation stage are employed to explore the smoothest motion possible. The goal is to find a signal that is periodic in time with a period equal to the grating period divided by the translation speed. While the grating is translating, multiple captures of the signal are performed on the oscilloscope. The capture time is much less than the overall time that the grat-
ing is moving in order to ensure that the grating has reached a time stable translation velocity.

2.4.1 Initial Results

Initial measurements were performed with a low-cost positioner that used a ball bearing system to reduce friction. An example of the measured data when the stage is translating at 100 µm/s is shown in Figure 2.8. Many measurements similar to this one are made at different speeds. The peak-to-peak time delay is measured and then statistically compared to the theoretical time delay (grating period divided by translation speed). Due to several contributions to measurement noise (both electrical and mechanical), fewer than 10% of the recorded signal captures exhibit periodic behavior. In captures where the signal displays periodic nature, the average peak-to-peak spacing corresponds to a distance that is on average within 5% of the grating period. Moreover, the individual peak-to-peak spacing in periodic traces also varied. The noise and lack of experimental repeatability are attributed to stage vibrations and a random velocity profile of the translator movement. The first noise source is due to mechanical instabilities in the measurement setup. The random velocity profile of the translator movement is attributed to the translator itself and its components. The drive motor for the translator is a stepper
motor turns turns a leadscrew. More importantly, the translation platform is supported by metallic ball bearings. These two mechanical features result in friction sufficient to ultimately cause inconsistencies in the translation velocity of the stage.

It is important to note that in situations where the movement of the grating is relatively smooth, the sensor is able to give position variations (as read from oscilloscope traces) that were within 5% of their theoretical value, as shown in Figure 2.8. This indicates that the position sensing scheme is feasible. In a case like this, one can resort to tallying the number of voltage peaks to give an estimation of the distance traveled. This of course will result in a loss of resolution, as now the position can determined within one grating period. In a real-world situation where stage vibrations and acceleration of the translation stages must be taken into account, a signal processing and interpolation algorithm can be employed in order to assure that functionality of the sensors is preserved, even in situations where the movement is sporadic and random.
2.4.2 Measurements Using High Precision Stage

In order to obtain data that better matched the simulation shown in Figure 2.5, a high-
precision stage was used. This experiment was performed within the center for Nanoscale
Chemical-Electrical-Mechanical Manufacturing Systems at the University of Illinois [13].
This stage consisted of a high-precision, air bearing gantry system manufactured by
Aerotech [14]. Implementation of this stage allowed for the grating to be translated in
a highly controlled manner. Examples of the photodetector response taken at speeds
of 5 µm/s and 50 µm/s are shown in Figures 2.9 and 2.10, respectively. Using the
precision stage, measurements showed high periodicity that correlated to the grating
period. Measurement repeatability also increased to over 90% of data captured showing
high periodicity. In this case, the measurement of non-periodic signals was attributed
to damage to the replica grating. This was determined by scanning the sensor over the
same area of the grating multiple times and measuring similar non-periodic nature.

Figure 2.9 Voltage vs. time when the grating is translated at 5 µm/s relative to the
grating using an air bearing positioner.
Figure 2.10 Voltage vs. time when the grating is translated at 50 µm/s relative to the grating using an air bearing positioner.

For the cases measured, speeds were varied from 5 µm/s to 1 mm/s, and all yielded similar results. There was more noise in the measured signal when the movement was relatively fast, but this is expected since vibrations in the mechanical parts of the measurement setup will increase as the speed of the stage is increased. Even though the signal did become slightly noisy in the case of 1 mm/s translation, the periodicity was well maintained. Measured peak spacings fell within 2% of the predicted peak spacing and were even measured to be as close as 0.09%. The measurement error in peak spacing is attributed to the manner in which the peak spacing was determined as well as the orientation of the grating. The peaks were determined from the voltage-versus-time plots. The grating orientation also plays a role in the accuracy of the measured spacing. The grating grooves were placed perpendicular to the direction of motion, as judged visually. If the grooves are not exactly perpendicular to the direction of motion, then the effective
periodicity of the grating would be increased, with an apparent decrease in translation speed.

In order to obtain a high-precision measurement using the voltage signals mentioned above, a more advanced technique than counting the voltage peaks in time could be employed. The utilization of a signal interpolation technique using some type of data learning method would likely provide highly accurate measurements. Alternatively, in order to obtain velocity information, one could use the Fourier transform of the voltage signal. As an example, the Fourier transform of the voltage signal when the stage travels at 200 $\mu$m/s is shown in Figure 2.11. Here the horizontal frequency axis has been scaled by the grating period and the average value of the voltage signal was subtracted from the signal prior to performing the Fourier transform. The highest peak at 200 $\mu$m/s can thus

![Figure 2.11](image)

**Figure 2.11** Fourier transform of the measured signal when the grating is translated at 200 $\mu$m/s using the air bearing system. The signal average was subtracted from the signal prior to performing the Fourier transform. The horizontal frequency axis has been scaled by the grating period.
be interpreted as the translation speed. Other smaller peaks in the Fourier transform are due to the non-sinusoidal grating profile and finite nature of the measured signal.

2.5 References


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2Ga

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[13] www.nano-cemms.uiuc.edu

CHAPTER 3

Photonic Crystals and Photonic Crystal Lasers

This chapter considers optically pumped photonic crystals and photonic crystal lasers. It begins with a basic introduction to some of the basic properties of photonic crystals. Using these properties, the functionality of photonic crystal cavity lasers is explained. Fabrication of a photonic crystal cavity in the InP material system is also discussed. The thermal properties of a suspended membrane photonic crystal laser are analyzed using a finite element method. The chapter ends with a discussion of a novel type of cavity, the decimated photonic crystal cavity, which may provide benefits for improved operations, including diode operation.

3.1 Characteristics of Photonic Crystals

Like an atomic crystal that is formed by a periodic array of electronic potentials, a photonic crystal is formed by a periodic arrangement of optical parameters. Permittivity, permeability, conductivity, and nonlinear optical parameters can all be periodically arrayed by choosing the appropriate materials and geometric patterns. The photonic crystals that are discussed in this work, however, are comprised predominantly of peri-
odically modulated dielectrics. Resonant nonlinearities, such as semiconductor quantum wells, are not addressed. The periodicity of the refractive index determines the relevant optical properties.

The plane-wave expansion method can be used to understand the optical properties of photonic crystals [1], [2]. Since the permittivity of the photonic crystal varies in a periodic manner, the electric and magnetic fields can be written in a Bloch form. Fourier series expansion of the electric and magnetic field Bloch functions for a given momentum, $k$, as well as the inverse of the permittivity over the photonic crystal reciprocal space yields an eigenvalue problem. In this procedure, the electric or magnetic field Fourier components are the eigenvectors and the frequency is the eigenvalue. Since values of $k$ outside of the first Brillouin zone can be mapped back into the first Brillouin zone, only momenta that lie in this region need to be considered. Figure 3.1 shows the normalized eigenfrequency for a given $k$ vector inside the first Brillouin zone for a hexagonal array of air holes perforating a dielectric material. Here, the electric field is polarized in the plane of photonic crystal periodicity. This diagram is commonly referred to as a photonic band diagram. Here, $\Gamma$, $M$, and $K$ are the symmetry points of the first Brillouin zone. In this diagram, the refractive index of the dielectric material is 3.4, and the ratio of the hole radius, $r$, to nearest neighbor hole spacing, $a$, is 0.35. There are two important phenomena displayed in the band diagram. First, notice that for $\omega a/2\pi c = a/\lambda = 0.22$ to 0.33 there exists no corresponding momentum. This range of frequencies for which no propagating electromagnetic modes exist is called a photonic band gap. The other important phenomenon is the varying group velocity, $v_g$, which is defined by $v_g = \partial \omega / \partial k$. Notice that around the symmetry points, at certain frequencies, $v_g \to 0$. This is often referred to as slow light.

Both of these phenomena, band gaps and slow light, can greatly alter the spontaneous emission spectrum of an atomic system. Figure 3.2 shows the photoluminescence
Figure 3.1 (a) Hexagonal array of air holes in dielectric material with refractive index 3.4. (b) Reciprocal space showing first Brillouin zone and symmetry points. (c) Photonic band diagram calculated using BandSOLVE [2]. The shaded regions denote a photonic band gap.

Figure 3.2 The photoluminescence spectrum of a quantum well membrane with and without a photonic crystal fabricated at the University of Illinois. The effects of the photonic crystal are dependent on the photonic crystal parameters.

measured from a membrane containing quantum wells. The red and blue curves show the emission from regions containing graphene honeycomb lattices with nearest neighbor
hole spacings, $a$, of 400 nm and 410 nm, respectively. The black curve shows the emission spectrum of an unpatterned region for comparison. The emission, being proportional to the optical density of states, is inhibited for wavelengths in the photonic band gap and is enhanced for wavelengths near the dispersion extrema (approximately 1530 nm and 1570 nm for $a = 400$ nm and $a = 410$ nm, respectively). The overall intensity is also higher due to more efficient light coupling out of the membrane as a result of the phase matching that the photonic crystal provides.

3.2 Photonic Crystal Resonators and Lasers

Slow light and photonic band gap effects can be manipulated in order to create optical resonators and, therefore, photonic crystal lasers. Photonic crystal lasers utilizing the band gap phenomenon, also called photonic crystal membrane defect cavity lasers, will be discussed first. These types of resonators are formed by the patterning of a photonic crystal that includes some type of defect in the periodicity. This defect forms the resonant cavity of the device. Often this type of resonator is formed by the patterning of an array of air holes in a semiconductor membrane in which the exclusion of one or more holes creates the resonant cavity. Figure 3.3 shows a scanning electron microscope image of a fabricated photonic crystal defect cavity laser. The band gap of the surrounding photonic crystal provides high reflectivity back into the central defect and results in in-plane (parallel to the membrane) confinement. The optical confinement out-of-plane (perpendicular to the membrane) is due to the total internal reflection resultant from the index contrast between the semiconductor and air. Optical gain is provided to the cavity by optically exciting carriers in the semiconductor quantum wells buried in the membrane. Much work has been done to optimize the quality factor of such cavities [3]–[6] as well as to decrease the modal volume [7] in order to take advantage of the Purcell
effect [8] and induce regimes of strong coupling between the optical cavity and atomic systems.

Slow light can also be used to create laser feedback. As the group velocity decreases, the effective interaction time between radiation and matter increases, resulting in higher optical gain per length [9]. This results in the ability to create lasers solely by patterning large areas of photonic crystal patterns [9]–[11]. An example of a slow-light-based laser, or band-edge laser, can be seen in Figure 3.4. In this device, a kagome array of air holes was patterned in a semiconductor membrane containing quantum wells at the University of Illinois Micro and Nanotechnology Laboratory. Low group velocity at the Γ point allows for lasing at the band edge of the photonic crystal. The quality factor in this type of laser is limited essentially by three aspects. First, operation at the Γ point causes a large decrease in the out-of-plane quality factor. Second, the finite size of the laser results in a nonzero group velocity. As the laser size shrinks, the group velocity increases, resulting in less optical gain and a smaller quality factor. Third, the finite size of the optical pump spot (the means of interband excitation) also results in optical loss in regions that are not atomically inverted. These last two effects require, in general, that the slow light
laser occupy a large area and must be optically excited with a similarly large excitation area.

![Image of Kagome photonic crystal band-edge laser emission spectra](image)

**Figure 3.4** Kagome photonic crystal band-edge laser emission spectra fabricated at the University of Illinois. The black and red curves have nearest neighbor hole spacing of 400 nm and 410 nm, respectively.

### 3.3 Fabrication of Photonic Crystal Membrane Lasers

Figure 3.5 shows the fabrication procedure for InP-based, optically pumped photonic crystal lasers, as well as an example of an epitaxial structure that can be used. The devices are fabricated in the InGaAsP/InP material system. The photonic crystal devices are fashioned in the portion of the epitaxy that will eventually result in a suspended membrane. The example epitaxial structure shown in Figure 3.5 is a double heterostructure containing six quantum wells emitting at 1550 nm. The membrane is comprised of InGaAsP alloys and is 277 nm thick. The InP cap layer is used to protect the top surface of the wafer during fabrication.
Fabrication begins with the deposition of a 200 nm layer of SiO\(_2\) using plasma enhanced chemical vapor deposition (PECVD). This layer is to be used as an etch mask in an inductively coupled plasma reactive ion etch (ICP-RIE) process. A 200 nm layer of poly(methyl-methacrylate) (PMMA) is then spun on the sample and electron-beam lithography is used to define the photonic crystal patterns. The PMMA is developed using a mixture of methyl isobutyl ketone and isopropanol. A CH\(_3\)F (Freon 23) reactive ion etch is used to transfer the pattern into the SiO\(_2\) etch mask.

An ICP-RIE process is used to transfer the photonic crystal pattern into the semiconductor material. Anisotropic etching is accomplished using a high-density and high-power chlorine-based plasma. Since one of the etch by-products, InCl, is non-volatile at room temperature, etch temperatures above 200 °C are used. Care has to be taken to ensure that the etched profile remains smooth and vertical, so as not to negatively impact the
quality factor of the cavity. The varying composition within the membrane contributes
to the challenge of this task. The InP cap layer, which is removed in subsequent steps,
helps to minimize damage to the membrane during the etch. The air holes, which have
diameters generally less than 350 nm, must be etched over a micron deep to ensure sub-
sequent membrane formation. Ultimately an etch using Cl₂, Ar, and H₂ at high power
and at 250 °C is used to accomplish the anisotropic hole etching. A cross-section of an
etched photonic crystal hole is shown in Figure 3.6.

![Figure 3.6](image)

**Figure 3.6** A cross-section of photonic crystal membrane after ICP-RIE. The hole depth
is approximately 1.1 µm.

The InP cap layer and InP regions just beneath the photonic crystal patterns are
removed using a wet chemical process in order to create a suspended membrane. Two
chemistries can be used: a 1:1 mixture of HCl:H₃PO₄ at room temperature or a 4:1
mixture of HCl:H₂O at 4 °C. Both solutions etch InP much faster than InGaAsP and
can thus be used to selectively remove the InP regions. The difficulty in removing the
InP below the membrane, or undercutting the membrane, is that both of the chemical
solutions etch in an anisotropic, crystallographic manner. The etch rate is quite quick
(a few microns per minute), until the slow etch planes are reached. Once a slow etch plane has been reached, the undercut etch effectively ceases. This necessitates the deep etch ICP-RIE process described earlier. If the photonic crystal holes are etched deep enough, the slow etch planes will intersect and expose a fast etch plane allowing for complete undercut of the membrane. If the holes are not deep enough, the slow etch planes will not intersect underneath the membrane, and a fast etch plane will not be exposed. This results in having to wet etch for a very long time. The issue with long chemical etches is that both of the undercut solutions attack the membrane to some degree. The HCl:H₃PO₄ solution attacks the defects formed on the inner surfaces of the photonic crystal holes after the ICP-RIE process, ultimately leading to the disintegration of the membrane. Because of this, etch times using this solution generally need to be under 10 min. The HCl:H₂O solution at 4 °C has much better selectivity. Even though this solution does slowly etch the membrane, etch times up to 45 minutes are possible with negligible damage to the photonic crystal membrane. A cross-section of a photonic crystal membrane suspended in air is shown in Figure 3.7.

### 3.4 Thermal Modeling of Photonic Crystals

In order to gain a better understanding of the conditions under which a photonic crystal laser can operate, simulation of the temperature profile inside a photonic crystal laser is desired. Heat transfer analysis using a finite element method is performed. The heat transfer equation can be written as

$$\nabla \cdot (k(r)\nabla T(r)) = -Q(r)$$  \hspace{1cm} (3.1)

where $k(r)$ represents the local thermal conductivity of the material, $T(r)$ is the local temperature, and $Q(r)$ is the heat source represented in terms of energy density. While
many factors contribute to the heating of a photonic crystal membrane, the pump source is one of the more dominant (non-radiative recombination and carrier-carrier scattering are not considered in this analysis). Since in most cases, the pump or excitation laser is at a higher energy than the emitted light, all of the excess pump energy above the emitted photonic energy is simply converted to heat. In the analysis described here, it is assumed that the pump source is a laser emitting at 980 nm and the photonic crystal laser emits at 1550 nm. This equates to roughly 37% of the absorbed pump power being converted to heat.

A finite element method as described in [12] is performed to obtain the temperature profile in the membrane. In order to simplify the problem, the suspended photonic crystal laser is modeled as a body of revolution. The local thermal conductivity in regions where the membrane is punctured with holes is taken as a volumetric average of the actual thermal conductivity. This essentially becomes the thermal conductivity of
the membrane multiplied by the photonic crystal fill factor. Since the membrane in an optically pumped structure is likely composed of InGaAsP and the actual composition is often unknown, it is assumed that the thermal conductivity of the membrane is an average of the thermal conductivities of GaAs and InP. The substrate is modeled as being entirely InP. It is important to note that the thermal conductivity of the semiconductor material is dependent on temperature, and an iterative approach is taken in order to ensure accuracy. An approximation to the thermal conductivity over the temperature ranges of interest is

\[ k(T) = k(300 \text{ K}) \left( \frac{T}{300 \text{ K}} \right)^{-\alpha} \]  

(3.2)

where \( k(300 \text{ K}) \) is the measured thermal conductivity at 300 K and \( \alpha \) is a material dependent exponent \([13]\). The variables \( k(300 \text{ K}) \) and \( \alpha \) for InP are 68 W/mK and 1.4, respectively \([13]\). For GaAs these values are 46 W/mK and 1.25, respectively \([13]\). To begin the iterative process, the local thermal conductivity is assumed to be that at 300 K. The temperature is then calculated using this conductivity. The calculated temperature is then used to calculate a new profile to the thermal conductivity, and the temperature is calculated again. The new temperature is compared to the old temperature and if the difference is greater than 0.5%, then the calculation is repeated using the new temperature to calculate the thermal conductivity. The process generally takes between three and five iterations until the standard for convergence is met.

In order to provide some type of heat sinking as well as make the problem more realistic, the part of the substrate at which the membrane is still attached is included in the simulation domain. Convective boundary conditions in the form

\[ k \frac{\partial T(r)}{\partial n} = h(T(r) - T_c) \]  

(3.3)

are used at the semiconductor-to-air interfaces. Here, \( h \) and \( T_c \) are the thermal convection coefficient and the temperature of the convective medium, respectively. For air, this value
is between 10 W/m²K and 100 W/m²K. The simulation used 50W/m²K. Its actual value has little effect on the temperature profile achieved in the membrane as long as it remains within these bounds. Dirichlet boundary conditions are enforced at the boundaries of the substrate. It is assumed the the lasers are operating at room temperature, and therefore 300 K is chosen as the heat sink temperature and the temperature of the air. Figure 3.8 shows the temperature profile of a photonic crystal laser as well as the labeled boundary conditions. The membrane is centered around \( z = 0 \), and the substrate is in the right part of the figure. The boundary condition

\[
\frac{\partial T(r)}{\partial n} = 0 \tag{3.4}
\]

is automatically enforced at \( r = 0 \) by the finite element implementation.

In Figure 3.8 the membrane is assumed to be 280 nm thick. In this example, 5mW of pump power is assumed to be absorbed uniformly in the membrane in the regions bound by \( 0 < r < 1\mu m \) and \(-140 \text{ nm} < z < 140 \text{ nm} \) (this is the innermost \( 1\mu m \) of the photonic crystal cavity and is assumed to have no holes). The region in the membrane between \( r = 1\mu m \) and \( r = 5\mu m \) is assumed to be punctured with photonic crystal holes, and thus the thermal conductivity is modified appropriately. The angle of the substrate is determined by the crystallographic nature of the chemical wet etch performed to undercut the membrane. The conditions present here indicate that the photonic crystal laser could be operating more than 70 K above ambient temperature. This is consistent with [14], which showed than under some conditions the cavity could heat up to over 100 K above ambient. Also evident in this calculation is the effectiveness of the substrate as a heat sink. The membrane reaches ambient temperature almost exactly where it comes in contact with the substrate.

The actual photonic crystal parameters can also play an important role in the thermal properties of the photonic crystal cavity laser. Consider the effect of photonic crystal fill
Figure 3.8 Temperature profile in a photonic crystal cavity laser. The boundary conditions used in the calculation have been indicated for clarity.

factor, which can be determined by the hole-radius-to-period ratio, $r/a$. Optically, there are benefits to increasing $r/a$ for a photonic crystal. As $r/a$ increases, the band gap can increase. This can lead to higher quality factors for band gap-confined photonic crystal cavity resonance. Unfortunately, as $r/a$ increases, the effective thermal conductivity of the membrane decreases due to the decrease in dielectric material. The effects of this decrease can be quite dramatic. Figure 3.9 shows the maximum temperature in the photonic crystal cavity as a function of $r/a$. The previously mentioned geometry was used with the only change being the thermal conductivity of the membrane due to the change in fill factor. The hole radii considered in this calculation are ones that are commonly found in the literature. The temperature increases rapidly as a function of hole radius. This necessitates the consideration of thermal effects when optically designing a photonic crystal cavity. This topic is considered again in Section 3.5.
3.5 Decimated Photonic Crystal Lasers

Previous devices have omitted or modified the photonic crystal holes in order to obtain single-mode operation of photonic crystal defect cavities [15]. The modal symmetry was exploited in order to selectively increase the loss of certain modes. In this section, the omission of holes in a photonic crystal cavity is motivated by the subsequent increase in semiconductor material. These decimated photonic crystal cavities exhibit quality factors close to those of complete photonic crystal cavities, but can have a significantly fewer number of air holes. Since the omitted holes form a semiconductor path towards the optical cavity, the thermal impedance and electrical resistance from the center of the cavity to the bulk membrane will both decrease. The decimation design approach employed is relatively straightforward. Air holes are omitted from locations in which there is little overlap with the mode and are thus not necessary. Consider the L3 cavity as described in [5] and shown in Figure 3.10. A line defect is formed in a hexagonal photonic

![Figure 3.9](image.png)

**Figure 3.9** Maximum temperature in the center of the cavity as a function of the relative hole radius \((r/a)\).
Figure 3.10 Modal profiles of (a) full and (b) decimated L3 photonic crystal defect cavities.

crystal by omitting three holes along the Γ-K direction. For the cavities fabricated in our study, the membrane is 135 nm thick, the nearest neighbor hole spacing, \( a \), is 470 nm, and the hole radius is 0.3a. The two holes at the ends of the cavity are made slightly smaller (0.25a) than the other holes and shifted away from the center of the cavity by 0.15a. Using a three-dimensional finite-difference time-domain method, the resonant
wavelengths, quality factors, and modal profiles are calculated for this cavity. The modal profile of interest is shown in Figure 3.10(a). The mode predominantly occupies the cavity and regions to the right and left of the cavity. This allows for the removal of holes above and below the cavity without significantly affecting the optical confinement. The cavity is decimated by the removing of 10 holes above and below the cavity, and the resonance, modal profile, and quality factor are calculated again. The modal profile is shown in Figure 3.10(b). There is no significant change in the resonant wavelength and to the modal distribution after the decimation process. The quality factor for the decimated cavity is approximately 17% less than that of the full cavity. This difference in quality factor, while already small, will be even less noticeable when real devices are fabricated and fabrication imperfections play a role in optical quality factor.

Decimated and full L3 photonic crystal defect cavities are fabricated in a 135 nm thick InGaAsP membrane grown on an InP substrate using the fabrication technique described in Section 3.3. The membrane contains 5 quantum wells with a nominal photoluminescence peak at 1350 nm. Figure 3.11 shows a scanning electron microscope image of a decimated L3 cavity. The trenches to the right and left of the photonic crystal assist in undercutting the cavity to create the suspended membrane. The lighter regions around the cavity denote the undercut area.

The devices are tested at room temperature by optical pumping using a 980 nm laser diode. The excitation is 100 ns pulses with a 1% duty cycle. The pump light is focused onto the sample using a 20× objective. The laser light is collected using the same 20× objective and coupled to a multimode fiber that is coupled to an optical spectrum analyzer. The device characteristics presented in Figures 3.12 and 3.13 are for a decimated and full L3 photonic crystal laser with the dimensions described above. Figure 3.12 shows the subthreshold spectra for the L3 and decimated L3 cavities at 1386.1 nm and 1387.4 nm, respectively. A fit to the data gives an upper limit to the
quality factor of the full cavity of 5022 and of the decimated cavity of 4953. Measurement error, spectrometer sensitivity, and slightly different pump geometry between the cavities are likely causes of the quality factors being closer than the calculated values. Figure 3.13 shows the instantaneous light input-versus-collected light output for both lasers. The optical performance characteristics for both devices are quite similar. The linearly extrapolated lasing thresholds for the L3 and decimated L3 lasers are 0.37 mW and 0.46 mW, respectively. This is approximately a 20% difference in threshold, which can be attributed to differences in quality factor indicated by simulation in combination with pump variations previously mentioned.

In addition to the measurement of quality factor and threshold, a qualitative assessment of the thermal properties of the decimated L3 lasers is performed. Using the same optical pumping technique, the highest duty cycle operating conditions are determined. Adjusting both duty cycle and pulse width in accordance with the limitation of our equipment, the conditions for which the laser ceases stimulated emission are determined. In the case of the decimated L3 cavity, the device stops lasing when the duty cycle is set
Figure 3.12 Subthreshold spectra with fit for a full L3 cavity at 1386.1 nm and a decimated L3 cavity at 1387.4 nm.

Figure 3.13 Instantaneous light input vs. collected light output for full L3 (●) and decimated L3 (○) cavities.
to 22% with a 300 ns pulse width. This is an improvement over the full L3 cavity which requires a 100 ns pulse width and duty cycles less than 10%. This behavior is consistent with the decimated L3 cavity having decreased thermal impedance as compared to the full cavity.

The properties of a different decimated cavity have also been studied. The decimated H2 whispering gallery mode (H2 WGM) cavity [16] is shown in Figure 3.14. As can be seen, more than half of the holes are omitted as compared to the full H2 WGM. The lasing spectrum of the decimated H2 WGM with \( a = 470 \) nm is shown in Figure 3.15. Thermal characteristics of this device were probed by varying the pump duty cycle as described previously. The device maintained laser operation up to a 27% duty cycle with a 300 ns pulse width.

![Decimated H2 whispering gallery mode photonic crystal cavity.](image)

Figure 3.14 Decimated H2 whispering gallery mode photonic crystal cavity.

Figure 3.16 shows the calculated temperature profiles for an H2 WGM cavity laser and a decimated H2 WGM cavity laser. The geometry mentioned in Section 3.4 was used. The thermal effects of the decimation process are simply modeled by altering the fill factor of the cavities by using a volumetric average. The fill factor for the regular
Figure 3.15 Lasing spectrum of an H2 whispering gallery mode photonic crystal laser.

Figure 3.16 Calculated temperature profile of an H2 WGM cavity and a decimated H2 WGM cavity.

H2 WGM cavity is 63%, while the fill factor for the decimated H2 WGM cavity is 83%. This change in fill factor causes a calculated 17 K change in temperature. It is likely that the actual improvements are greater, since the decimated cavity has large regions of conductive material surrounding the cavity and not just an increase in average thermal
conductivity as used in our model. Hence, the increased thermal conductivity of the
decimated cavity photonic crystal laser would benefit laser diode operation. Moreover,
the electrical conductivity will also be improved

3.6 References


CHAPTER 4

Photonic Crystal Heterostructure Cavity Lasers

4.1 Introduction

As mentioned in the previous chapter, two basic characteristics of photonic crystals can be employed to make lasers: photonic band gaps and slow light. Photonic crystal defect cavity lasers rely on the defects of a photonic crystal to act as optical cavities. In this case, the laser relies on the high reflectivity of the photonic crystal at frequencies inside the photonic band gap. Alternatively, slow light effects at the dispersion symmetry points, or band edges, in photonic crystals can also be used to create lasers [1]–[3]. In band-edge lasers, the slow group velocity at the dispersion symmetry points acts to increase the interaction between the optical field and the gain material, effectively enhancing the available optical gain. The modal areas in the plane of a two-dimensional photonic crystal slab of the photonic crystal defect cavity lasers can range from less than 1 to a few µm$^2$ and still maintain high spectral fidelity [4]–[8]. In contrast, the resonator area for efficient band edge lasers is generally larger than 100 µm$^2$ (approximately 300 µm$^2$ in [1]). While small area defect lasers support only a few modes within the gain
bandwidth of the material system, larger area defect cavities can support many modes. Band edge lasers operate with a few modes or a single mode lasing, but are somewhat impractical for micro- and nanophotonics due to the large pump and device area required to operate efficiently. Thus, there exists an area gap for efficient and high spectral fidelity photonic crystal lasers. Spectral control and fidelity will be critical for sensing applications using these lasers.

Recent work has indicated that the combination of these two phenomena, photonic band gaps and slow light, can yield promising results [9]–[13]. In particular, a hexagonal lattice with two regions containing different hole diameters was used to localize a band edge mode within a heterogenous defect, resulting in low lasing thresholds [9]. The work presented in this chapter focuses on the incorporation of a kagome photonic crystal as the defect area within a hexagonal photonic crystal to form a photonic crystal heterostructure cavity. A scanning electron micrograph of a photonic crystal heterostructure cavity is shown in Figure 4.1. The use of a kagome inner lattice allows for an increase in the semiconductor material of the cavity region while maintaining spectral fidelity. The design of the laser is such that a band-edge confined mode of the kagome inner lattice is also in the photonic band gap of the surrounding hexagonal lattice. This results in optical feedback to a slow light mode of the inner region.

In this chapter, the design and testing of photonic crystal heterostructure cavity lasers using kagome lattices will be discussed. Single mode lasing is observed and explained using simulation techniques. The modal properties of photonic crystal heterostructure cavities are characterized in terms of the cavity size dependence. The effects of the formation of the heterostructure on the optical mode will also be quantified experimentally and numerically.
4.2 Design by Band Diagram Analysis

One of the main advantages of using a kagome lattice as the inner defect of a photonic crystal heterostructure laser is to increase the overall semiconductor area. Figure 4.2 shows the percentage of semiconductor material for kagome (solid) and hexagonal (dashed) 2-D lattices as a function of hole radius, \( r \), to nearest neighbor hole spacing, \( a \). The percentage of more semiconductor material in a kagome lattice is also shown (dotted). As the \( r/a \) ratio increases, the difference in semiconductor material between the two lattices increases. In the design range of the photonic crystal heterostructure laser, this results in the kagome having about 25\% more semiconductor material. This is advantageous in that more material provides better mechanical and thermal stability. As shown in the previous chapter, a decrease in fill factor can result in a significant decrease in the operating temperature of a photonic crystal laser. The other important advantage to using the kagome lattice is that for the modes of interest, the kagome lattice has a
higher overlap between the semiconductor and the optical field. This leads to a more efficient use of the available material gain. As an example, when \( r/a = 0.37 \), the overlap of the K-point mode closest to the bottom of the band gap is 78% and 69% for the kagome and hexagonal lattices, respectively.

The photonic crystal heterostructure cavity using a kagome lattice as the inner defect region and an outer hexagonal lattice can be designed by considering the band diagrams of the two photonic crystals. Figures 4.3(a) and (b) show the band diagrams for a hexagonal lattice and kagome lattice, respectively. In order to avoid lattice mismatch between the kagome and hexagonal regions, \( a \) is equal for both lattices. The \( r/a \) ratio of each lattice is used to tune the dispersion. The \( r/a \) ratios of the kagome and hexagonal lattices are 0.37 and 0.32, respectively, in Figure 4.3. The band gap of the hexagonal lattice, which lies between \( a/\lambda = 0.259 \) to 0.348, is tuned to overlap a dispersion maximum at the K-point of the kagome lattice that lies at \( a/\lambda = 0.274 \). The high reflectivity of the hexagonal lattice due to the band gap effect thus provides feedback to the slow light.
modes at the K-point of the kagome lattice. This results in a decrease of in-plane losses when compared to the case when the hexagonal cladding is absent. Out-of-plane losses are minimized by operation below the light cone of both lattices, shown by the shaded area of Figure 4.3. Although analysis of the band diagrams predicts a cavity resonance close to $a/\lambda = 0.274$, a more rigorous simulation is performed as described in Section 4.4.

![Figure 4.3](image)

**Figure 4.3** Photonic band diagrams of a hexagonal (left) and kagome (right) 2-D membrane photonic crystal. The gray regions correspond to modes not confined with the membrane. The band gap of the hexagonal lattice (horizontal lines) overlaps the dispersion maximum at the K-point of the kagome lattice.

### 4.3 Experimental Measurement of a Nine-defect Kagome Heterostructure

The photonic crystal heterostructure cavity laser considered in this section is that shown in Figure 4.1. There are 9 periods of kagome lattice surrounded by 10 periods of hexagonal lattice. The nearest neighbor hole spacing, $a$, is 418 nm, and the hole radii are $0.37a$ and $0.32a$ in the kagome and hexagonal regions, respectively. These
design parameters result in a kagome cavity that has an area of $36.7 \, \mu m^2$ (approximately $15.3 \, \lambda^2$) of which approximately 63% is semiconductor. The device is tested according to the method described in Section 3.5. The collected power at the lasing wavelength versus instantaneous pump power is plotted in Figure 4.4. The input power has not been calibrated to the pump spot size, and a pump spot larger than the cavity is used. The device has a soft turn-on with a linearly extrapolated threshold of approximately 8.0 mW. Figure 4.5 shows the lasing spectrum at 13 mW input power. Single mode lasing is observed at a wavelength of 1551.5 nm. The inset in Figure 4.5 shows the subthreshold emission spectrum at a pump power of 7.0 mW. A Lorentzian fit to the emission spectrum at 7 mW pump power gives a line width of approximately 0.64 nm (spectrometer limited), corresponding to a quality factor of about 2400.

**Figure 4.4** Collected laser output power as a function of instantaneous pump power at 980 nm.
Figure 4.5 Lasing spectrum of the photonic crystal heterostructure cavity laser. The inset shows the spectrum on a linear scale just below threshold.

4.4 Calculation of Resonant Modes

Simulation of the photonic crystal heterostructure cavity lasers requires the use of a large simulation domain. In order to reduce the computation time and increase the computational efficiency, the modes are calculated using the dual-primal finite element tearing and interconnecting method (FETI-DPEM) as discussed in [14], [15]. The FETI-DPEM uses a full-wave technique based on a domain decomposition implementation of the finite element method. It allows for efficient broadband frequency domain solutions of large-scale electromagnetics problems by exploiting geometrical repetition. The FETI-DPEM is particularly well suited for photonic crystal problems because the computational cost increases sublinearly with overall domain size in cases where geometrical elements are repeated [15].

Figure 4.6 shows the calculated modal spectrum of a photonic crystal heterostructure cavity with 9 periods of kagome lattice, $a = 418$ nm, and $r/a = 0.37$ and 0.32 for the
Figure 4.6 Calculated stored energy spectrum of a photonic crystal heterostructure cavity laser using the FETI-DPEM.

kagome and hexagonal lattices, respectively. The calculation using the FETI-DPEM is performed by placing a randomly in-plane polarized current sheet in the kagome defect area, varying the frequency of this current, and measuring the stored energy in the cavity. The line widths in Figure 4.6 are related to the loss of the particular mode. There are no resonances below approximately 1550 nm due to the overlapping band gaps of the kagome and hexagonal photonic crystals. The shortest-wavelength mode appears at about 1552 nm, and there are many modes at longer wavelengths. The intensity profile of the three shortest wavelength modes at 1552 nm, 1560 nm, and 1573 nm are shown in Figures 4.7(a)–(c), respectively.

Even though the calculated spectrum shows many modes above 1550 nm, only one mode at about 1552 nm is experimentally observed in the lasing spectrum. The single-mode operation is due to several factors. First, it should be noted that closer proximity to the K-point implies that a given mode should have a smaller group velocity and, therefore, experience the greatest gain enhancement that the slow group velocity provides. The
The calculated modal profiles of the modes at (a) 1552 nm, (b) 1560 nm, and (c) 1573 nm.

Figure 4.7 The calculated modal profiles of the modes at (a) 1552 nm, (b) 1560 nm, and (c) 1573 nm.

mode at 1552 nm is closest to the K-point obtained using the plane wave expansion method. Spatial overlap between the gain and mode also needs to be taken into account. The mode at 1552 nm is well confined inside the kagome lattice, which is denoted by the dashed lines in Figure 4.7. This plays a crucial role because the parts of the field that lie within the hexagonal region experience significant optical loss. When considering the small scale (on the order of \( a \)) variation of the field, the mode at 1552 nm looks similar to the hexapole mode often encountered in single-defect hexagonal photonic crystal cavities. The field is localized mostly in the semiconductor region away from the holes. The mode at 1560 nm, however, is primarily confined between three adjacent holes and, thus, greatly overlaps the air holes. Fabrication imperfections also influence the latter mode more than the shorter-wavelength mode. Lastly, the mode at 1552 nm has a well-defined intensity maximum at the center of the kagome region and is likely easiest to optically excite. These
criterion in combination lead to single-mode lasing in the mode shown in Figure 4.7(a), as evident in Figure 4.5.

### 4.5 Quality Factors of Different Sized Cavities

In this section, simulation of different-sized kagome cavities is discussed. The wavelength and quality factors of different-sized photonic crystal heterostructure cavities are analyzed using the FETI-DPEM. The relative hole sizes and lattice spacing are the same as described in the previous section. Resonance and quality factor calculations are performed using the FETI-DPEM technique. Figure 4.8 shows the calculated cavity resonances and quality factors for 3, 5, 7, and 9 kagome periods in the inner region of the photonic crystal heterostructure cavity. The wavelength increases slightly as the inner kagome cavity decreases in size. This can be attributed to the uncertainty in dispersion maximum at the K-point of the band diagram. Similar phenomena have been described in [3]. As the size of the kagome region decreases, the distribution of the mode in momen-

![Figure 4.8 Resonant wavelength (squares) and quality factor (triangles) of the shortest-wavelength mode as a function of the number of kagome inner periods.](image-url)
tum space increases. As a result, the mode moves away from the dispersion maximum at
the K-point to points lower in the band where a larger spread in the momentum vector is
supported. Since the mode effectively moves away from the dispersion maximum, it also
starts to include momentum-space components with a larger group velocity. This in turn
decreases the quality factor as the cavity gets smaller. As the kagome region becomes
smaller, the optical mode overlap with the hexagonal cladding region also increases. This
causes the mode to experience greater loss as these wavelengths lie with the band gap
of the hexagonal cladding. The decrease in quality factor and increase in optical loss for
decreasing cavity size are expected to eventually inhibit lasing. Experimentally, photonic
crystal heterostructure cavities with inner defect diameters equal to or less than 5 periods
do not lase. Cavities with larger defect diameters exhibit lasing at room temperature.

4.6 Decomposition of Heterostructure

The photonic crystal heterostructure cavity laser can be experimentally compared to
a kagome band-edge laser. During heterostructure laser operation, the overlap of the
photonic band gap of the exterior hexagonal lattice with the slow group velocity K-point
of the kagome lattice dictates the predominant feedback mechanism. It is this union
that creates a high quality factor and thus results in laser action. In the absence of the
hexagonal cladding, the mode should shift to a longer wavelength due to the decrease
in optical confinement. The lack of heterostructure feedback should also decrease the
quality factor at the lasing wavelength and result in a higher threshold pump power.

In order to experimentally confirm the above, a kagome band-edge laser identical
to the inner region of the photonic crystal heterostructure described in Section 4.3 was
fabricated and optically pumped using the same previously mentioned excitation condi-
tions. Figure 4.9(a) shows the lasing spectra of a photonic crystal heterostructure cavity
(solid line) and a kagome band-edge laser (dashed). The kagome band-edge laser operates at 1592 nm, whereas the photonic crystal heterostructure operates at 1552 nm. Figure 4.9(b) shows the measured light input versus light output for the heterostructure (triangles) and kagome band-edge (squares) lasers. The kagome band-edge laser has a longer lasing wavelength and a higher threshold.

**Figure 4.9** Comparison between the lasing spectrum (a) and light input vs. light output (b) of a photonic crystal heterostructure and a kagome band-edge laser. The kagome band-edge laser has a longer lasing wavelength and a higher threshold.
higher threshold than does the heterostructure-cavity laser. This is attributed to the lack of feedback of the heterostructure, resulting in a lower quality factor.

In order to investigate the exact cause of the shift in lasing wavelength, the FETI-DPEM technique was employed in order to calculate the optical modes of the kagome band-edge laser. Figure 4.10 shows the stored energy as a function of wavelength for the kagome band-edge laser. There are two local maxima at around 1565 nm and 1590 nm that lie within the gain bandwidth of our material. The mode at 1590 nm has a larger quality factor than the mode at 1565 nm. The resonance at 1565 nm has a modal profile similar to that of the heterostructure lasing mode at 1552 nm (shown in Figure 4.7(a)), and the resonance at 1590 nm has a modal profile similar to that of the heterostructure mode at 1560 nm (shown in Figure 4.7(b)).

![Figure 4.10 Stored energy vs. wavelength for a kagome band-edge cavity calculated by the FETI-DPEM.](image)

A comparison between the two lasing modes (≈1552 nm for the heterostructure and ≈1590 nm for the kagome band-edge laser) is made by considering the distribution of the modes in momentum space. Figures 4.11(a) and (b) show the spatial Fourier transforms of the calculated heterostructure and kagome band-edge modes, respectively. To be precise, the sum of the magnitude squared of the Fourier transform of the in-plane electric field
components is shown in Figure 4.11. For both lasers, the momentum contribution about $k_y = 0$ is from the $y$-polarized part of the field. The heterostructure mode is seen to contain maxima at the six $K$-points of the first Brillouin zone. In this case, the mode
is strictly localized to near the K-point. This is in contrast to the kagome band-edge mode, which exhibits a broader momentum space representation. While the kagome band-edge mode has momentum localization around the K-points, the momentum space representation actually has nulls at the six K-points. Instead, the mode is spread out and has lobes that contain momentum components in the the K-M and K-Γ directions. This arises presumably from the lack of heterostructure confinement. When a heterostructure is created, there is strong feedback into the central kagome cavity. This in effect makes the kagome region act similarly to a large-sized kagome photonic crystal and results in a more well-defined wave vector. The kagome band edge, on the other hand, experiences minimal feedback from the edge of the kagome lattice. The result is that the optical modes will contain more momentum space variation and the wavelength will diverge from the K-point. Similar phenomena are described for a hexagonal lattice in [3].

4.7 References


CHAPTER 5

Progress Toward Electrically Injected Photonic Crystal Lasers

5.1 Background

This chapter deals with the progress towards making electrically injected photonic crystal emitters. As was previously discussed, it is the photonic crystal cavity itself that creates great difficulties in producing electrically injected lasers. Specifically, the thermal and electrical properties are degraded due to two principal features of the cavity: it is formed in a thin semiconductor membrane and it is punctured with holes. The membrane is typically suspended in air and is provided heat sinking to the substrate only at the extreme periphery of the membrane. The reduction in semiconductor volume due to the hole formation also greatly decreases the thermal conductivity of the membrane. Some researchers have bonded the devices to thermally conductive substrates. While this greatly improves the thermal properties of the device, it lowers the quality factor of the cavity by reducing the index contrast between the substrate and the membrane. The substrates used are typically non-conductive, as high conductivity substrates are very detrimental to the optical performance of the cavity. The thin membrane also has greatly reduced electrical conductivity, which is exacerbated by being punctured with
holes. For these reasons, there is no clear way to provide electrical current to the center of the cavity without some type of materials modification.

While the success of creating electrically injected emitters has been limited, there are a number of different approaches. One approach focuses on selectively doping certain areas of the wafer in order to create a laterally injected PIN diode in a thin suspended membrane [1]. The photonic crystal cavity is then formed in the intrinsic part of the PIN diode. Cavity altered electroluminescence was observed using this technique. Another approach focuses on creating a conductive path between the substrate and the center of the cavity [2]–[6].

Researchers at the Korea Advanced Institute of Science and Technology partially undercut a photonic crystal membrane resonator leaving a narrow post under the defect cavity [2], [3]. The devices are fabricated in the InGaAsP/InP material system. An n-type, intrinsic, p-type diode structure is formed by doping the membrane and substrate appropriately. Current is channeled from a ring contact surrounding the laser, through the photonic crystal, and down through the semiconductor post. Functionality of the laser relies on getting a narrow post that will not strongly interfere with the optical field but at the same time will provide a suitable current path. Reproducibility is difficult because the diameter of the post is a strong function of etch time and conditions. These lasers also exhibit very high series resistance. First, electrons need to flow across the top n-type region. This region is perforated by the many holes that form the photonic crystal resulting in a reduced conductivity. Secondly, holes (p-type majority carriers) need to enter the active region through the submicron-sized post under the membrane. This also adds a considerable amount of series resistance since the post has a diameter on the order of a couple of hundred nanometers.

In the work presented in [2], and most of the other work in electrically injected photonic crystal emitters [1] as well as the previously mentioned demonstration of optically
pumped photonic crystal emitters, the lasers are fabricated in the InGaAsP/InP material system. This material system is chosen predominantly due to the effects of the many etched surfaces of the photonic crystal. The patterning of photonic crystal holes creates many semiconductor-to-air interfaces at the quantum well region of the device. This results in non-radiative carrier recombination at the edges of the quantum well. The InGaAsP/InP material system is generally used because the non-radiative surface recombination rate is one to two orders of magnitude slower than that of the InGaAs/GaAs material system [7].

At the University of Illinois, previous researchers created electrically injected photonic crystal emitters in a GaAs-based material system [4]–[6]. This material system was chosen due to the maturity of related processing techniques as well as the large optical gain that InGaAs/GaAs quantum wells provide. The wafer structure consists of a single $\text{In}_{0.25}\text{Ga}_{0.75}\text{As}$ quantum well emitting around $1\,\mu\text{m}$ embedded in the intrinsic region of an n-type, intrinsic, p-type doped GaAs membrane. An AlAs oxidation layer underneath the membrane is used for carrier and optical confinement. Thermal oxidation of this layer leaves a small conductive post embedded in a non-conductive, low-index dielectric. The oxidized dielectric layer acts then as a heat sink to the photonic crystal membrane.

Difficulties associated with carrier loss due to non-radiative recombination in GaAs were overcome by using spatially localized gain [6]. Spatially localized gain is achieved by having the quantum wells only in regions where they are needed, i.e. in the cavity, and away from the holes in the membrane. Two techniques were used to achieve this. Selective area epitaxy (SAE) is a means of creating spatially localized gain by limiting the crystalline growth of the quantum to the desired regions only. The growth of the quantum well over the entire wafer, lithographic patterning, and use of chemical means to remove it from undesirable areas is another method. Both of these techniques require
patterning using electron beam lithography. The photonic crystal emitters described in [4]–[6] use the quantum well patterning method.

Electroluminescence testing of these photonic crystal emitters showed the effects of spatially localized gain. The light output was confined to the region inside the defect cavity where the quantum well exists. The emission spectrum was tunable by the various cavity parameters. The electroluminescence signal intensity was greatly increased as compared to a device without a patterned quantum well. Yet, even though the photonic crystal effects strongly determined the spontaneous emission spectra, relatively low values of cavity quality factor were observed and lasing was not achieved.

While the previous two chapters dealt with cavity design as a means of creating favorable characteristics for electrical injection, this chapter deals with the epitaxial materials and fabrication aspect. The technique previously explored at the University of Illinois and described in [4]–[6] provides the motivation. First, the material design and fabrication procedure will be discussed. Measured data from bulk membranes will be discussed, and simulation will be used to analyze the cavities.

5.2 Material Design and Fabrication

This section discusses the epitaxial design and fabrication procedure for electrically injected photonic crystal emitters. The epitaxial structure is shown in Table 5.1. The membrane is 201 nm thick with three InGaAs quantum wells emitting at 980 nm. A 40 nm, heavily Si-doped contact layer serves as the anode of the device. The oxidation layer is a 1000 nm thick \( \text{Al}_{0.96}\text{Ga}_{0.04}\text{As} \) layer and is heavily C doped.

There are three important differences in the epitaxial design compared to the prior efforts. First, the stoichiometric composition of the oxide layer was chosen such as to decrease the adhesion problems experienced when oxidizing thick AlAs layers buried in
Table 5.1 Epitaxial structure for InGaAs/GaAs electrically injected photonic crystal emitters.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Material</th>
<th>Thickness</th>
<th>Dopant</th>
<th>Concentration (cm$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contact Layer</td>
<td>GaAs</td>
<td>40 nm</td>
<td>Si (n)</td>
<td>$\approx 10^{19}$</td>
</tr>
<tr>
<td>Upper Membrane</td>
<td>GaAs</td>
<td>30 nm</td>
<td>intrinsic</td>
<td></td>
</tr>
<tr>
<td>Cap Layer</td>
<td>GaAs</td>
<td>10 nm</td>
<td>intrinsic</td>
<td></td>
</tr>
<tr>
<td>Well</td>
<td>InGaAs (980 nm)</td>
<td>7 nm</td>
<td>intrinsic</td>
<td></td>
</tr>
<tr>
<td>Barrier</td>
<td>GaAs</td>
<td>10 nm</td>
<td>intrinsic</td>
<td></td>
</tr>
<tr>
<td>Well</td>
<td>InGaAs (980 nm)</td>
<td>7 nm</td>
<td>intrinsic</td>
<td></td>
</tr>
<tr>
<td>Barrier</td>
<td>GaAs</td>
<td>10 nm</td>
<td>intrinsic</td>
<td></td>
</tr>
<tr>
<td>Well</td>
<td>InGaAs (980 nm)</td>
<td>7 nm</td>
<td>intrinsic</td>
<td></td>
</tr>
<tr>
<td>Lower Membrane</td>
<td>GaAs</td>
<td>80 nm</td>
<td>intrinsic</td>
<td></td>
</tr>
<tr>
<td>Oxidation</td>
<td>Al$<em>{0.96}$Ga$</em>{0.04}$As</td>
<td>1000 nm</td>
<td>C (p)</td>
<td>$\approx 10^{19}$</td>
</tr>
<tr>
<td>Buffer</td>
<td>GaAs</td>
<td>500 nm</td>
<td>C (p)</td>
<td>$\approx 10^{19}$</td>
</tr>
<tr>
<td>Substrate</td>
<td>GaAs</td>
<td></td>
<td>Zn (p)</td>
<td>$\approx 10^{18}$</td>
</tr>
</tbody>
</table>

GaAs. The greater thickness also will prevent the optical mode from leaking into the high refractive index GaAs substrate. Optical mode leakage into the substrate greatly limits the out-of-plane quality factor [8]. According to [8], doubling the thickness of the oxide layer can increase the out-of-plane quality factor by approximately a factor of 40. Secondly, in order to provide more optical gain in the cavity, three InGaAs quantum wells emitting at 980 nm are used. Most optically pumped photonic crystal lasers use multiple quantum wells, and the electrically injected diodes reported in [2] and [3] use 6 quantum wells. Thirdly, high C doping is employed in the oxidation layer and buffer layer in order to decrease the series resistance of the device and increase the control in the quasi-Fermi levels in the intrinsic regions. Carbon was chosen specifically as the dopant so that it could be placed in high concentrations relatively close to the quantum well region without the concern of diffusion and resultant disordering of the quantum wells.

The fabrication procedure begins with epitaxial growth of the membrane through the the cap layer. The membrane is only partially grown so as to make it easier to pattern the
quantum wells. As will be described later, the partial growth will also affect the quality factor of the cavity. A layer of SiO$_2$ is deposited by PECVD. Alignment marks are then deposited using a layer structure of Ti/Pt/Au/Pt/Ti in a total thickness of approximately 180 nm. The alignment marks are then encapsulated in another layer of SiO$_2$. The SiO$_2$ is then removed from the wafer everywhere except for the alignment marks. This encapsulation protects the alignment marks from diffusion into the semiconductor during subsequent high-temperature material growth steps.

5.2.1 Quantum Well Patterning

In order to reduce non-radiative sidewall recombination in the quantum well areas that have been perforated by a photonic crystal hole, quantum well patterning is used. This technique selectively removes the quantum well in regions that will be perforated by photonic crystal holes. It is performed as the first step following the deposition of the alignment marks. This process is made more efficient by not having the upper part of the membrane present.

In the initial efforts, quantum well patterning was performed using PMMA as a wet etch mask. First, a 140 nm thick layer of 4% 950 K PMMA is spun on the sample and baked at 200 °C for 2 minutes. Electron beam lithography is performed using the previously deposited marks for alignment, and the patterns are developed in 1:2 methyl isobutyl ketone:isopropanol for 2 minutes. A 30 second bath in 1:1 HCL:H$_2$O with subsequent flooding by H$_2$O is used to remove the native oxide on the GaAs surface. The sample is then immersed in 1:50 H$_2$O$_2$:citric acid for 105 seconds in order to etch through the cap layer, three quantum wells, and their barriers. The etch depth should be approximately 55 nm in order to etch slightly into the layer directly below the bottom quantum well. The sample is then immersed in H$_2$O$_2$ for 15 seconds and then 1:1 HCl:H$_2$O
in order to assure a smooth and clean surface. The PMMA is stripped using various solvent baths and an O\textsubscript{2} plasma. The sample is then loaded into the reactor for growth of the upper part of the membrane.

There were multiple issues using PMMA as an etch mask. First, it is difficult to dose properly during electron beam lithography. The area that is dosed during the lithography is the area that will be removed. The challenge that arises is leaving a small island of PMMA, where the center of the cavity will be, in the center of a large dosed area. Any slight underdosing leaves PMMA residue on the sample, and the wet etch process is not uniform. Any slight overdosing will destroy the small central island. This necessitates a dose test immediately prior to electron beam lithography every time that quantum well patterning is performed. While this issue is not catastrophic, it does result in extra expense and time during the fabrication procedure. A more catastrophic problem occurs during the actual wet etch process. Since the sample with PMMA is immersed in liquid for almost 3 minutes, the PMMA film absorbs water. This causes the film to release from the surface in some areas, causing etching of areas that were previously masked. When the sample is removed from the liquids, it becomes very difficult, if not impossible, to remove the PMMA layer without adversely affecting the semiconductor membrane because the PMMA randomly re-adheres to the semiconductor surface. This renders the sample ultimately useless because the alignment marks become unusable, and growth cannot be performed when a film of residual PMMA is stuck to the surface.

In order to overcome this issue, a different etch mask is used. Electron beam lithography is performed again, but this time using a 200 nm thick layer of PMMA. The areas in which the quantum wells are to remain are dosed during lithography. After the development of the PMMA, the sample is loaded into an evaporator and 10 nm of Ti are deposited. Liftoff is performed using methylene chloride. Now, small islands of Ti act as etch masks in the previously mentioned wet etch process. After etching the quan-
tum wells, the Ti layer is subsequently removed by etching in a buffered HF solution. Scanning electron microscope (SEM) images of the sample after wet etching, with and without the Ti layer, are shown in Figures 5.1(a) and (b), respectively. The etch process using Ti has two major advantages over using only PMMA. First, the dosing process is much more robust. Since only a small area is dosed during the electron beam lithography, small changes in the dose do not make much of a difference in the final pattern. This allows for dose testing to be performed much less frequently than when using PMMA alone. The overall write time is also greatly reduced. The second benefit to using Ti as an etch mask is that it is completely unaffected by the wet etch used, making the process repeatable and robust.

![Figure 5.1 Patterned quantum wells (a) with and (b) without Ti etch mask.](image)

### 5.2.2 Photonic Crystal and Trench Definition

In order to expose the 1000 nm thick Al$_{0.96}$Ga$_{0.04}$As layer for oxidation, a trench is patterned around the photonic crystal cavity. The trench is circular for reasons described later. The photonic crystal and trench are patterned at the same time using electron
beam lithography. This ensures that, after oxidation, the remaining current aperture is directly in the center of the photonic crystal cavity.

After the upper part of the membrane is grown, the sample is quickly rinsed in a concentrated solution of HF. This helps remove any amorphous GaAs buildup on the alignment marks. Using PECVD, 100 nm of SiO$_2$ are deposited in order to act as an etch mask in later ICP-RIE steps. A 200 nm layer of 4% 950 K PMMA is spun onto the sample and baked at 200 °C for 2 minutes. Electron beam lithography is performed and the sample is developed in 1:2 methyl isobutyl ketone:isopropanol for 2 minutes. The pattern is then transferred into the SiO$_2$ layer using a CHF$_3$ dielectric etch. Multiple solvent baths and an O$_2$ plasma are used to remove the PMMA from the surface.

The alignment marks used during quantum well patterning are used during the lithography in order to ensure that the patches of active region are well aligned to the photonic crystal cavity. Figure 5.2 shows a patterned quantum well aligned to a photonic crystal cavity. This alignment can be somewhat challenging because the alignment marks degrade during the high-temperature growth of the upper membrane. In Figure 5.2 the misalignment between the patterned quantum well and photonic crystal cavity is estimated to be approximately 75 nm.

Following photonic crystal cavity and trench definition in the SiO$_2$ mask layer, the trenches must be selectively etched. An AZ 5214 photoresist is used to cover the photonic crystal patterns while leaving the trench patterns exposed. Trenches are etched using ICP-RIE. The trench width is approximately 1 μm, and it is etched at least 1.5 μm deep to ensure that the high Al-content oxidation layer is fully exposed. While etching this aspect ratio is not necessarily challenging, ensuring vertical sidewalls in the trench can be. Care has to be taken to have a perfectly vertical etch profile. If the walls of the trench are slanted, then the resulting current aperture after oxidation will retain this etched profile. This could cause the upper part of the current aperture to be larger than
the bottom, thereby degrading the optical quality of the photonic crystal cavity. After etching, the photoresist mask is removed in order to prepare for the oxidation process.

5.2.3 Steam Oxidation

In order to provide a current path to the center of the photonic crystal cavity, as well as create higher index contrast between the membrane and the substrate, steam oxidation is used. The sample is held in a furnace around 400 °C while N\textsubscript{2} carries 95 °C water vapor into the furnace. The AlGaAs layer is converted into an Al\textsubscript{2}O\textsubscript{3} layer, which is electrically isolating and has a smaller refractive index than Al\textsubscript{0.96}Ga\textsubscript{0.04}As. This process is well understood in the GaAs material system and is a crucial element of oxide VCSEL fabrication [9]. The challenging aspect of this oxidation relative to VCSEL oxidation is that the oxidation layer is 1 μm thick and of a generally lower Al content. The relatively low Al content of the oxidation layer necessitates the use of longer oxidation times. This
creates complexity in ensuring that the oxidation conditions are stable during the entire
time that the sample is in the furnace and that the oxidation process is repeatable.

The other major issue with the oxidation is that the oxidation layer is 1 µm thick. During the oxidation process, there is volumetric change in the oxidation layer [10]. It either expands or contracts depending on the temperature and flow rate of steam into the furnace. This expansion or contraction ultimately increases the strain between the oxidized regions and the GaAs and Al$_{0.96}$Ga$_{0.04}$As layer. This results in two issues. First, the membrane will have a raised region where the unoxidized current aperture remains. The height of this region can be on the order of tens of nanometers, which will affect the optical quality of the cavity. Also, the increase in strain can cause a delamination of the oxide layer from the substrate and of the oxide layer from the membrane, as well as a cracking and bowing of the membrane. In order to make the strain more uniformly distributed, circular trenches are used instead of trench patterns with corners, such as squares or hexagons.

In order to probe the effects of temperature on the oxidation process, long, narrow trenches were patterned using electron beam lithography and then etched using ICP-RIE. These trenches were then oxidized at various temperatures. The samples were then cleaved through the oxidized trenches, and the oxidation was inspected using an SEM. Figure 5.3 shows the resultant oxidation when the furnace temperature is set to 410 °C. The dark regions are the oxidized layer. Two aspects are evident in Figure 5.3: volumetric change and delamination of the oxide layer from the substrate. The expansion is larger in the direction of oxidation. The height difference between oxidized and unoxidized regions is approximately 25 nm at this temperature. While this may seem insignificant, it will affect a photonic crystal membrane that is only 200 nm thick. The delamination from the substrate, while not catastrophic in this experiment, would cause great mechanical instability in actual devices. In a fabricated photonic crystal emitter, this would result in
Figure 5.3 An oxidation trench after oxidation at 410 °C. The oxidized layer has delaminated from the substrate. Note also the volumetric expansion of the oxide layer (dark region) relative to the GaAs layers.

the entire photonic crystal membrane and oxidation layer (which would have a diameter of tens of microns) being supported only by a small post with diameter generally less than 500 nm. This delamination also degrades the thermal conductivity of the oxide layer to semiconductor interfaces.

Oxidation at 400 °C proved to give the most desirable results. Temperatures above this exacerbated the problems described when the oxidation was performed at 410 °C. Temperatures below this resulted in too much volume change as well. The volumetric expansion was minimal, and the measured height change is less than 5 nm (limited by the measurement). The oxidation rate at this temperature is 0.23 µm/min. Figure 5.4 shows the interface between an oxidized Al$_{0.96}$Ga$_{0.04}$As and an unoxidized one. Here the darker region is the oxidized layer. Above and below this dark region are the GaAs membrane and the substrate, respectively. To the left of the region is the unoxidized Al$_{0.96}$Ga$_{0.04}$As layer. Even though the etched profile was smooth and vertical, the
oxidation front is not. This is due to the chemistry of the oxidation process [11],[12]. This ultimately causes a problem in device performance. In order to maintain a conductive path to the substrate, the oxidation fronts coming in from all sides of the aperture cannot converge. If there are regions in the oxide layer that protrude or oxidize faster than others, then the diameter of the unoxidized region will have to remain larger than desired in order to accommodate these protrusions. This will ultimately result in the part of the conductive post that contacts the center of the photonic crystal cavity being large enough to negatively impact its optical quality.

Figure 5.4 The oxidation front after oxidation through a trench at 400 °C.

5.2.4 Completion of Fabrication

After oxidation, the samples are returned to the ICP-RIE in order to etch the photonic crystal holes. The oxidized layer now acts as an etch stop in a SiCl\(_4\)-based etch. Care again has to be taken to ensure vertical and smooth sidewalls inside the photonic crystal holes. After hole etching, the SiO\(_2\) layer is removed. This is done by either wet etching
using a buffered HF solution or a CHF$_3$-based dielectric etch. Electrical contacts are then deposited on the sample. Contact to the backside of the p-type substrate is made using Ti and Au deposited in that order. Photolithography is used to pattern a ring contact for making electrical connections to the top of the wafer. The contact to the n-type GaAs is comprised of AuGe, Ni, and Au deposited in that order. Typically, n-type contacts to GaAs are annealed at temperatures above about 400 °C. However, since the n-type region is so thin, diffusion of the metal contact through the diode junction is likely. To overcome this issue, the anneal is performed at a lower temperature of 275 °C for 90 seconds according to [13] and [14]. A sketch of a finished photonic crystal diode emitter with an integrated photonic crystal heterostructure cavity is shown in Figure 5.5.

**Figure 5.5** Schematic of a fabricated photonic crystal diode emitter.

### 5.3 Electroluminescence and Voltage Characteristics

To ensure the quality of the quantum wells in the epitaxial structure as well as to gain an understanding of the electrical properties of the material, simple, mesa-type structures are fabricated. The upper part of the membrane is grown without any type of quantum
well patterning. Using a SiO$_2$ mask and an ICP-RIE process, mesa structures are formed.
Oxidation and metallization are then performed as previously mentioned. While the oxide apertures obtained are generally much larger than the oxide apertures needed for photonic crystal devices, the devices still provide good insight into the electrical and luminescent properties of the material.

The devices are electrically probed using a continuous wave current source. The light output from the membrane is butt coupled to an optical fiber whose other end is connected to an optical spectrum analyzer. Figure 5.6 shows the electroluminescence spectrum of a full membrane structure with a 4 $\mu$m diameter oxide aperture. The electroluminescence peak is about 960 nm. The overall power collected was low, even under continuous wave operation. It is suspected that this is due to the small aperture as well as inefficiency in butt coupling a fiber to this type of structure.

![Electroluminescence spectrum](image)

**Figure 5.6** Electroluminescence from a 4$\mu$m diameter oxide aperture.

By connecting the butt-coupled fiber to a detector, a qualitative measurement of the light output of the membrane can be made. Figure 5.7 shows the voltage and collected light output as a function of input current to the same 4 $\mu$m aperture device. The
collected light output is left in terms of the photocurrent that it generated (for reference, the detector responsivity is approximately 0.5 A/W). The turn-on voltage and series resistance of the diode are approximately 1.2 V and 200 ohms, respectively. The light output increases somewhat linearly after diode turn-on and then begins to saturate and roll over. This saturation and roll-over is attributed to heating of the device at higher currents. The small kink in the light output versus current near 0 mA is attributed to the generated photocurrent being less than the dark current of the detector.

Figure 5.8 shows the calculated series resistance as a function of the inverse of the aperture area. The series resistance is calculated by performing a linear fit to the voltage versus current plot above the diode turn-on voltage. There are a number contributions to the series resistance of the device: the contact resistance due to the low temperature anneal, the resistance encountered by electrons that drift across the thin, top, n-type part of the membrane as they make their way toward the oxide aperture, and the resistance of the narrow, p-type oxide aperture. Since it is continuous and not punctured with photonic crystal holes, as an approximation, it is assumed that the resistance of the top
n-type layer is negligible compared to the other two. This results in the y-intercept of a linear fit to the plot in Figure 5.8 being equal to the contact resistance, and the slope being related to the resistivity of the oxide aperture multiplied by the thickness of the oxide layer. The estimated contact resistance and oxide aperture for this material system and anneal technique are approximately 143 ohms and 0.148 ohm cm, respectively. This indicates that the contact anneal step, while allowing for stable diode operation, did not completely anneal the contacts.

![Figure 5.8](image)

**Figure 5.8** Series resistance vs. inverse aperture area.

## 5.4 Optical Properties of the Diode Design

The design pursued has several limitations that adversely affect the cavity quality factor. The incorporation of a current path and the oxide layer play a role in the optical quality factor of a photonic crystal cavity fabricated in a vertically injected diode. The current post as suspended in air and embedded in a dielectric has been extensively studied [8], [15]–[17]. The authors concluded that proper mode selection for a given cav-
ity coupled with a very narrow post could provide quality factors large enough to lase. As was mentioned in section 5.2.3, however, using the techniques in this dissertation, fabricating a small current aperture via oxidation will be challenging. The analysis of a photonic crystal on or embedded in a low-index dielectric has also been performed [15]–[18]. The general consensus in these works is that a higher quality factor is obtained when the photonic crystal holes extend far into the low-index dielectric layer. For the devices fabricated in this dissertation work, the holes end abruptly at the top of the oxide layer, thus limiting the cavity quality factor.

The optical properties of the cavity are also affected by the quantum well patterning process and the number of quantum wells. Since three quantum wells are used in this structure, a depth of 55–60 nm must be etched in order to remove all of the quantum wells in the regions where the holes will penetrate. This means that after growth of the upper membrane, the membrane outside the cavity will be approximately 60 nm thinner than the membrane inside the cavity. That is an appreciable thickness as the entire membrane is only 201 nm thick. Ultimately, this will result in a modal mismatch between the cavity and the surrounding photonic crystal. It can be thought of as an abrupt interface between two dielectric slab waveguides of different thicknesses, which will create optical scattering.

Commercial FDTD software distributed by RSoft [19] is used to study the effects of the aforementioned issues. The cavity used in the calculation is a modified single-defect photonic crystal cavity as given in [15]. The quality factor for the hexapole mode (which possesses a central field null) in this cavity when suspended in air can reach a few thousand. When a dielectric substrate is included underneath the cavity without the photonic crystal holes penetrating it, the quality factor drops to 939. This can be attributed to a shrinking of the light cone in the momentum space of the photonic crystal. As the light cone shrinks due to increased cladding index, the momentum space
distribution of the electric field begins to overlap more into the radiation zone (region outside of the light cone). Ultimately, this means that more light is radiated out of the cavity, and the quality factor decreases.

When a 200 nm diameter current post or aperture is introduced into the center of the cavity, the quality factor stays relatively constant at 1054. This is likely due to the fact that the hexapole mode is used, which has a field null at the center of the cavity. If the monopole mode or any other mode with a maximum at the center of the cavity were considered, the quality factor would likely be less and decrease very rapidly as the size of the post increased. Finally, the effects of quantum well patterning are introduced. The membrane outside the cavity is shrunk by 60 nm, and the calculations are repeated. Now, the quality factor of the cavity decreases to 630. The authors in [16] recommend using whispering-gallery-type photonic crystal modes in order to achieve higher quality factors. Using the same physical geometry as before and changing only the cavity to a two defect whispering-gallery-type cavity increases the quality factor to 1012. Ultimately what this indicates is that the cavity design must be optimized for a given diode structure in order to achieve high quality factors.

5.5 References


CHAPTER 6

Summary of Research

6.1 Summary

Lasers can be used for a multitude of sensing applications. This dissertation deals with two types of lasers appropriate for use as sensors. The integrated VCSEL and photodetector as a position sensor is detailed. Photonic crystal lasers, a type of nanoscale laser, are well suited for use as lasers because of their compactness and ultra-small modal volume. Different aspects and properties of photonic crystal membrane lasers are discussed, and a means of creating an electrically injected emitter is examined.

Chapter 2 discusses the use of an integrated VCSEL and PIN photodetector for use as a position sensor. A position sensing scheme using the VCSEL and detector die as a sensor and a grating as a position gauge is introduced and is then studied via simulations. Calculations indicate that the position sensing resolution is comparable to the wavelength of light emitted from the VCSEL. The design and fabrication of the integrated VCSEL and photodetector die is also briefly discussed. The sensors are incorporated into an electronically controlled translations stage for testing. Measured data indicates the feasibility of using the integrated VCSEL and photodetector die as position and velocity sensors.
Chapter 3 gives an introduction to photonic crystals and photonic crystal lasers. The optical properties relative to making a photonic crystal laser are presented, as is a fabrication procedure for optically pumped photonic crystal membrane lasers. The thermal properties of a photonic crystal laser are investigated using a finite element method. Results indicate that the internal temperature of a photonic crystal laser can be over 100 K over the ambient temperature and that physical properties such as fill factor greatly affect the temperature. Means of improving the electrical and thermal conductivity of a photonic crystal membrane laser are discussed, and the decimated photonic crystal cavity is presented as a solution.

The design and testing of photonic crystal heterostructure cavity lasers in the InP material system is discussed in Chapter 4. The photonic crystal heterostructure will allow exquisite control of the laser emission while using a large cavity size and semiconductor mode volume. A heterostructure cavity is formed by interfacing two different photonic crystals such that a dispersion maximum of the inner lattice lies within the band gap of the surrounding lattice. Feedback to slow-light modes of the central region results in a lower threshold and single-mode operation. The use of a kagome lattice as the inner defect area increases the semiconductor volume as well as the modal overlap with the gain material. Simulation is used to verify experimentally observed-single mode operation as well as to quantify the effects of the heterostructure cavity formation.

The progress toward making electrically injected photonic crystal emitters is discussed in Chapter 5. A new material structure is proposed, and the fabrication technique is described, as are its drawbacks. Measurements indicative of materials properties are shown. Finally, simulation of the photonic crystal cavity in a diode configuration is discussed. Calculations indicate that the cavity must be specifically optimized for the diode material system before further progress can be made.
6.2 Future Work

The integrated VCSEL and photodetector position sensor showed limitations in accuracy when the motion during the position measurement was not smooth. Ultimately, the resolution of the sensors becomes as large as the period of the grating used as a position gauge. In order to improve this, a data learning and interpolation technique must be employed. Real-time analysis of the measured detector signals combined with an advanced signal processing technique could provide accuracy smaller than the wavelength of light emitted from the VCSEL.

In order to leverage the benefits of even smaller modal volume in photonic crystal nanolasers, electrical injection remains the greatest challenge. Two issues with the material structure and fabrication techniques of the diode configuration photonic crystal emitter are described in this dissertation: the need to create patterned quantum wells and the treatment of the oxidation layer. The necessity of creating patterned quantum wells ultimately reduces the optical quality factor of the photonic crystal membrane by creating an optical cavity that is thicker than the surrounding photonic crystal membrane. Yet, reducing the number of quantum wells in order to decrease the height difference is not practical since the cavity quality factors are relatively low. One possible means of avoiding this problem is to not etch the quantum wells. Instead of quantum well patterning, quantum well disorder or mass transport should be investigated. Another approach would be to used stacked quantum dot layers as an active region.

Since the oxidation is performed before photonic crystal hole etching, the holes terminate on top of the oxidized layer, ultimately lowering the quality factor of the cavity. In addition to this, the oxidation process must be tightly controlled in terms of not just rate, but also oxidation profile. A means of avoiding these issues would be to perform two oxidation steps. The first oxidation would be performed prior to etching the pho-
tonic crystal holes. The current aperture should be just inside the extent of the photonic crystal. After photonic crystal hole etching, the oxidation can be completed to form an aperture confined to the cavity by oxidizing through the photonic crystal holes. This would result in the photonic crystal holes penetrating the low-index dielectric and result in a higher optical quality factor. Also, since the rate will necessarily need to be much slower to oxidize through the holes, a more controllable oxidation can be achieved.

A completely new approach to reduce optical leakage into the substrate of a dielectric-mounted photonic crystal cavity can also be suggested. A metal layer directly below the semiconductor membrane will essentially confine the light to inside the membrane [1]. In order to provide some means of feedback, a band-edge photonic crystal cavity can be fabricated. In order to make the cavity more compact, instead of etching a typical air hole photonic crystal pattern, a metallic grating or photonic crystal can be patterned via electron beam lithography and deposited using standard techniques. This will result in a uniform semiconductor membrane that is confined on both sides by layers of metal. The metal on one side of the membrane has a photonic crystal pattern in it. By adjusting the metallic photonic crystal to slow the group velocity of the light emitted from the membrane, constructive feedback can occur. Taking advantage of this slow light effect should help alleviate some of the losses present in metals at optical frequencies and could lead to laser action.

6.3 References