Design and Fabrication of an Electrically-Activated Photonic Crystal Nanocavity Laser

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B.S.E., Electrical Engineering and Computer Science
University of Michigan (2003)

Submitted to the
Department of Electrical Engineering and Computer Science
in partial fulfillment of the requirements for the degree of

Master of Science in Electrical Engineering

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 2005
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Abstract

In the future, optical networks may see an expanded role not only in telecommunications, but also in computers and other common electronic devices. These optical networks will require small, on-chip light sources. By using the photonic crystal’s ability to strongly confine light, photonic crystal lasers can be built very small and very efficient, making them ideal for photonic integrated circuits. This thesis describes the design and fabrication of an electrically-activated photonic crystal nanocavity laser using an active layer with quantum dots. Hydrogen silsesquioxane (HSQ) was studied as an electron-beam lithography resist, and reactive ion etching of AlGaAs and InGaAlP was investigated.

The laser described herein is very small, only \( \sim 5 \, \mu\text{m} \) in length and width. The design is also very flexible. By simply changing the active material and the size and spacing of the holes which create the one-dimensional photonic crystals, the emission wavelength can be easily varied. The laser is anticipated to be more efficient than the current technology from both the energy and chip design standpoints, and should represent a major improvement in on-chip light sources.

Thesis Supervisor: Leslie A. Kolodziejski
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Acknowledgements

My graduate work at MIT, much of which is contained in this thesis, would not have been possible without the help of a great number of people.

First and foremost, I would like to thank Professor Leslie Kolodziejski for allowing me to join her outstanding research group. Her support and encouragement made my graduate research experience challenging, exciting, and fun. I would also like to thank Dr. Gale Petrich, who seemed to have a good answer to every one of my questions and was never too busy to explain it to me. I would like to thank my group members, Dr. Sheila Tandon, Ryan Williams, Reginald Bryant, Aleksandra Markina, and Sarah Rodriguez for answering all of my many questions and keeping a straight face while doing it. I also owe a debt of gratitude to Dr. Solomon Assefa for passing a great project on to me, and for showing me the ins and outs of both lab work and graduate school as a whole. I greatly appreciate the efforts Mark Mondol and Jim Daley made to aid me in my research, and the National Science Foundation for funding me during my two year graduate school tenure.

I want to thank all of my friends in Boston for making my graduate school experience a whole lot of fun. We didn't make it to every bar in Boston, but we gave it a good shot! Special thanks to my roommate, Ryan Tabone, for providing friendship, entertainment, motivation, and on-site tech. support every time the virus' in my home computer threatened to seize control.

I want to thank my family for always being supportive and interested in what I was working on - even though some of them still think my research involved building a device to emit futons. And to my grandmother, who passed away in the final days of this thesis work, thank you for passing on to me the confidence and stubbornness that have never allowed me to give up.

And, finally, to all those who have made fun of me over the years for being a nerd...lets see if you have the guts to come say those things to the face of a Science Master!
# Table of Contents

Abstract .................................................................................................................. 3  
Acknowledgments ................................................................................................. 5  
Table of Contents .................................................................................................. 7  
List of Figures ....................................................................................................... 9  
List of Tables ....................................................................................................... 13  

I. Introduction ....................................................................................................... 15  

II. Photonic Crystal Nanocavity Laser Design .................................................... 20
   i) Photonic Crystal Technology ......................................................................... 20  
   ii) Quantum Dots ............................................................................................... 23  
   iii) Laser Design ............................................................................................... 24  
   iv) Simulations .................................................................................................... 27  

III. Research Approach ......................................................................................... 31  
   i) Crystal Growth ............................................................................................... 31  
   ii) Fabrication Process ....................................................................................... 32  

IV. Discussion and Results .................................................................................... 38  
   i) HSQ .............................................................................................................. 38  
   ii) Electron-Beam Lithography ......................................................................... 40  
   iii) Reactive Ion Etching .................................................................................... 47  

V. Future Work .................................................................................................... 65  

VI. Conclusion ..................................................................................................... 69  

References .......................................................................................................... 70
List of Figures

Figure 1: Depiction of an optically pumped, surface emitting laser using a quantum well (QW) active region developed by Painter et al. [2]...........................................................................................................16

Figure 2: Image of a photonic crystal laser utilizing a cavity formed by a defect hole that is smaller than those of the surrounding photonic crystal lattice. By elongating a row of holes in line with the defect cavity, the quality (Q) factor, defined as the ratio of energy stored to energy dissipated in the cavity, is greatly increased [3]..............................................................................................................17

Figure 3: Scanning electron micrograph (SEM) image of three cavities of the coupled-cavity waveguide laser [4].............................................................................................................18

Figure 4: (a) Schematic diagram of the single-cell photonic crystal laser with a 50 nm etched mesa. (b) SEM of a broken sample showing the region around the central pillar [5].................................................................19

Figure 5: Examples of one-, two-, and three-dimensional photonic crystals. Different colors represent materials with different indices of refraction [6].................................................................21

Figure 6: Depiction of the frequency vs. wave vector diagrams of dielectric stacks when (a) $e_1 = 13$ and $e_2 = 13$, (b) $e_1 = 13$ and $e_2 = 12$, (c) $e_1 = 13$ and $e_2 = 1$. The horizontal black stripes in (b) and (c) represent the photonic band gap. The photonic band gap grows as the permittivity (and thus index of refraction) differences increase [6].................................................................................................22

Figure 7: Example of a nanocavity formed in a two-dimensional photonic crystal system by introducing a defect; in this case one rod that is smaller than the rest [6].................................................................22

Figure 8: Atomic Force Microscope (AFM) image of an InGaAs/GaAs quantum dot array of the type used in the photonic crystal laser. The pancake-shaped dots are roughly 23 nm wide and 10 nm tall ..........24

Figure 9: Schematic of the electrically-activated photonic crystal nanocavity laser.................................................................25

Figure 10: Simulation of the modal confinement in the photonic crystal nanocavity (where the two waveguides overlap). Pink represents air, blue is oxidized AlGaAs, yellow is InGaAlP, red is the quantum dot layer, and brown unoxidized AlGaAs. Note that the light is confined almost entirely to the waveguide, and the mode is centered on the red quantum dot layer.................................................................28

Figure 11: Photonic band diagram for a GaAs waveguide ($n = 3.37$) surrounded by air ($n = 1$) and containing air holes [8].................................................................................................29

Figure 12: Vector plots of the electric field distributions for dielectric band, air band, and defect states for a GaAs waveguide ($n = 3.37$) surrounded by air ($n = 1$) and containing air holes [8].................................................................................................30

Figure 13: (a) The photonic crystal laser structure, and (b) the measured room temperature photoluminescence.................................................................31

Figure 14: Process flow used to fabricate the electrically-activated photonic crystal nanocavity laser......32

Figure 15: The chemical structure of HSQ, let R = H: (a) cage form, (b) network form [10].................38

Figure 16: SEM of the 300 nm thick layer of Fox-140® HSQ used in the laser process......................40

Figure 17: Schematic of the VS-26 electron-beam lithography tool [12].................................................41
Figure 18: Depiction of the two electron-beam lithography masks used to fabricate the photonic crystal laser. Notice that there are fewer holes on the right side, allowing for the laser emission.

Figure 19: SEM images of (a) the five contact pads in HSQ from the first lithography step, (b) and (c) the contact pad and waveguide, and (d) a magnified view of the intersection of a contact pad with a waveguide.

Figure 20: SEM images of (a) the contact pads from the second electron-beam lithography step, (b) the crossed waveguides, and (c), (d) the holes that will form the photonic crystals at the intersection of the two waveguides.

Figure 21: SEM images of stitching errors from the first electron-beam lithography step. The stitching errors are about (a) 1 μm, (b) 200 nm.

Figure 22: SEM images showing slight misalignment of the HSQ from the second electron-beam lithography step on top of the waveguide patterned in the first lithography step.

Figure 23: Examples of crossed waveguide patterns in HSQ that have moved during development due to poor adhesion to the sample surface.

Figure 24: Diagram of a standard parallel plate reactive ion etching system [14].

Figure 25: HSQ (green) is used as an etch mask during the methane etch of InGaAlP (red) to define the upper waveguide from the structure.

Figure 26: SEM images of waveguides patterned in HSQ before etching.

Figure 27: SEM image of the HSQ and InGaAlP waveguide after the methane etch.

Figure 28: SEM images of the HSQ and InGaAlP waveguide after the methane etch and oxygen clean.

Figure 29: HSQ hardness versus its Si-H/Si-O bond ratio [15].

Figure 30: SEM images of HSQ-covered waveguides after the methane etch and oxygen clean. In (a) no oxygen ashing was done, (b) was ashed for 10 minutes at 100 W, (c) was ashed for 15 minutes and 100 W, and (d) was ashed for 10 minutes at 200 W. Notice there is very little, if any, difference between the pictures, which shows that oxygen ashing was unable to increase the HSQ's resistance to the methane etch.

Figure 31: SEM images of HSQ-covered waveguides after the methane etch and oxygen clean when (a) no curing step is done and (b) when the sample is cured for one hour at 400°C. Again, there is little difference between the cured and uncured samples.

Figure 32: SEM image of an HSQ-covered waveguide after a low-powered methane etch and oxygen clean.

Figure 33: SEM images of the upper InGaAlP waveguide after the HSQ is removed by (a) the higher powered CF$_4$ process and (b) the lower powered CF$_4$ process. Notice the sidewall roughness due to the inability of HSQ to withstand the methane etch.

Figure 34: Contact Pad and waveguide after the HSQ is removed following the first electron-beam lithography write and etch step.
Figure 35: SEM image of the pattern defined by the second electron-beam lithography write in PMMA. The waveguides are areas where the PMMA has been removed, while the circles in the waveguides are small cylinders of PMMA which will eventually be used to form the photonic crystal holes. 

Figure 36: SiO$_2$ (light blue) is deposited onto the sample, and then PMMA (yellow) is applied. After electron-beam exposure and development, the PMMA covering the waveguides is removed. Nickel (silver) is then evaporated onto the sample. The PMMA is removed, leaving nickel only over the waveguides. The nickel is then used as a mask to etch the SiO$_2$, and is removed with a wet etch. The result is a SiO$_2$ mask in place for the following methane and BCl$_3$ etches.

Figure 37: With SiO$_2$ (light blue) as a mask, a methane etch is used to trim the InGaAlP (red) waveguide to size and to etch the holes. Next, a BCl$_3$ etch is used to define the lower AlGaAs (grey) guide and etch holes. The two etches complete the photonic crystals.

Figure 38: SEM image of waveguides when only an oxygen clean is carried out between the methane and BCl$_3$ etches. Note the severe sidewall roughness due to polymer formation during the methane etch step.

Figure 39: SEM image of waveguides when a combination of chamber scrubbing, oxygen cleaning, and sacrificial etching is done between the methane and BCl$_3$ etches. Notice the dramatic improvements in sidewall roughness compared to the result shown in Figure 30.

Figure 40: The AlGaAs (gray) contact pad must be etched down to below the quantum dot layer, so that when a voltage is applied to the pads, the p-n junction surrounding the quantum dots is forward biased, producing light.

Figure 41: A thick layer of photoresist is spun onto the sample, and photolithography is then used to define two parallel lines that intersect the upper waveguide just outside of the nanocavity. A sulfuric acid-based wet etch is then used to etch through the AlGaAs (gray) layer without harming the upper InGaAlP (red) waveguide. The photoresist is then removed.

Figure 42: The final step in the laser process is to add metal contacts to the pads on the ends of the waveguides.
List of Tables

Table 1: Measured HSQ thicknesses for different types of HSQ, HSQ:MIBK ratios, and spin speeds. The spin time was 60 seconds in all cases. .......................................................... 39
I. Introduction

In recent years, great advances in information processing electronics have been made. In the near future, however, the inherent physical limitations of electronics will begin to slow the technological growth of this area. Already major problems with power dissipation and consequent hardware heating are being encountered in computers, which are running at ever higher frequencies. The problem is even more severe in optical communication networks, where data is electronically processed at yet higher frequencies. The solution to these problems may very well be optics, since light can be used effectively for interconnects, processing, and routing at frequencies too high for electricity. In the future, the use of optics may see an expanded role not only in telecommunications, but also in computers and other common electronic devices [1].

Future optical networks will require small, on-chip light sources. Currently semiconductor lasers commonly fill this niche. As chip features continue to grow smaller, however, smaller lasers are preferable. Standard edge-emitting semiconductor lasers use cleaved facets as mirrors to form a cavity in which the light is confined. In the laser cavity, the light experiences gain, meaning that it is amplified. At the facets, however, some light will leak out as output, which acts as a loss mechanism. In general, the net gain in the cavity must be greater than the losses in the cavity, including the losses at the end-mirrors, for light amplification and subsequent lasing to occur. The gain/loss relationship introduces a limitation to the size of standard semiconductor lasers, since as cavity length decreases, the light experiences a smaller gain region making it more difficult to overcome the cavity losses. Thus to build smaller lasers, the end-mirror reflectivity must be increased.
Photonic crystals have the ability to miniaturize standard semiconductor lasers by confining light much more effectively. Improved confinement means that the light experiences less loss, allowing photonic crystal laser cavities to be made much smaller than those of standard semiconductor lasers. Smaller lasers are advantageous not only because of their size, but also because a smaller, less lossy cavity means less input power is required to induce lasing.

Numerous lasers have been designed to take advantage of the photonic crystal’s ability to confine light [2,3,4,5]. The vast majority of photonic crystal lasers made thus far have been optically-pumped, meaning that in order to induce lasing, a second separate light source such as a laser must be directed onto the cavity of the photonic crystal. O. Painter et al. demonstrated an optically-pumped, surface emitting laser in 1999 [2]. The O. Painter et al. laser, as depicted in Figure 1, had a high threshold pump power, in part due to the fact that the pump beam was more than thirty times larger than the laser cavity; thus, much of the input pump power was wasted.

**Figure 1:** Depiction of an optically-pumped, surface emitting laser using a quantum well (QW) active region developed by Painter et al. [2]
More recent optically-pumped photonic crystal lasers, such as that made by Loncar et al. and shown in Figure 2, have improved efficiency and threshold power, but still suffer from the design drawbacks associated with having a separate pump laser [3]. Optically-pumped lasers tend to be inefficient both from a power standpoint and from a chip design standpoint.

![Figure 2: Image of a photonic crystal laser utilizing a cavity formed by a defect hole that is smaller than those of the surrounding photonic crystal lattice. By elongating a row of holes in line with the defect cavity, the quality (Q) factor, defined as the ratio of energy stored to energy dissipated in the cavity, is greatly increased [3].](image)

Recently, a few electrically-activated photonic crystal lasers have been demonstrated [4,5]. Electrically-activated lasers need only have a voltage applied to them to produce light; an advantage over the optically-pumped photonic crystal lasers described previously. Increased power efficiency and ease of integration with other opto-electronic devices make electrically-activated photonic crystal lasers a very desirable option for on-chip light sources.

Happ et al. used two-dimensional photonic crystals to build a coupled-defect laser diode in 2002 [4]. The laser cavity was composed of a line of 40 coupled hexagonal defect microcavities in a lattice of air holes etched into an InGaAsP/InP structure. A Scanning Electron Micrograph (SEM) image of three of the hexagonal microcavities is
shown in Figure 3. While offering stable, single mode, continuous-wave operation around a wavelength of 1.55 μm, the coupled-cavity waveguide laser exhibited a threshold current of 15 mA, yielding a maximum output power of only 2.6 mW. The laser described in this thesis is expected to exhibit an improved external efficiency, meaning a lower threshold for a comparative amount of output power.

More recently, in 2004, an electrically-activated photonic crystal laser was demonstrated by Park et al. [5]. The device consists of a single-cell, two-dimensional photonic crystal slab on a pillar, which is designed to emit single photons. Electrons are supplied through an electrode on top of the device, while holes are injected through the pillar, which serves as a lower electrode. The device is shown in Figure 4. The laser emits light at roughly 1.55 μm, and has a threshold current of about 260 μA. The output is very small, however, measuring about 5 nW, and the structure is complicated. The photonic crystal laser described herein should be both more efficient and easier to build than the mesa device in Figure 4, and should emit a more intense beam of light.

Figure 3: Scanning electron micrograph (SEM) image of three cavities of the coupled-cavity waveguide laser [4].
Since electrical activation of photonic crystal lasers is a relatively new technology, there is still much work to be done in the quest to build an efficient laser. This thesis describes a novel design for an electrically-activated photonic crystal laser. The laser is anticipated to be more efficient than the current technology from both the energy and chip design standpoints, and should represent a major improvement in on-chip light sources.

The following sections describe the electrically-activated photonic crystal nanocavity laser. Section II describes the design of the photonic crystal nanocavity laser, along with an introduction to photonic crystal technology and quantum dots. Section III will detail the fabrication process initially used to build the device. Section IV discusses the results of the fabrication process detailed in Section III, and Section V provides insight into the direction in which the photonic crystal laser project will go in the future. Finally, the thesis is concluded in Section VI.
II. Photonic Crystal Nanocavity Laser Design

i) Photonic Crystal Technology

The laser described in this thesis utilizes photonic crystals and their unique ability to control light propagation. Photonic crystals are optically analogous to semiconductor crystals’ control over electricity. Semiconductors are made up of a periodic arrangement of atoms or molecules, called a lattice. The lattice presents a periodic potential to electrons; a potential which can affect the electron’s propagation. Specifically, the lattice creates energy band gaps which forbid electrons with certain energies from propagating in certain directions. If the lattice potential is strong enough, the energy band gap will exist in all directions, leading to a complete band gap such as that between the valence and conduction bands in a semiconductor. The complete bandgap between the valence and conduction bands is the basis for semiconductor devices [6].

Photonic crystals, similarly, are made up of a periodic arrangement of dielectric media. If the dielectric constants of the materials that are used are different enough, scattering at the material interfaces can create many of the same phenomena for photons that electrons experience in semiconductors. In this way, materials with photonic band gaps are created. Photonic band gaps can then be used to prevent light with certain energies from propagating in certain directions. The photonic band gap phenomenon can be used to confine light effectively in photonic crystal lasers [6].

Photonic crystals can be made one-dimensional, two-dimensional, or three-dimensional, as shown schematically in Figure 5. The dimensionality of a photonic crystal refers to the number of dimensions in which there exists a periodic change in the dielectric constant, which is proportional to the index of refraction. In the case of the
laser described in this thesis, a one-dimensional photonic crystal is used. Instead of a series of slabs as shown in Figure 5, the laser's photonic crystal is made up of a single row of air holes etched into a single mode waveguide composed of a higher index material. Since the air holes lead to a periodic change in the dielectric constant, the effect is the same as that experienced in the one-dimensional slab photonic crystal.

![1-D 2-D 3-D](image)

Figure 5: Examples of one-, two-, and three-dimensional photonic crystals. Different colors represent materials with different indices of refraction. [6]

Figure 6 depicts the photonic band structure of a one-dimensional photonic crystal. In (a), there is no index of refraction difference between the layers, and therefore no photonic band gap. In (b), a small contrast in index of refraction leads to a small photonic band gap. Finally, in (c), a large index contrast between the alternating layers of dielectrics is shown to create a larger band gap. When a band gap is present for certain energies in a one-dimensional photonic crystal, propagation along the axis of the crystal is forbidden for light with energies in the photonic band gap. The only light to pass into the crystals will be in the form of evanescent fields within the photonic crystal, which attenuate exponentially with distance. The bandgap in a photonic crystal can be tailored to a certain wavelength by altering the size, spacing, and index of refraction of the periodic media.
Figure 6: Depiction of the frequency vs. wave vector band diagrams of dielectric stacks when (a) $e_1 = 13$ and $e_2 = 13$, (b) $e_1 = 13$ and $e_2 = 12$, (c) $e_1 = 13$ and $e_2 = 1$. The horizontal black stripes in (b) and (c) represent the photonic band gap. The photonic band gap grows as the permittivity (and thus index of refraction) differences increase [6].

By introducing a point defect into a photonic crystal, and thus breaking the periodicity of the structure, a cavity can be formed. Light with energy that is within the photonic bandgap will be trapped in the cavity, as it is unable to propagate. The defect can be created in multiple ways, such as decreasing the size of a rod as shown in Figure 7. Other defect options include increasing the size of one rod, or leaving a rod out of the lattice entirely. The formation of a cavity, by breaking the periodicity of the photonic crystal, is very important to the operation of the photonic crystal laser described herein.

Figure 7: Example of a nanocavity formed in a two-dimensional photonic crystal system by introducing a defect; in this case one rod that is smaller than the rest [6].
ii) Quantum Dots

The electrically-activated photonic crystal nanocavity laser uses a thin quantum dot active region to generate light. Quantum dots are small structures that confine carriers in three dimensions and are on the order of nanometers in size. Since the electrons are confined in such a small space, quantum effects dominate, leading to quantized electron energy levels. With electrons located at certain energy levels in shells, quantum dots are sometimes described as artificial atoms.

Changing the size of a quantum dot can affect its properties, such as its emission. For example, as the quantum dots grow larger, the emission wavelength increases. Altering the number of electrons confined in the quantum dot can have the same effect. Quantum dots have the potential to make more efficient lasers than bulk material due to the charge in the available density of states. Quantum dot lasers’ performances are less likely to degrade at higher temperatures, they require lower threshold powers to lase, and finally population inversion is more easily obtained in quantum dots than in bulk material, increasing the gain.

The quantum dots used in the photonic crystal laser are grown by a technique known as self-assembly. Self-assembly involves depositing a thin epitaxial layer of the quantum dot material on top of an existing lattice-mismatched layer. The lattice mismatch strains the quantum dot material, causing it to form ‘islands’, which result in the formation of the quantum dots. The dots are not perfectly spherical, but can be pyramidal, cylindrical, or dome-shaped. The result is a layer of quantum dots like that shown in Figure 8 [7].
Figure 8: Atomic force microscope (AFM) image of an InGaAs/GaAs quantum dot array of the type used in the photonic crystal laser. The pancake-shaped dots are roughly 23 nm wide and 10 nm tall.

iii) Laser Design

The photonic crystal laser is composed of two crossed photonic crystal waveguides, one on top of the other, as depicted in Figure 9. The bottom waveguide, referred to as the “active region”, consists of an InGaAs quantum dot layer sandwiched between two GaAs and AlGaAs layers. The AlGaAs below the quantum dots is doped p-type with beryllium, while the material above the quantum dots is doped n-type with silicon. The result is a p-n junction with the quantum dots serving as the active material. When the junction is forward-biased, the quantum dots produce light at a wavelength of about 1.3 μm. The output wavelength of the photonic crystal laser was chosen to be 1.3 μm due to applications in optical communication systems.
Figure 9: Schematic of the electrically-activated photonic crystal nanocavity laser.

Once light is generated in the “active region”, it will be confined above and below, as well as laterally, by index confinement. The waveguide ($n \sim 3.4$) is surrounded by air ($n = 1$) above and to the sides, and by a layer of oxidized AlGaAs ($n \sim 1.6$) below. Into the two ends of the waveguide, however, a series of holes are etched, forming a one-dimensional photonic crystal, which will confine the light lengthwise. The holes are 225 nm in diameter and are separated by 435 nm center to center.

The optical mode in the “active region” will be centered on the quantum dot layer, since this layer has the highest index of refraction, and the bulk of the generated light will stay in the bottom waveguide. A small part of the mode, however, will extend into the top InGaAlP waveguide, referred to as the “guiding region”. In this thesis, the “guiding region” crosses the top of the “active region” at a 90° angle, although in the future that angle can be varied in order to change the direction of the emitted light. The top waveguide is similar to the bottom waveguide, but with a few important changes. First,
the top waveguide is composed entirely of InGaAlP, with no quantum dots. The lack of quantum dots makes the “guiding region” less lossy than the “active region”. Second, the top guide has fewer holes etched into one end than the other, which allows light to leak out, directing the laser emission. The holes are of the same diameter and spacing as in the lower guide, and are consistent with 1.3 \mu m emission.

The laser nanocavity is located where the two waveguides cross, and is formed by leaving a roughly 1 \mu m gap between the photonic crystal holes in both waveguides. As previously discussed, the gap breaks the periodicity of the photonic crystal, and allows light to exist in the cavity. It is important that the two one-dimensional photonic crystal nanocavities’ resonances overlap, both physically and optically, for the device to operate effectively. The nanocavity and surrounding photonic crystals, depicted above in Figure 9, are roughly 5 \mu m in length and width.

The photonic crystal laser design described in this thesis has numerous advantages over existing lasers. First, the laser is only few microns in size, making it ideal for small, densely packed chips. The laser is also edge-emitting and electrically-activated, meaning that by simply applying a voltage to the laser, light can be emitted in the plane of the chip. Another advantage is that the “active region” and the “guiding region” are separated, allowing light to be created in one waveguide, and then couple into a less lossy waveguide from which it will eventually be emitted; having two separate waveguides increases the overall efficiency of the device. Also increasing the laser’s efficiency are the small size of the nanocavity and the use of quantum dot active material. The cavity size and quantum dots will lead to a very small threshold power for the photonic crystal laser. Finally, the laser is very flexible in that by simply changing the
active material, causing the quantum dots to emit light at a different frequency, and changing the size and spacing of the photonic crystal holes accordingly, the laser can easily be built to emit light at wavelengths other than 1.3 \mu m. The top waveguide can also cross the bottom waveguide at angles other than 90°, giving the laser the flexibility to emit light in almost any direction required by the layout of the chip.

iv) Simulations

An important step in designing the electrically-activated photonic crystal nanocavity laser was verifying that the laser would operate as designed. In order to verify the design, computer simulations were used to ensure that the laser structure described in this thesis would indeed confine the light in the expected manner.

The simulation results in Figure 10 show how the optical mode resides within the nanocavity where the two waveguides cross. As expected, the 2 \mu m thick oxidized AlGaAs layer (blue) prevents the light from coupling into the substrate and being lost. The oxidized AlGaAs layer, along with the surrounding air (pink), also serves to keep the bulk of the optical power in the waveguide. The mode will also be centered on the quantum dot layer (red) in the guide, as expected. Finally, the simulation shows that some of the mode overlaps with the top InGaAlP waveguide (yellow). The mode overlap is very important to the device, since the light that couples into the upper waveguide will eventually form the laser emission.
Figure 10: Simulation of the modal confinement in the photonic crystal nanocavity (where the two waveguides overlap). Pink represents air, blue is oxidized AlGaAs, yellow is InGaAlP, red is the quantum dot layer, and brown is unoxidized AlGaAs. Note that the light is confined almost entirely to the waveguide, and the mode is centered on the red quantum dot layer.

The simulation results in Figure 11 show the photonic band diagram for a series of air holes etched into a GaAs medium (n = 3.37) as illustrated in the inset. In the simulation, the holes are separated by a lattice constant a, the waveguide width is 1.2a, the waveguide thickness is 0.4a, and the hole diameter is 0.6a. The simulation parameters are close to those used in the electrically-activated photonic crystal nanocavity laser design, and therefore the band diagram is expected to be very similar to that for the photonic crystal laser. In Figure 11, a photonic bandgap in the guided modes with frequency between 0.28 and 0.4 can be seen. The bandgap separates the upper most state in the dielectric band from the lowest state in the air band. Light of a frequency that falls into this bandgap, such as that used in the photonic crystal laser, will not be able to propagate. The light will thus be confined to the cavity by the air holes [8].
Figure 11: Photonic band diagram for a GaAs waveguide \((n = 3.37)\) surrounded by air \((n = 1)\) and containing air holes [8].

Figure 12 shows vector plots for the electric field intensity of the dielectric-band, air-band, and for the defect state. As expected, for the dielectric band the bulk of the electric field is in the dielectric, while the electric field is in the air holes for the air-band. The defect state is formed by increasing the distance between two of the air holes, causing more of the lowest air-band state’s electric field to intersect the dielectric region. The energy of the lowest air-band state is therefore reduced, pulling the defect state down into the photonic bandgap. In Figure 12, the defect state is concentrated in the cavity, as it will be in the photonic crystal laser. The photonic crystal and index change at the edges of the guide are sufficient to contain the defect state, which is a key component to the laser, allowing it to confine light lengthwise in the cavity. The cavity containing the defect state in the simulation that is shown in Figure 12 is smaller in relation to the hole size than that in the laser described herein. As the hole separation increases, the defect
state will sweep across the photonic bandgap, but with the dimensions used in the photonic crystal laser process, the field confinement should be very similar to that shown in the defect state simulation [8].

Figure 12: Vector plots of the electric field distributions for dielectric-band, air-band, and defect states for a GaAs waveguide ($n = 3.37$) surrounded by air ($n = 1$) and containing air holes [8].
III. Research Approach

i) Crystal Growth

The photonic crystal laser structure is grown using gas source molecular beam epitaxy, and consists primarily of InGaAlP, AlGaAs, and GaAs (substrate). The structure and its measured photoluminescence are shown in Figure 13.

Figure 13: (a) The photonic crystal laser structure and (b) the measured room temperature photoluminescence.
The quantum dot layer is grown by the aforementioned technique known as self-assembly. First, a 25 nm GaAs layer is deposited. A 6 nm layer of InAs is then grown. Due to lattice constant differences between these two materials, strain forces the InAs to form quantum dots. The quantum dot layer is then buried by a 6 nm In$_{0.15}$Ga$_{0.85}$As quantum well layer. A second 25 nm layer of GaAs is then grown on top of the quantum dots, and the rest of the growth proceeds as shown in Figure 13.

ii) Fabrication Process

The initial process flow used to fabricate the photonic crystal laser is shown schematically below in Figure 14.

**Figure 14:** Process flow used to fabricate the electrically-activated photonic crystal nanocavity laser.

1. The first processing step is to spin a 300 nm thick layer of hydrogen silsesquioxane (HSQ) on the structure depicted in Figure 13(a).
2. Next, electron-beam lithography is used to define the upper waveguide in the HSQ (green), as shown after development of the HSQ.

3. In the next step reactive ion etching (RIE), using CH$_4$/O$_2$ gas chemistry, is used to etch through the InGaAlP (red) layer, defining the upper waveguide. While the final waveguide will be 500 nm in width, here it is left wider, 700 nm, to facilitate alignment of the second mask in step 5.

4. The remaining HSQ is now removed from the sample by ashing with CF$_4$. 
5. Another 300 nm layer of HSQ (green) is spun on the sample, after which electron-beam lithography is used to pattern the lower waveguide as well as the holes. Also, the wider upper waveguide can now be trimmed down to its final width.

6. In this step, the InGaAlP (red) layer is etched using the same CH$_4$/O$_2$ RIE process that was used in step 3. The RIE process also etches the holes into the top waveguide, forming the upper photonic crystal.

7. Next, a BCl$_3$ RIE step is used to etch through the two AlGaAs (grey and blue) layers, defining the lower waveguide and etching the holes to form the lower photonic crystal.
8. Again, a CF$_4$ ash is used to remove the remaining HSQ from the sample.

9. The AlGaAs (gray) contact pad must be recessed to expose the lower p-doped material, since the contacts must be on either side of the quantum dot active layer. After spinning resist, a photolithography step will open a space above the contact. A reactive ion etch can then be used to etch down to the p-doped AlGaAs region, and the resist removed.

10. To prepare for the wet etch in step 11, photoresist (yellow) is spun onto the sample, and two parallel lines are patterned using photolithography. The wet etch will undercut the upper waveguide, isolating it and ensuring that all light and current traveling in that direction flow in the InGaAlP (red), and not in the lower AlGaAs (grey).
11. An H$_2$SO$_4$/H$_2$O$_2$/H$_2$O wet etch is now used to remove the exposed AlGaAs (grey). The AlGaAs will be preferentially etched over the InGaAlP (red), thus minimizing the etch damage to the upper waveguide. The remaining photoresist will then be removed.

12. Next, the lower AlGaAs (blue) layer is oxidized, lowering the refractive index and thus optically and electronically isolating the laser from the substrate.

13. Finally, metal contacts are added to the two pads. Much like step 9, photoresist will be spun, and photolithography will open spaces above the two contacts. Metal can then be deposited, and the photoresist lifted off, leaving metal only on the contact pads.
Upon completion of the final step, the addition of metal contacts, the laser will be characterized. A voltage will be applied to the two contacts, and a sensitive detector apparatus will be used to characterize the emitted light. Characterization will involve electroluminescence measurements, to determine the wavelength of laser emission, and also output power versus input current, to determine the efficiency of the device.

Since the fabrication process is still being investigated, in the future some steps may be altered. The fabrication steps that have been completed will be discussed on a step-by-step basis in Section IV, and the steps that must still be completed to finish the device will be discussed in Section V.
IV: Discussion and Results

i) HSQ

Hydrogen Silsesquioxane (HSQ) was the resist used at the start of the electrically-activated photonic crystal laser process, detailed in Section III. HSQ, a spin-on glass, has a general chemical formula of (HSiO$_{3/2}$)$_m$, and initially has the cage molecular structure shown in Figure 15 (a) [10]. When exposed to an electron-beam, the Si-H bonds in the HSQ disassociate, causing the cage structure to rearrange into a network structure, as depicted in Figure 15 (b). The rearrangement hardens the HSQ, such that following a one hour CD-26 development the exposed portions remain while the unexposed portions are removed. HSQ behaves as a negative resist, and also forms a film durable enough to withstand etching, meaning that HSQ acts as both a resist and an etch mask. Many resists are not durable enough for use as an etch mask, making HSQ very efficient for the photonic crystal laser process. HSQ also allows resolution of sub-20 nm features; sufficient for the laser described herein [9].

![Figure 15: The chemical structure of HSQ, let R = H: (a) cage form, (b) network form. [10]](image)

The first step for using HSQ in the laser process was determination of the ideal layer thickness. The HSQ was required to be thick enough to act as a hard mask for the
methane and BCl₃ etches, but thin enough to allow for alignment of the second mask. A thickness of 300 nm provided a good compromise between these two constraints. Two options are available for spinning HSQ to achieve a thickness of 300 nm. FOX®-14 from Dow Corning, if left undiluted, will spin on at about 300 nm. Alternatively, the thicker FOX®-16, which spins on at about 500 nm, can be diluted with methyl isobutyl ketone (MIBK) in order to lower its layer thickness.

Experiments were conducted diluting FOX®-16 HSQ with MIBK in an attempt to reduce the layer thickness to the desired 300 nm. Adding different amounts of MIBK to the HSQ effectively altered the thickness of the film, but the mixing process also presented new sources of contamination. Spinning FOX®-14 at 2500 rpm for 60 seconds yielded HSQ thicknesses of approximately 300 nm, and provided a clean and repeatable process. Table 1 summarizes the thicknesses of HSQ applied with different concentrations of MIBK and at different spin speeds.

<table>
<thead>
<tr>
<th>HSQ</th>
<th>Spin Speed (rpm)</th>
<th>HSQ:MIBK Ratio</th>
<th>Thickness (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fox-16®</td>
<td>3600</td>
<td>1:0</td>
<td>500</td>
</tr>
<tr>
<td>Fox-16®</td>
<td>3600</td>
<td>1:1.5</td>
<td>175</td>
</tr>
<tr>
<td>Fox-16®</td>
<td>3600</td>
<td>1:1</td>
<td>210</td>
</tr>
<tr>
<td>Fox-16®</td>
<td>3600</td>
<td>2:1</td>
<td>250</td>
</tr>
<tr>
<td>Fox-14®</td>
<td>3600</td>
<td>1:0</td>
<td>270</td>
</tr>
<tr>
<td>Fox-14®</td>
<td>2500</td>
<td>1:0</td>
<td>300</td>
</tr>
</tbody>
</table>

Table 1: Measured HSQ thicknesses for different types of HSQ, HSQ:MIBK ratios, and spin speeds. The spin time was 60 seconds in all cases.
After spinning, two hot plate bakes were utilized to cure the HSQ. The first was two minutes long at 150° C, and the second was two minutes long at 220° C. Figure 16 shows a cross-sectional view of the resulting 300 nm layer of HSQ that was used in the laser process.

![Figure 16: SEM of the 300 nm thick layer of Fox-14® HSQ used in the laser process.](image)

**ii) Electron-Beam Lithography**

After applying HSQ, electron-beam exposure was carried out in the Scanning Electron-Beam Lithography Laboratory. The VS-26 Scanning Electron-Beam Lithography tool was used, and is shown in Figure 17. The VS-26 uses lenses, deflection plates, and apertures to focus a beam of electrons that are emitted from an electron gun. The spot size of the focused beam can be as small as 40 nm. The beam is deflected by electric and magnetic fields to write individual pixels. Since the scanning fields can only deflect the electron beam to a certain degree, large patterns are sub-divided into smaller
fields, 245.76 μm squares for the laser process, which are written individually and ‘stitched’ together to form the entire pattern. A laser-interferometer controlled stage is used to move from field to field [11].

Note: There is a molybdenum "heat shield" above each of the apertures on the VS-6 column.

Figure 17: Schematic of the VS-26 electron-beam lithography tool [12].
Two lithography steps using the VS-26 are necessary for the successful completion of the laser. The mask for the first step has five separate, horizontal (x-direction) waveguides with contact pads at one end. The second mask, which is aligned on top of the first, has five horizontal waveguides with contact pads, each of which in turn intersects a vertical (y-direction) waveguide. The vertical waveguides also have contact pads at one end. In addition, the second mask contains circular holes that are used to create the one-dimensional photonic crystals. The two masks are depicted in Figure 18, and will pattern the photonic crystal laser structure shown in Figure 9.

1) First Mask Level, Defining Horizontal Guides and Contact Pads  
2) Second Mask Level, to be Aligned on Top of the First, Defining Vertical Guides, Contact Pads, and Photonic Crystal Holes  
3) Close Up of the Intersection of the Two Guides, Where the Holes will be Patterned

**Figure 18:** Depiction of the two electron-beam lithography masks used to fabricate the photonic crystal laser. Notice that there are fewer holes on the right side, allowing for the laser emission.

After the electron-beam lithography write, the samples are developed in Microposit® MF CD-26 for one hour. SEM images from the first electron-beam lithography step are shown in Figure 19. In Figure 19 (a), a view of the five contact pads patterned in HSQ is shown. The contact pads are 100 µm square, and a waveguide connected to one of the pads is visible. In (b), (c), and (d), magnified views of a
waveguide attaching to one of the contact pads are shown. The connection between pad and waveguide will eventually let current flow to the nanocavity, powering the device.

Figure 19: SEM images of (a) the five contact pads in HSQ from the first lithography step, (b) and (c) the contact pad and waveguide, and (d) a magnified view of the intersection of a contact pad with a waveguide.

SEM images of the HSQ structures patterned by the second electron-beam lithography and development steps are shown in Figure 20. The two contact pads are visible, along with the intersecting waveguides. At the intersection of the waveguides are the holes that will form the photonic crystals. The holes are not well formed; optimizing the dose should improve their size and shape. A benefit of photonic crystals is that there is flexibility in the exact size and shape of the periodic air holes – therefore, even without perfectly formed holes the device is anticipated to work.
Stitching errors that occurred during the exposure were problematic during the electron-beam lithography step. Stitching errors occur when individual fields are misaligned with respect to each other; the waveguides in the photonic crystal laser are of sufficient length to require multiple fields to be stitched together. Stitching errors can be due to miscalibration between the VS-26 field size and the actual size measured by the laser interferometer, a pitch or yaw in the stage, stage position detection problems, thermal expansion of the system, or drifts in electrical sources [13]. Figure 21 shows SEM images of stitching errors in the waveguides after the electron-beam write step. In the first electron-beam exposures, the stitching errors were around 1 μm, as shown in
Figure 21 (a). With improved calibration and alignment the stitching errors were first reduced to about 200 nm, as shown in Figure 21 (b), and eventually became unnoticeable.

Aligning the second mask to the structure patterned by the first mask also presented a problem during the electron-beam lithography step of the photonic crystal laser process. Since the imaging contrast between the upper InGaAlP waveguides and the underlying AlGaAs is low, the alignment marks on the first mask are very important. The marks are used to find the proper location for exposure with the second mask. The original alignment marks used in the laser process were not of the ideal size, nor in the ideal location, and led to misalignments such as those shown in Figure 22. By adding larger and easier to see alignment marks on the edges of the mask, and by placing smaller alignment marks near the structures right at the corners of the fields that were written, the alignment was greatly improved to within the tolerances of the process.

Another problem that was encountered was that the air holes used to form the photonic crystals were not always present in the HSQ after development. The 225 nm holes should be easily visible in Figure 22, but instead they do not exist. It is possible
that noise in the system during the electron-beam write caused the holes to be ill-defined, but that is unlikely due to their size. Another possibility is that the stigmation was incorrectly set during the electron-beam lithography step, which again could affect the definition of the holes to the point where they were not noticeable after development. The electron gun in the VS-26 was also nearing the end of its lifetime at the time the lithography in Figure 22 was carried out, and it may be that the electron gun was simply not capable of consistently exposing small features accurately. Finally, the HSQ used in the process was nearing its expiration date at the time the writes in Figure 22 were done, and the resolution may have degraded. When a new bottle of Fox-16 HSQ was used, very faint holes resulted, implying that the problem was not the age of the HSQ. The most likely explanation for the poor hole quality was that the electron-beam dose was wrong, or the electron gun was simply unstable. The existence of ill-defined holes when the thicker Fox-16 was used may imply that the dose was the problem.

Figure 22: SEM images showing slight misalignment of the HSQ from the second electron-beam lithography step on top of the waveguide patterned in the first lithography step.

HSQ does not adhere well to certain materials. GaAs and AlGaAs substrates, for example, must be coated with an adhesion promoter, often SiO₂, before the HSQ can be
applied. Adhesion to InGaAs and InGaAlP is good, so no adhesion promoter was used in the photonic crystal laser process. Occasionally an adhesion problem does occur, however, due to an unclean or otherwise abnormal sample surface, or possibly an error in the HSQ spinning/baking process. The problem was very rare, and was therefore not studied in depth. Example SEM images of HSQ waveguides that did not adhere to the sample surface are shown in Figure 23.

![Figure 23: Examples of crossed waveguide patterns in HSQ that have moved during development due to poor adhesion to the sample surface.](image)

iii) Reactive Ion Etching

Reactive ion etching (RIE) was used in the photonic crystal laser process to define the waveguides that were patterned in HSQ by electron-beam lithography. RIE is commonly used for waveguide processing because it is capable of producing anisotropic etches with very good sidewall quality. Two different RIE tools were used in the laser process, but they were both of the standard parallel plate variety. An example of a parallel plate reactive ion etching system is shown in Figure 24.
In the parallel plate geometry, gases flow into an evacuated chamber, and are then sparked with an RF source, converting some of the gas molecules into ions. The sample to be etched sits on an electrode, and a bias between that and an upper electrode serves to accelerate the ions towards the sample. Reactive ion etching occurs by means of two mechanisms, chemical and physical etching. Chemical Etching involves reactive neutral species, and often times free radicals from the plasma, striking and interacting with the surface of the wafer via a chemical reaction. The byproduct of the reaction is typically a volatile species, which will vaporize and expose more of the wafer to be etched. The chemical etching component is similar to wet etching, and is likewise very selective, but also isotropic. Physical etching is opposite in the sense that it is not very selective, but it is an anisotropic process. Physical etching occurs when ions in the plasma are accelerated by the electric field, strike the wafer, and sputter off surface atoms. Most RIE processes use a combination of chemical and physical etching to achieve selective, anisotropic etches.
Two types of reactive ion etches are used during fabrication of the photonic crystal laser. The first is a methane (CH\text sub{4}) etch of InGaAlP. The methane etch is 15 minutes long using 15/30 sccm of CH\text sub{4}/H\text sub{2}. While methane is the primary etchant, adding H\text sub{2} results in improved anisotropy due to hydrogen passivation of the sidewalls. The pressure used in the methane etch is 5 mT, the auxiliary voltage is 110 V, and the DC bias is 680 V. The second RIE step is a 10 minute etch of AlGaAs with 15 sccm BCl\text sub{3}. The BCl\text sub{3} etch uses a pressure of 5 mT, 100 V auxiliary, and a 635 V DC bias. The auxiliary voltage is read on a separate meter attached to the RIE system used, and serves as a check to insure the accuracy of the DC bias voltage reading.

After the first electron-beam lithography step, the methane etch is used to pattern the upper waveguide into the InGaAlP layer as shown in Figure 25. Methane etching of InP-based materials, however, results in polymer formation. The polymer coats the sample and chamber, and must be removed before the process can continue. An O\text sub{2} clean is conducted after the methane etch to remove the polymer. The clean is 10 minutes long, using 20 sccm of O\text sub{2} at a pressure of 10 mT, 100 V auxiliary, and a 635 V DC bias.

![Figure 25: HSQ (green) is used as an etch mask during the methane etch of InGaAlP (red) to define the upper waveguide from the structure.](image)

The electron-beam write resulted in well defined patterns in the HSQ. SEM images of the developed HSQ before etching are shown in Figure 26. While the quality
of the HSQ was acceptable before etching, however, it was seriously degraded by the combination of methane etching and oxygen cleaning. Figure 27 is a SEM image of the HSQ and waveguide after the methane etch. The HSQ has sloped, rough sidewalls, which implies that the InGaAlP waveguide being defined has rough sidewalls as well.

Figure 26: SEM images of waveguides patterned in HSQ before etching.

Figure 27: SEM image of the HSQ and InGaAlP waveguide after the methane etch.
The sloped HSQ sidewalls are more problematic after the oxygen cleaning step. The oxygen appears to sputter the remaining HSQ, as shown in Figure 28. While the oxygen cleaning step should not have a detrimental effect on the InGaAlP, having the HSQ thinned at the edges after the oxygen clean is unacceptable. After the second electron-beam lithography step, a 10 minute BCl₃ etch directly follows the methane etch. The HSQ must have a uniform layer thickness great enough to withstand the BCl₃ etch; the HSQ layer in Figure 28 does not exhibit the required uniformity.

Figure 28: SEM images of the HSQ and InGaAlP waveguide after the methane etch and oxygen clean.

In order to improve the resistance of the HSQ to the methane etch and subsequent oxygen clean, methods of increasing the hardness of HSQ were investigated. Upon electron-beam exposure, Si-H bonds in the HSQ disassociate, and the cage structure becomes a network structure, as shown in Figure 15. Networking causes the HSQ to harden. However, electron-beam lithography does not fully disassociate the Si-H bonds, meaning that the HSQ does not become fully networked, and therefore not fully hardened. Two common methods to further disassociate Si-H bonds after electron-beam lithography and development are ashing the developed HSQ with oxygen and curing the HSQ at high temperatures in an oven. Both methods cause Si-H bonds to break and Si-O
bonds to form, increasing the degree of networking and hence the hardening of the HSQ. Figure 29 shows experimental results relating the hardness of HSQ to its Si-H/Si-O ratio; as the ratio decreases, hardness increases.

![Graph showing HSQ hardness versus its Si-H/Si-O bond ratio](image)

**Figure 29:** HSQ hardness versus its Si-H/Si-O bond ratio [15]

Oxygen ashing is less damaging to the laser structure than curing at high temperatures, so ashing was the hardening method first investigated for use in the photonic crystal laser process. Four different ashing processes were investigated. First, a 700 nm wide sample waveguide structure was simply etched after development without any ashing. The other three 700 nm wide sample waveguides were ashed in a 20% O₂/He mixture. The first sample was ashed for 10 minutes at 100 W, the second for 15 minutes at 100 W, and the third for 10 minutes at 200 W. The previously described methane etch and oxygen cleaning step were then performed, and the resulting waveguides were viewed using the SEM, as shown in Figure 30.
Figure 30: SEM images of HSQ-covered waveguides after the methane etch and oxygen clean. In (a) no oxygen ashing was done, (b) was ashed for 10 minutes at 100 W, (c) was ashed for 15 minutes and 100 W, and (d) was ashed for 10 minutes at 200 W. Notice there is very little, if any, difference between the pictures, which shows that oxygen ashing was unable to increase the HSQ's resistance to the methane etch.

Unfortunately the results shown in Figure 30 suggest that ashing the HSQ with oxygen did little to improve its durability under the methane etch and subsequent oxygen cleaning step. There were no noticeable differences between the HSQ samples that had been ashed, shown in Figure 30 (b), (c), and (d), and the sample that was not ashed shown in Figure 30(a). In addition, the InGaAlP did not etch as well on the ashed samples. The etches did not go to the expected depth, and often times the etches were inconsistent – both problems that were not encountered with samples that were not ashed. Diffusion of substances out of the HSQ and into the sample during ashing was also a concern. In the
case of the photonic crystal laser, diffusion could alter the waveguide properties.

Whether or not this was occurring during the laser process was not determined, although no sign of diffusion was seen in SEM images. Since ashing was ineffective and therefore not used in the process, the diffusion problem was not studied further.

Since ashing did not have the desired hardening effect on the HSQ, curing the material was investigated. After electron-beam lithography and development, the samples were placed into an oven at 400°C and baked for one hour. The samples were then etched for fifteen minutes with methane, followed by the ten minute oxygen clean, as was done throughout the process. A SEM image of the result of the etch is shown in Figure 31 (b); for comparison an image of the resulting etch using un-cured HSQ is shown in Figure 31 (a).

![Figure 31: SEM images of HSQ covered waveguides after the methane etch and oxygen clean when (a) no curing step is done and (b) when the sample is cured for one hour at 400°C. Again, there is little difference between the cured and un-cured samples.](image)

Curing, much like ashing, appeared to have little success in increasing the HSQ’s resistance to the methane etch and oxygen cleaning step. The HSQ did appear to hold up slightly better in Figure 31 (b) than in (a), but the sidewalls of the InGaAlP waveguide under the HSQ still appear to be very rough. Surface roughness of this magnitude is
unchacceptable for waveguide sidewalls. Since hardening the HSQ was ineffective, changing the etch chemistry and power to improve the resistance of the HSQ is the only way for it to be effective as an etch mask in the laser process.

The methane etch at 110 V auxiliary and 680 V DC bias led to the sloped HSQ sidewalls seen in Figure 27. Residual HSQ that was sputtered from the mask may have adhered to the sidewalls of the InGaAlP, causing roughness and resulting in an etch that was less anisotropic. Sloped sidewalls are more prone to physical sputtering than vertical sidewalls, and so the oxygen clean further sputtered the HSQ. In an attempt to remedy the sputtering problem, the methane etch and oxygen clean were carried out at a reduced power level – 80 V auxiliary and 535 V DC bias for each. Lower power was expected to decrease the physical sputtering, keeping the HSQ from being removed from the corners of the etch mask layer, leading to improved sidewalls. An image of a HSQ-covered waveguide, following a 21 minute etch with 15/30 sccm of CH\textsubscript{4}/H\textsubscript{2} at 5 mT pressure and then a 10 minute clean with 20 sccm of O\textsubscript{2} at 10 mT bias, is shown in Figure 32.

**Figure 32:** SEM image of an HSQ-covered waveguide after a low-powered methane etch and oxygen clean.
In Figure 32, the HSQ is sputtered significantly after etching approximately 100 nm into the InGaAlP layer. If the etch had proceeded through the entire 200 nm InGaAlP layer, the HSQ would have been in worse condition than it was following the high powered etches used previously. Using lower RF power to protect the HSQ during the laser process etch steps was therefore determined to be ineffective.

Numerous methods for obtaining smooth, anisotropic InGaAlP waveguides using a HSQ hard mask have been tested, and none have proven effective for the photonic crystal laser process. While HSQ would be an ideal material to use in the process, it does not appear to be able to provide the required sidewall quality when being etched with methane. The next option is to use PMMA to pattern a SiO$_2$ hard mask. The use of PMMA will be discussed later in this section.

HSQ can still be utilized for the laser process, however. In the first electron-beam lithography write, the waveguides and contact pads are left larger than necessary to facilitate alignment of the second mask during the second lithography step. The InGaAlP layer will then be ‘trimmed’ to size, as shown in Figure 36, meaning that the sidewall quality of the waveguides after the first etch is unimportant. Since the sidewall quality does not matter, HSQ can still be used to simplify the first electron-beam lithography step. Only in the second step, when sidewall quality becomes very important, will PMMA be needed.

Once the upper waveguide was patterned by the first electron-beam lithography step and etched, the HSQ was removed using a CF$_4$ reactive ion etch. Different powers and etch durations can be used for this step, but in general the two options are to use higher power for a shorter time or lower power for a longer time. The RF power of the
Plasmatherm RIE that was used for CF$_4$ etching can be increased significantly by placing a glass slide over the hole in the plate on which the sample resides. The hole serves as a path to ground; since the glass slide impedes that path, it forces the RIE system to increase the power in order to maintain the DC bias set by the user. With the slide in, etching was performed for 10 minutes at 300 V DC bias and 10 mT pressure. The power was near 500 W. Without the slide, the etch was carried out for 20 minutes, again at 300 V DC bias and 10 mT. The power in this case was much smaller, around 200 W. SEM images in Figure 33 compare the results of these two methods.

![SEM images](image)

**Figure 33**: SEM images of the upper InGaAlP waveguide after the HSQ is removed by (a) the higher powered CF$_4$ process and (b) the lower powered CF$_4$ process. Notice the sidewall roughness due to the inability of HSQ to withstand the methane etch.

Both the CF$_4$ processes remove the HSQ effectively, but the etches at higher power seem to result in more damage to the waveguide, leading to rounded edges. The waveguides have slightly sloped sidewalls after the methane etch, and are thus susceptible to sputtering during this step. The sputtering effect is more noticeable at higher powers, and is probably what caused the rounded edges. Therefore the CF$_4$ etch at lower power, with no glass slide in the RIE system, was used in the process for 20 minutes at 300 V DC bias and 10 mT pressure.
SEM images of the contact pads and waveguides from the first electron-beam lithography step are shown in Figure 34. The InGaAlP layer has been etched, and the HSQ has been removed. The contrast between the InGaAlP contact pad and waveguide and the surrounding AlGaAs layer is low. The contact pads can be seen by eye under the proper lighting, but when viewed from directly above it can be difficult to discern the structures. The lack of contrast makes the second electron-beam lithography step difficult, since the structures must be discernable from above after being covered by layers of SiO₂ and PMMA. The fact that the sidewalls are rough actually helps the waveguide and contact pad stand out in Figure 34.

![Figure 34](image.png)

**Figure 34:** Contact Pad and waveguide after the HSQ is removed following the first electron-beam lithography write and etch step.

Once the upper waveguide is defined using the methane etch, and the HSQ layer removed, a 150 nm thick layer of SiO₂ is deposited on top of the sample. A 200 nm thick layer of 2% PMMA is then spun onto the SiO₂ at 2500 rpm for 60 seconds. Next, the PMMA is baked for thirty minutes at 180°C. After baking, electron-beam lithography is used to pattern the underlying waveguide and the holes within the waveguides that form the photonic crystals. Since PMMA is a positive resist, unlike HSQ, the parts that are
exposed are removed during development. Development first involves a one minute dip in a solution that is two parts isopropyl alcohol (IPA) and one part MIBK. The sample is then dipped for one minute into pure IPA, and is finally sprayed off with IPA and dried. The result is that the entire sample is covered with PMMA, except where the waveguides reside. An SEM image of the crossing waveguide pattern in PMMA is shown in Figure 35. The PMMA cylinders in the middle of the waveguide will be used to form the photonic crystal holes.

![SEM image of the pattern defined by the second electron-beam lithography write in PMMA. The waveguides are areas where the PMMA has been removed, while the circles in the waveguides are small cylinders of PMMA which will eventually be used to form the photonic crystal holes.](image)

The SiO$_2$ in the photonic crystal laser process must be able to hold up to a 15 minute methane etch, followed by a 10 minute oxygen clean, which is then followed by a 10 minute BCl$_3$ etch. Therefore a SiO$_2$ layer thickness of at least 150 nm is necessary. During the second electron-beam lithography step, however, the underlying waveguide could not be seen; therefore alignment could not be done. The combination of 150 nm of
SiO₂ and the 200 nm top layer of PMMA was not transparent and the 200 nm InGaAlP waveguides were not visible.

PMMA is transparent; hence the resist was not likely to have been the problem. Although the waveguides were visible optically, the SiO₂ thickness appears to have prohibited alignment in the SEM. The SiO₂ thickness cannot be reduced without detrimentally affecting the etch resistance, and the InGaAlP waveguide thickness cannot be increased without affecting the desired properties of the photonic crystal laser.

A potential solution to the waveguide-to-waveguide alignment problem is to deposit small gold alignment marks within each electron-beam field after the first electron-beam lithography step. The gold is easier to view through the PMMA and SiO₂ layers than the existing alignment marks, and is expected to allow for alignment of the second mask. In order to deposit the gold, PMMA must be deposited onto the sample after the HSQ is removed following the first etch step. Electron-beam lithography can then be used to pattern small marks at the corners of the electron-beam fields. Once the PMMA is developed, resist will cover the entire sample with the exception of the marks that were patterned. Gold is then deposited, followed by PMMA removal. The PMMA lift-off process will leave only the gold alignment marks.

Gold alignment marks will enable the second mask to be aligned to the waveguide defined by the first lithography step and subsequent etch. Once the pattern is aligned and written, the PMMA can be developed to create the crossed photonic crystal waveguide structure shown in Figure 35. Nickel can then be deposited onto the sample for a second lift-off process. After the PMMA is removed, the nickel is layered on the SiO₂ only in the places where the waveguides were patterned. The nickel is then used as a mask to
etch the SiO₂, which in turn will serve as a hard mask for the InGaAlP and AlGaAs etches. A general depiction of these steps is shown in Figure 36.

Figure 36: SiO₂ (light blue) is deposited onto the sample, and then PMMA (yellow) is applied. After electron-beam exposure and development, the PMMA covering the waveguides is removed. Nickel (silver) is then evaporated onto the sample. The PMMA is removed, leaving nickel only over the waveguides. The nickel is then used as a mask to etch the SiO₂, and is removed with a wet etch. The result is a SiO₂ mask in place for the following methane and BC₃ etches.

After the crossed waveguide pattern is successfully defined in SiO₂, two etches are required to define the rest of the laser structure. First, a methane etch identical to the first is used to trim the upper InGaAlP waveguide to size and to etch the holes to form the top photonic crystal. The methane etch is 15 minutes using 15/30 sccm of CH₄/H₂. The pressure used is 5 mT, the auxiliary voltage is 110 V, and the DC bias is 680 V. The second etch is a 10 minute etch of AlGaAs using 15 sccm BCl₃. The BCl₃ etch is performed at 5 mT, 100 V auxiliary, and a 635 V DC bias. The BCl₃ etch will define and etch holes into the AlGaAs waveguide, forming the photonic crystal in the waveguide that is orthogonal to the top waveguide. An illustration of this step is shown in Figure 37.
With SiO$_2$ (light blue) as a mask, a methane etch is used to trim the InGaAlP (red) waveguide to size and to etch the holes. Next, a BCl$_3$ etch is used to define the lower AlGaAs (grey) guide and etch holes. The two etches complete the photonic crystals.

During the second etching step, cleaning becomes very important. Polymer formation during the methane etch can hamper the following BCl$_3$ etch. The polymer will coat the sample, and depending on its thickness, can act as an etch mask, causing the BCl$_3$ to etch nonuniformly. The result is very rough sidewalls, which will scatter light in the waveguide. An oxygen cleaning step in between the methane and BCl$_3$ etches was insufficient to solve the polymer problem. Figure 38 shows the results of the methane etch, followed directly by a 10 minute oxygen clean, followed by the BCl$_3$ etch. The oxygen clean used 20 sccm of O$_2$ at 10 mT pressure, 100 V auxiliary, and a 635 V DC bias. A SiO$_2$ mask was used for the etch. The SEM image shows serious sidewall roughness and “grass” in the trenches, caused by polymer particles hindering or masking the etch.
Various cleaning measures were tested in an attempt to improve the quality of the waveguides. Eventually, a combination of cleaning steps that gave satisfactory results was found. More specifically, after the methane etch, the sample was removed and the chamber scrubbed. The sample was then placed back into the chamber, and a ten minute oxygen clean was carried out, as described above. Next the sample was again removed, the chamber scrubbed, and a dummy GaAs wafer placed in the RIE. The GaAs wafer was then etched with BCl₃ for a half hour to ‘recondition’ the chamber. Finally, the GaAs wafer was removed, the chamber scrubbed for a third time, and the laser sample put back in and etched with BCl₃. The cleaning process yielded good results, as shown in Figure 38. The lower AlGaAs layer is still rough, but the important upper AlGaAs and InGaAlP layers, which will eventually guide the light, have smooth sidewalls. The sidewall quality is much better with the SiO₂ mask as shown in Figure 39 than it was with the HSQ mask that was used earlier in the process.
Figure 39: SEM image of waveguides when a combination of chamber scrubbing, oxygen cleaning, and sacrificial etching is done between the methane and BCl₃ etches. Notice the dramatic improvement in sidewall roughness compared to the result shown in Figure 38.
V: Future Work

While an excellent start has been made on the photonic crystal laser fabrication process, a few important steps must still be completed in order to fabricate a working device.

First, the intersecting waveguide structure, with photonic crystal holes, must be fabricated as shown in Figure 37. Alignment of the second mask to the waveguide from the first lithography step and etch is very important, and should be made possible through the use of the gold alignment marks described in Section IV. The second etch step, which uses methane and BCl$_3$ to etch the one-dimensional photonic crystal waveguides, must then be used to fabricate waveguides with smooth sidewalls and well-defined photonic crystal holes. Patterning holes in PMMA was shown to be effective in Figure 35, and using a SiO$_2$ mask and combination of cleaning steps to obtain waveguides with good sidewalls was shown in Figure 39.

Once the intersecting one-dimensional photonic crystal waveguides have been patterned, four major fabrication steps must still be completed before the device can be tested.

Investigation of a fabrication step to etch the AlGaAs contact pad is needed to expose the p-doped layer lying below the quantum dots. The etch to expose the p-doped region is necessary, so that contact to the p-n junction enables forward biasing when a voltage is applied to the pads. A schematic of this step is shown in Figure 40.
Figure 40: The AlGaAs (gray) contact pad must be etched down to below the quantum dot layer, so that when a voltage is applied to the pads, the p-n junction surrounding the quantum dots is forward biased, producing light.

To complete this step, photoresist must first be applied onto the sample. The ideal resist will be negative and have good etch resistance properties. After spinning resist, a photolithography step will cover the AlGaAs contact pad. Upon development, the resist will be removed from the contact pad, to enable etching while protecting the rest of the sample. A BCl$_3$ reactive ion etch will then be used to etch the AlGaAs and the quantum dot layer. The RIE step will be short, since only 100 nm of AlGaAs must be etched. The remaining resist is then removed.

The next step requires an undercut to ensure that no current can flow, or light can propagate, through the AlGaAs layer that lies beneath the upper InGaAlP waveguide. The undercut will ensure that all current flows through the laser nanocavity. Otherwise, the voltage drop in the device, and thus light generation, could occur outside of the cavity, seriously hampering the device. A depiction of this step is shown in Figure 41. A thick layer of negative photoresist will be applied to the sample. A grating, or simply a mask with two horizontal lines, can then be used to pattern the resist. A wet etch that preferentially etches AlGaAs over InGaAlP will then be used to remove the AlGaAs layer underneath the upper waveguide. A sulfuric acid-based wet etch, H$_2$SO$_4$/H$_2$O$_2$/H$_2$O
should accomplish this. The AlGaAs should etch at a rate of about 500 nm/min, so the etch time will be short. The resist will then be removed.

![Image: A thick layer of photoresist is spun onto the sample, and photolithography is then used to define two parallel lines that intersect the upper waveguide just outside of the nanocavity. A sulfuric acid-based wet etch is then used to etch through the AlGaAs (gray) layer without harming the upper InGaAlP (red) waveguide. The photoresist is then removed.]

The third major step that needs to be completed is the oxidation of the lower AlGaAs layer, which is the blue layer in Figure 41. The upper AlGaAs layer, which makes up the bottom waveguide, is composed of Al\(_{0.3}\)Ga\(_{0.7}\)As. The Al\(_{0.3}\)Ga\(_{0.7}\)As is mostly gallium, and will be essentially unaffected by the oxidation step. The underlying AlGaAs layer, however, which is composed of Al\(_{0.9}\)Ga\(_{0.1}\)As, will be oxidized due to its high aluminum content. The wet oxidation process transforms the Al\(_{0.9}\)Ga\(_{0.1}\)As layer into Al\(_x\)O\(_y\), which has a refractive index of 1.6. Lowering the refractive index serves to confine the light effectively in the AlGaAs waveguide, which has an index of refraction of about 3.4, and optically and electrically isolates the laser from the substrate.

The final fabrication step that must be completed is a metallization step to create the contacts. The metallization step will likely proceed similarly to the step in which the lower AlGaAs contact was etched down to the p-doped material. Again, a negative photoresist will be spun onto the sample. Photolithography and subsequent development will serve to open up an area above the contact pads, while leaving the rest of the sample...
covered with resist. A metal can then be deposited onto the sample. The remaining resist will then be removed in a lift-off process, which will carry all the metal away except for that on the contact pads. This step is shown in Figure 42.

Figure 42: The final step in the laser process is to add metal contacts to the pads on the ends of the waveguides.

Once the laser has been fabricated, testing will begin. The testing phase will be challenging due primarily to the very small size of the device, and the low intensity of its output. A sensitive detector will be needed. The electroluminescence of the device will be measured, in order to characterize the wavelength of the output. Also, the output power versus input power will be measured to assess the efficiency of the device.
VI: Conclusion

The electrically-activated photonic crystal nanocavity laser described in this thesis represents a major potential improvement over the current technology. The use of a photonic crystal defect nanocavity allows the laser to be smaller and more efficient than standard semiconductor lasers using end-mirror defined cavities. The laser will also be more efficient from the power and chip design standpoints than optically-pumped photonic crystal lasers. The laser is electrically-activated and edge emitting, resulting in the emission of 1.3 μm light in the plane of the chip when a voltage is applied.

Demand for small, efficient lasers should increase in the near future as optical networks grow in popularity. The laser described in this thesis will fit this niche very well, as other photonic crystal devices have begun to fill niches in other important areas of photonics. In the future, photonic crystal technology will not only help increase the speed and efficiency of optical communications systems, but it will help improve the performance of many household electrical devices as well.
References


