

UNIVERSITY OF OTTAWA
DOCTOR OF PHILOSOPHY THESIS

**Design, fabrication and testing of novel
III-V waveguides architectures for
nonlinear integrated photonic applications**

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*A thesis submitted in partial fulfillment of the requirements
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Declaration of Authorship

I, Kaustubh VYAS, declare that this thesis, titled “Design, fabrication and testing of novel III-V waveguides architectures for nonlinear integrated photonic applications”, and the work presented in it are my own. I confirm that except where specific reference is made to the work of others, the contents of this dissertation are original and have not been submitted in whole or in part for consideration for any other degree or qualification in this, or any other university. This dissertation is my own work and contains nothing which is the outcome of work done in collaboration with others, except as specified in the text and Acknowledgements.

Kaustubh Vyas
July, 2022
Ottawa, Canada

Abstract

III-V semiconductors are compounds made of elements from groups III and V of the periodic table. Most of these materials exhibit a direct bandgap, which makes them suitable for light emission and detection. Furthermore, ternary and quaternary III-V semiconductors offer some freedom in adjusting their material compositions, which also allows one to modify their bandgap energies, refractive indices, and other optical properties. This quality makes such materials suitable for the monolithic integration of laser sources with passive optical devices and detectors on a single chip. For example, such integration is used in indium phosphide (InP) technology for large-scale photonic integration in optical communication networks. Commercial integrated photonic circuits' functionality can be augmented by the implementation of nonlinear optical devices, enabling all-optical signal processing, frequency conversion, and on-chip sources of quantum light.

This doctoral thesis focuses on design, fabrication, and testing of passive optical components based on III-V semiconductors. We explored various fabrication approaches for III-V nonlinear photonic devices. Among the III-V semiconductor platforms used in nonlinear photonics, we focused on AlGaAs as the most studied nonlinear optical platform, and InP and its quaternary derivatives as the most commercially developed platform. The fabrication processes for III-V photonic devices usually require the deposition of silica and chromium layers, and then three etch steps to etch the chromium, silica, and, finally, the III-V layer. In the thesis, we demonstrate a process which allows one to eliminate the chromium deposition and the associated etch step, thereby reducing the process complexity. We implemented this newly developed hard-mask process for etching numerous AlGaAs and InP photonic devices. This work was not only an important contribution to the University of Ottawa's cleanroom facility. The shared recipe can be used to recreate etch recipes for silica using soft masks like ZEP520a, PMMA, *etc.* at other similar university and research facilities around the world. The silica

mask created using this process was later used to fabricate InP/InGaAsP-based half-core-etched and nanowire waveguides, which were used to perform the first reliable measurement of the nonlinear refractive index coefficient n_2 of InGaAsP/InP waveguides.

We explored improved fabrication processes for AlGaAs waveguides, photonic crystals, and ring resonators. InP-based integrated optical devices are relatively difficult to fabricate because the etch byproducts are only volatile at elevated temperatures. Using a silica mask, we developed a very smooth etching process for InP waveguides with aspect ratios greater than 1:10. Suspended waveguide structures, where the guiding layer is surrounded by the air, are of great interest as they can exhibit large refractive index contrast for superior compactness and for achieving high intensity at low optical powers. We demonstrated fabrication process flows for creating suspended air-bridge structures in a 500-nm AlGaAs slab, which can be used in mid-IR sensing applications. The processes developed as part of this project cover a wide range of AlGaAs passive photonic devices such as waveguides, photonic crystals and ring resonators. Additionally, we demonstrated plasma etching selectivity improvements for AlGaAs etching using only a soft ZEP mask and were able to achieve a selectivity of 1:2.9. All these developments can be beneficial to other researchers working on III-V photonic devices.

We also completed the first theoretical study of third-harmonic generation in dispersion-engineered AlGaAs suspended photonic crystal waveguide. Most importantly, we introduced a reliable and efficient method for modelling higher-order modes in photonic crystal waveguides that is less computationally intensive and far more accurate compared to the 3D FDTD method. We also experimentally demonstrate guided modes lying above the light line in AlGaAs photonic crystal waveguides. In one of the addition projects, we experimentally demonstrate third-harmonic generation (THG) in Silicon Nitride waveguides.

In summary, this thesis presents details of the design and testing of different passive nonlinear III-V semiconductor photonic devices. In addition, this thesis presents the fabrication processes which can be used to reliably and repeatably fabricate photonic devices in these materials.

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List of Publications

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Dedicated to my biggest source of inspiration - Maa.

Chapter 1

Introduction

Photonics is the field of generation, detection, and control of photons in artificially structured devices. It enables the manipulation of the flow of light by means of specially designed artificial micro- and nanostructures that exhibit optical properties that are not commonly occurring in natural materials. Photonic devices and technologies find applications in areas such as optical communications, healthcare and medicine, defence and security, display, and imaging, and more[1]–[6]. The idea of photonic integration is similar to electronic integration where electronic chips or circuits can transmit electric signals. In a similar manner, photonic chips can emit, modulate route and detect optical signals thereby representing an optical equivalent to electronic chips.

1.1 Integrated Photonics

A few years after the invention of lasers in the 1960s, the idea of “laser miniaturization” and co-integration with other chip components was proposed, in which all the functionalities of a free-space optical setup, comprised of isolated bulk optical components, could be down-scaled and accommodated on an optical chip as small as $1\text{ cm} \times 1\text{ cm}$. This proposition is when the field of “integrated optics” started [7]. Thin film technology and guided wave optics formed the crux of integrated photonics. The first known integrated photonic waveguide was based on a ZnO sputtered thin film. Since then, several other material platforms such as glass, silicon, GaAs, InP, and more have been explored for integrated photonic circuits. Amongst all these materials, most of the passive integrated optics work has been done on the semiconductor platform silicon, which has been the workhorse of the semiconductor industry

due to its accessibility and low cost. Today, silicon represents a mature technology for integration of low-loss photonic devices such as waveguides, cavities, and resonators [8]–[10]. However, silicon has certain limitations specifically when used as a technology for photonic integration – the biggest one being its inability to emit light.

Bandgap energy is an important property of semiconductor materials. Most III-V semiconductors have a direct bandgap, meaning that the conduction band (CB) minimum and the valence band (VB) maximum correspond to the same carrier momentum (i.e., are vertically co-linear on an energy-momentum diagram, as shown in Fig. 1.1 (a)). Such an alignment allows for optical transitions that satisfy the momentum-conservation law [11]. In addition, direct-bandgap semiconductors can emit light by the process of radiative recombination. In contrast, silicon is an indirect-bandgap semiconductor (see Fig. 1.1 (b)), and radiative transitions would require a phonon to satisfy the momentum conservation. As a result, lasing is a highly inefficient process in silicon. Consequently, direct-bandgap semiconductor materials come into the picture as indispensable material platforms for active integrated photonic devices.

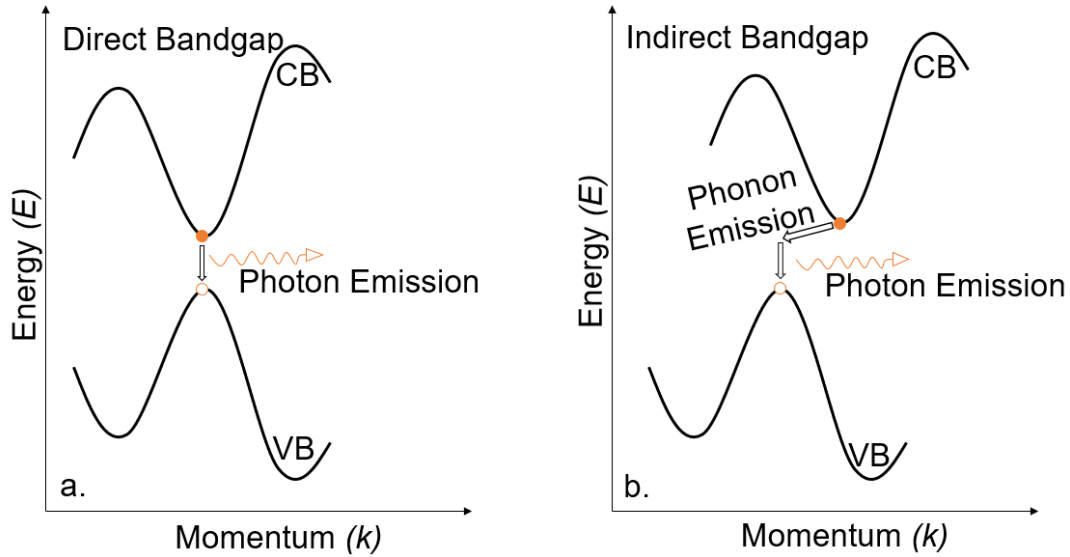


FIGURE 1.1: Band Diagram representation of (a) Direct-bandgap semiconductors such as GaAs; (b) Indirect-bandgap semiconductors such as Silicon. CB corresponds to conduction band and VB corresponds to valence band.

1.1.1 Guided-wave optics

Total internal reflection (TIR) is the basis of optical waveguiding. Explored earlier in optical fibers, this phenomenon was utilized to create compact optical waveguides and devices capable of confining and guiding light on a chip. The simplest waveguide arrangement with one-dimensional (1D) light confinement is a slab waveguide where a higher-refractive-index guiding layer (or core) is surrounded by lower-index claddings (see Fig. 1.2). Light can be coupled to the core layer and guided in it if its rays make an angle with the core-cladding interfaces greater than the critical angle determined by Snell's Law [12]. If this condition is satisfied, the light gets reflected back into the core and can travel through the core by multiple reflections at the boundaries between the high-index and low-index media.

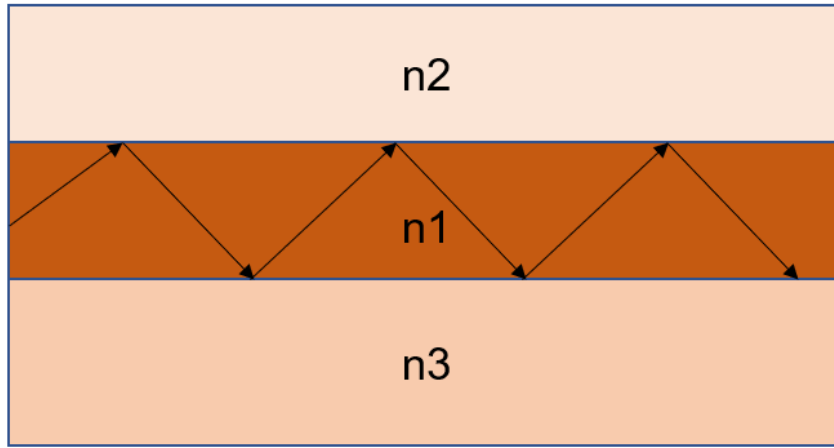


FIGURE 1.2: Schematic representation of TIR. n_1 , n_2 and n_3 are the refractive indices of the core, upper and lower claddings, respectively. The refractive index n_1 is greater than n_2 and n_3 .

The more practical form of waveguides in integrated photonics are the ones in which the light is confined in two dimensions. This is accomplished by geometrically defining two-dimensional (2D) ridge-like structures in the core and cladding layers by the process of lithography and etching. Based on these geometric structures, different types of waveguide structures can be defined like strip loaded waveguide, nanowire waveguide, suspended waveguide, etc [13].

Depending of the waveguide geometry and dimensions, an optical waveguide can host single or multiple guided modes. These waveguide modes are in essence solutions to Maxwell's equations. They can be found semi-analytically using effective index method [12] or numerically by using commercial software such as Ansys Lumerical MODE Solutions, which solves

the Maxwell's equation using a 2D cross-sectional mesh. Fig. 1.3 represents different modes or electric field distributions supported by a planar waveguide.

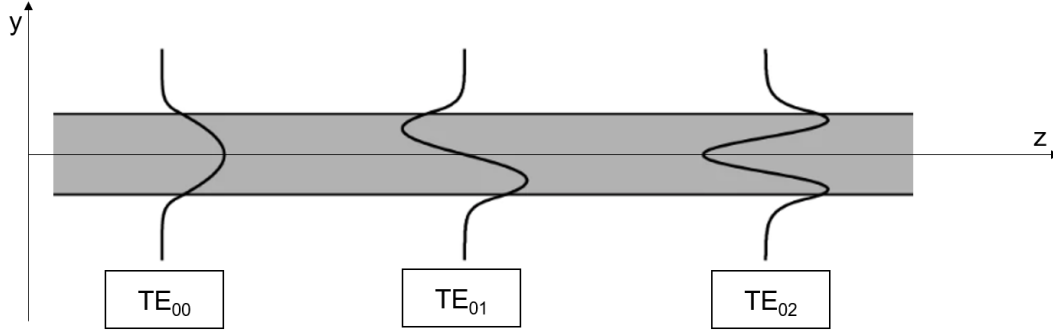


FIGURE 1.3: Field profile of waveguide modes inside a planar waveguide [14].

1.2 Nonlinear Optics

Nonlinear optics can be defined as the field studying light-matter interaction under high-strength applied optical fields [15]. When the incident light carries sufficient intensity, the optical material's polarization can exhibit nonlinear variations with the applied electric field strength. The relation between the material's polarization $P(t)$ and the applied electric field $E(t)$ strength can be described as:

$$P(t) = \epsilon_0 \left(\chi^{(1)} E(t) + \chi^{(2)} E^2(t) + \chi^{(3)} E^3(t) + \dots \right), \quad (1.1)$$

where $\chi^{(1)}$, $\chi^{(2)}$ and $\chi^{(3)}$ are the first-, second-, and third-order susceptibility terms. At the limit of low-intensity optical fields, only the first term on the right-hand side of Eq. (1.1) has significance, and the polarization scales linearly with the applied field strength.

The nonlinear optical interactions give rise to different optical processes. These can be majorly divided based on the $\chi^{(2)}$ processes called second-order nonlinear interactions and $\chi^{(3)}$ processes called third-order nonlinear interactions. Higher-order nonlinear optical interactions also exist and can be readily observed under certain conditions; however, $\chi^{(2)}$ - and $\chi^{(3)}$ -based processes represent the most common nonlinear optical interactions.

1.2.1 Second-Order Nonlinear Optical Processes

The second-order contribution to the nonlinear polarization leads to the effects which are called second-order nonlinear processes, or $\chi^{(2)}$ processes. Such nonlinear interactions only occur in noncentrosymmetric materials with the atomic or molecular unit structures lacking the center of inversion symmetry. This contribution can be represented as

$$P^{(2)}(t) = \epsilon_0 \chi^{(2)} E^2(t). \quad (1.2)$$

Considering two distinct incident electric fields $E_i(t) = E_i \exp(-i\omega_i t)$, where $i = 1, 2$, we can rewrite the equation as

$$P^2(t) = \epsilon_0 \chi^{(2)} \left(E_1^2 e^{-i2\omega_1 t} + E_2^2 e^{-i2\omega_2 t} + 2E_1^* E_2 e^{-i(\omega_1 + \omega_2)t} + 2E_1 E_2^* e^{-i(\omega_1 - \omega_2)t} + \text{c.c.} \right) + 2\epsilon_0 \chi^{(2)} (E_1 E_1^* + E_2 E_2^*). \quad (1.3)$$

The first two terms on the right-hand side of Eq. (1.3) represent the process of second-harmonic generation (SHG), also known as frequency doubling, where two input photons of the same frequency (ω_i) interact in a nonlinear medium to produce a single photon with twice the frequency ($2\omega_i$). The third and the fourth terms represent the process of sum-frequency (SFG) and difference-frequency generation (DFG), respectively. Finally, the last term represents optical rectification (OR) accompanied by zero-frequency (DC field) generation.

1.2.2 Third-Order Processes

Third-order processes happen in both centrosymmetric and noncentrosymmetric materials. The most common third-order effect is the Kerr effect, describing the intensity-dependent contribution to the overall refractive index of the optical material, which can be represented as

$$n = n_0 + n_2 I. \quad (1.4)$$

Here n_0 is the linear refractive index, and n_2 is the Kerr coefficient, which is the $\chi^{(3)}$ -related nonlinear coefficient. The Kerr coefficient can be represented as

$$n_2 = \frac{3}{4\epsilon_0 n_0 c} \chi^{(3)}, \quad (1.5)$$

where ϵ_0 and c correspond to the permittivity of free space and speed of light in vacuum respectively.

Some other third-order nonlinear optical processes are the third-harmonic generation (THG), four-wave mixing (FWM), self-phase modulation (SPM), and cross-phase modulation (XPM). These processes have many potential applications in all-optical signal processing, such as wavelength conversion and optical switching, as well as quantum-light generation [16]–[18]. Figure 1.4 gives a schematic representation of different $\chi^{(2)}$ and $\chi^{(3)}$ processes.

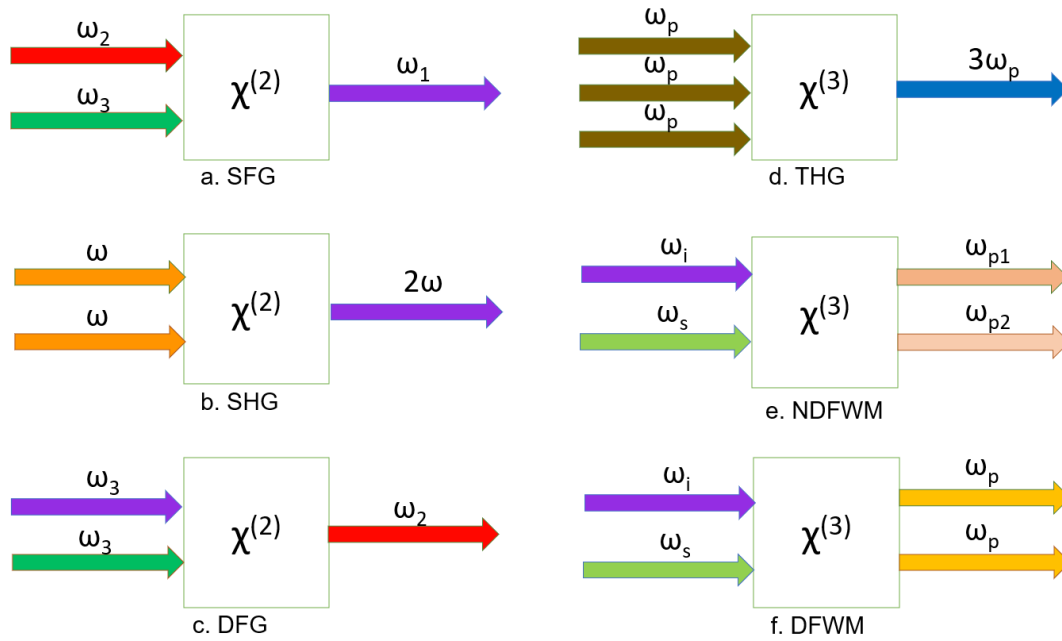


FIGURE 1.4: Schematic representation of $\chi^{(2)}$ and $\chi^{(3)}$ nonlinear optical processes.

The field of integrated and nonlinear optics has seen massive developments in the last two decades due to advancements in the nanofabrication tools, which facilitated the applications in a plethora of fields such as astronomy, medicine, defence, security, storage and quantum computing [19]–[22]. Nonlinear optics can augment the functionalities of current state-of-the-art optical devices. For instance, laser sources require a strong gain medium. However, there is no high-performing gain medium that exists for the wavelengths in the range of 510–560 nm, which is the spectrum of green light. Highly efficient green-light sources have been made possible by the nonlinear process of SHG [23]. The commonly used 532-nm laser sources are the results of SHG of a neodymium-doped yttrium aluminum garnet (Nd:YAG) laser output at

1064 nm. Similarly, moving to integrated photonics, enhanced nonlinear effects can be used for wavelength conversion and all-optical signal processing applications [16].

Silicon has been widely exploited for nonlinear optics. Although it does not exhibit second-order nonlinearities due to its centrosymmetric structure, it exhibits strong third-order nonlinear optical processes like FWM [24] and THG [25], [26]. As discussed earlier, silicon is a mature material platform and has been extensively explored due to its availability, affordability, and compatibility with CMOS fabrication processes. However, there are limitations such as indirect bandgap, absence of second-order nonlinearities, degraded performance at high temperature, and sub-par operation at mid-IR wavelengths. There is therefore a quest to find materials with more favorable nonlinear optical properties. Some of the material platforms that are being explored are silicon nitride, lithium niobate, II-VIs (materials from group two and group six of the periodic table) and III-Vs (materials from group III and V of the periodic table). Amongst all these platforms, III-V semiconductors offer a lucrative platform because of tunable refractive index, low linear and nonlinear losses, and strong inherent optical nonlinearities, offering a potential for wavelength conversion and all-optical signal processing in the C-band.

1.3 III-V photonics

III-V semiconductor materials are compounds made of materials from groups III and V of the periodic table. Unlike silicon, they naturally exhibit second-order nonlinearity due to non-centrosymmetry, and their refractive indices can be adjusted through a proper selection of the material composition during the epitaxial growth. In addition, III-V materials offer the possibility for monolithic optoelectronic integration, or a hybrid integration with other material platforms such as silicon and silicon nitride [27], [28].

Figure 1.5 represents the bandgap energy of III-V semiconductors as a function of lattice constant. The dots represent binary III-V compounds, comprised of two chemical elements. The lines connecting the dots represent the corresponding ternary alloys, and the areas subtended by the lines represent quaternary compounds based on the binaries at the corners. Ternary alloys have just one degree of freedom, namely the adjustment of the mutual material compositions of one pair of elements, and can be schematically

represented as $A_xB_{1-x}C$, with $0 \leq x \leq 1$. The quaternary compounds typically have two pairs of chemical elements, the concentrations of which can be mutually adjusted. They therefore exhibit an additional flexibility in adjusting the optical properties, and can be represented as $A_xB_{1-x}C_yD_{1-y}$, where $0 \leq x \leq 1$, and $0 \leq y \leq 1$. The lattice constant and bandgap energy of ternary and quaternary compounds can be calculated using Vegard's law [29] if the corresponding parameters of the constitutive binaries are known. Vegard's law for ternary and quaternary compounds can be represented as:

$$E_{ABC} = xE_{AB} + (1-x)E_{BC} \quad (1.6)$$

$$E_{ABCD} = xyE_{BC} + x(1-y)E_{BD} + y(1-x)E_{AC} + (1-x)(1-y)E_{AD}, \quad (1.7)$$

where E is the bandgap energy and A , B , C and D are single III-V elements. By changing the material concentration, one can tune the bandgap energy, refractive index, and nonlinear parameter values. Therefore, III-V materials offer a high degree of flexibility and tunability to meet the application requirements, such as a particular wavelength of operation.

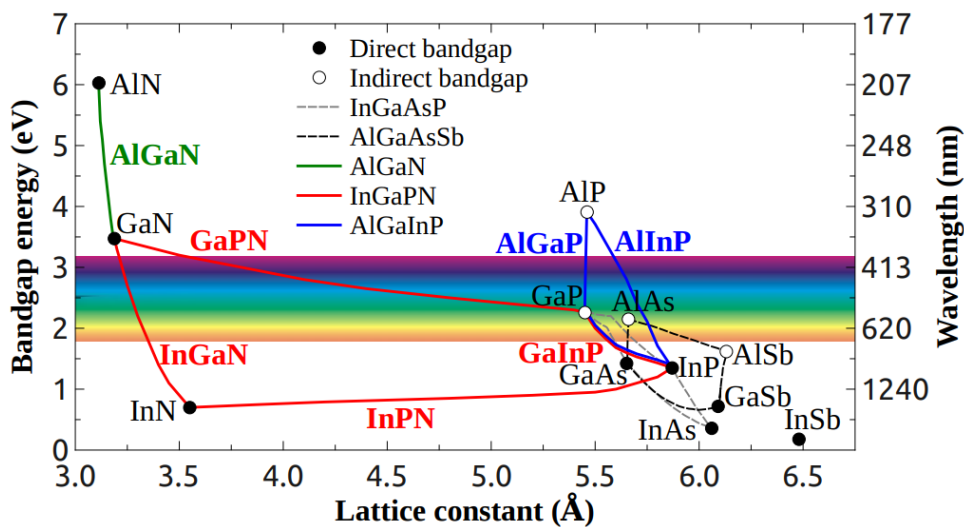


FIGURE 1.5: Bandgap energy as a function of lattice constant for different III-V semiconductors.

In addition to the fact that most III-V compounds can be used for light emission and detection, these materials have promising nonlinear optical properties which can facilitate new research directions in light-matter interactions. To understand these properties, several demonstrations have explored the

nonlinear properties in optical devices such as waveguides, micro-ring resonators, photonic crystal structures, quantum dots, and lasers, all of which have been possible because of advancements in the field of nanofabrication.

One of the most remarkable statements influencing the way the field of nanofabrication has evolved today goes to the visionary talk of Richard Feynman - *There is plenty of room at the bottom* [30]. This thesis is focused on the methods of nanofabrication, the detail of the tools used in a top-down fabrication process, and the process development for the fabrication of nonlinear passive nanostructures based on III-V semiconductors.

1.4 Nanofabrication in Photonics

Nanofabrication is the process of creating structures which are on the order of nanometers. The image shown in Figure 1.6 provides an illustration of the scale of interest for nanofabrication. When talking about nanophotonics, the dimensions are typically in the range of a few thousand nanometers down to tens of nanometers. The limits of the smallest feature size are constantly being pushed so as to pack the maximum number of components on a single chip. As mentioned in the previous section, this idea of pushing nanofabrication and making the components smaller in size goes back to 1959 when Richard Feynman gave a famous talk titled, “There is plenty of room at the bottom” [30]. In his talk, he mentioned that starting from the bottom, or the nanoscale, is the key to future technological advancements. In 1965, Moore’s law [31], which states that the number of components on a chip will double every eighteen months, was introduced. Following the visions of Dr. Feynman, and to keep pace with Moore’s law, there was a motivation to construct tools that can support making increasingly smaller devices and push fabrication limits to the nanoscale. Modern nanofabrication tools are sophisticated and mature to have reached a point where making devices on the order of tens of nanometers is easily possible. Some of these tools are discussed in detail in the next section.

There are two main approaches used in the process of optical device fabrication. The first one is the bottom-up approach [33], [34] in which smaller atoms and molecules self-assemble in a controlled environment to make a single larger structure; whereas in the second approach, a larger stack of material is ablated to achieve the desired dimensions of the nanostructure [35].

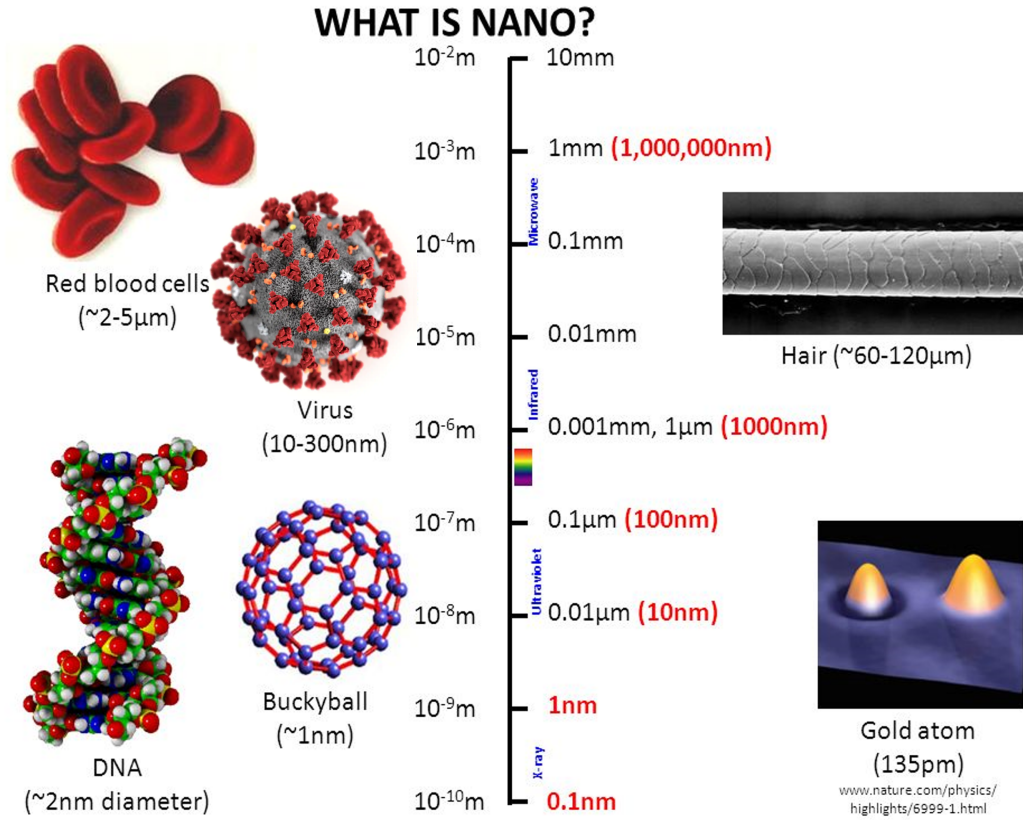


FIGURE 1.6: Representation of the nanoscale [32].

Most of the growth processes represent the examples of the bottom-up approach. On the other hand, planar processes, which involve lithography and etching, fall under the top-down methods. In this thesis, we primarily concern ourselves with describing the top-down fabrication approaches used to realize nonlinear integrated photonic devices as described further in the thesis. There are two major process flows that are used in the top-down fabrication process to create nanophotonic devices:

Fabrication of passive integrated photonic devices: This process is shown in Fig. 1.7. A clean semiconductor wafer is coated with a resist polymer, which is followed by lithography to write the desired patterns. Patterns of desired shapes are created using a GDS-II file which is the de-facto standard for electron beam lithography design files. The GDS file can be thought of as the top view of the designs to be written and contains the information about geometric shapes of the designs, texts and labels, the different layers and position of the structures to be fabricated. The pattern is then transferred into the underlying semiconductor by the process of plasma etching. This is a generic process flow, and it may include some additional steps, such as adding a hard mask in the middle or post-processing steps at the end. This process

flow has been used for the majority of works in this thesis. Integrated photonic devices such as waveguides, ring resonators, and photonic crystals can be realized using this fabrication approach.

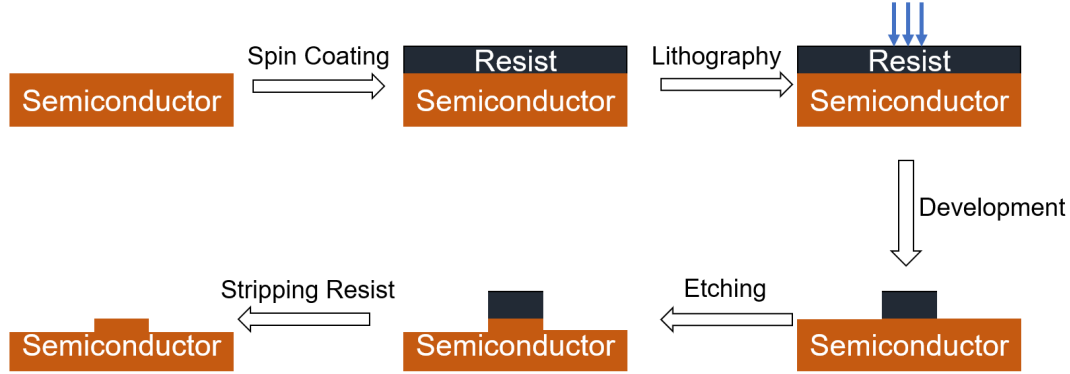


FIGURE 1.7: Process flow used for fabricating integrated optical waveguides and similar structures.

Fabrication of plasmonic metasurfaces: Most of the steps of this process are similar to those discussed above, i.e. the material is cleaned, which is followed by spin-coating of a resist layer of desired thickness. The patterns are then written using e-beam lithography followed by development which creates trenches or openings in the resist layer. The last step is the process of lift-off which removes the metal from all other places except for where it directly touches the semiconductor, this way one can attach metal to the semiconductor and create nanostructures of desired shapes, as shown in Fig. 1.8. A positive tone resist is commonly used in this case to open up the trenches for the metal deposition. Another important thing to note in this process is that a bi-layer resist is used. This refers to two distinct resists having different molecular weights which are spin-coated one on top of the other. The lower-molecular-weight resist is at the bottom, while the higher-molecular-weight resist is at the top. The point of the two-layer resist deposition is that for similar applied doses, the development for the lower layer (lower molecular weight resist) is larger as compared to the top, therefore creating an undercut-like structure. As shown in Fig. 1.9 (top), if a single-layer resist is used, the metals can stick to the sidewalls resulting in undesired features after lift-off which can further collapse on the actual nanostructures. The advantage of using a bilayer is shown in the bottom part of Fig. 1.9, where the bottom resist layer develops slightly more than the top resist layer thereby creating an undercut and hence a more defined opening for the metal to stick only to the substrate.

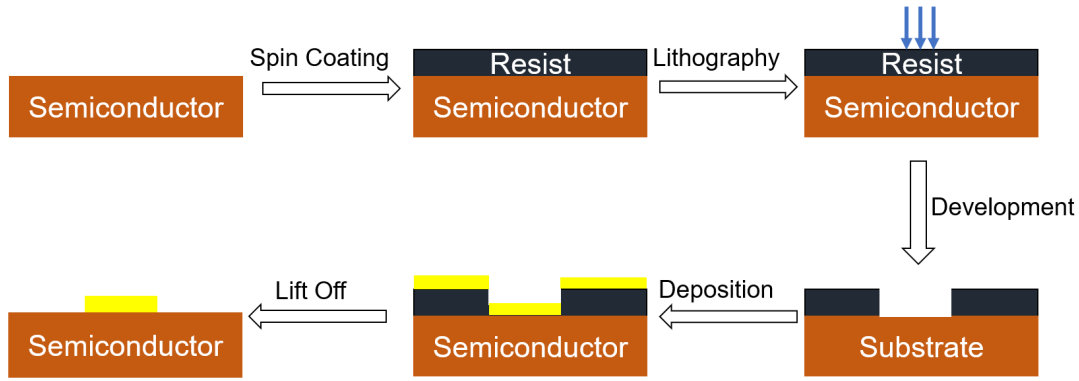


FIGURE 1.8: Process flow used for plasmonic metasurfaces.

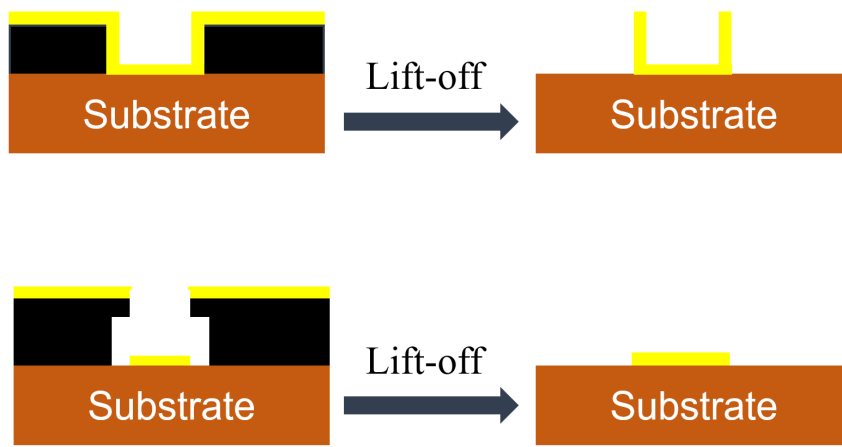


FIGURE 1.9: Single-layer resist lift-off (top) vs bi-layer resist lift-off (bottom).

Once the process flows are finalized and the structures can be repeatedly fabricated with minimum errors, such process flows can be employed for large-scale production of multiple copies of the same (or similar) structure on a larger wafer. The process of using a similar stack to make multiple copies of the same structure, or making many different structures using the same stack in one single process, is called multi-project wafer (MPW) run [36]. MPW runs accelerate photonic systems development as they provide an advantage of catering to the needs of multiple projects/clients in one single run. Fig. 1.10 represents a schematic of how a 4" wafer can be used for accommodating many different projects in one run. The large circle represents a 4" wafer and the smaller black boxes inside show the spaces allocated for each separate project. As can be seen from the figure, multiple projects can be accommodated in one single run using this process, and then every single piece (or box) is diced to separate out all the structures from the full wafer.

III-V semiconductor wafers (the starting material in the top-down approach

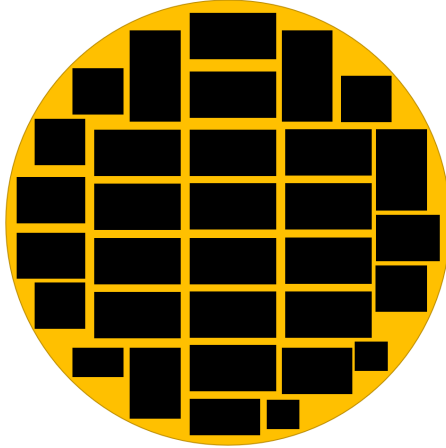


FIGURE 1.10: Schematic representation of an MPW. Each black box represents a space for one single project.

that we described above) are commonly grown using the bottom-up fabrication method of Metal Organic Chemical Vapor Deposition (MOCVD) or Molecular Beam Epitaxy (MBE). These processes, along with some other growth processes, will be further discussed in section 1.5.1. These methods provide a nanometer-scale precision in terms of the growth of epitaxial films. Light guiding in the vertical direction in optical devices follows the principle of TIR, as described above, which requires a higher-refractive-index medium to be sandwiched between lower-refractive-index media. Thin III-V semiconductor films can be epitaxially grown with varying concentrations of the chemical elements to satisfy the above requirement. This creates a heterostructure, which allows for light confinement via TIR in the vertical direction. An important consideration before deciding on the epitaxial stack is lattice matching [37], which is particularly important in integrated optics. Lattice mismatch can cause stress and strain in the epitaxial films, threading dislocations, and stacking faults, all of which can eventually lead to light scattering, poor efficiencies and optical losses [38]. Growing lattice-matched epitaxial layers is thus important for the quality of photonic devices.

The lattice-matching requirement imposes a restriction on the range of the material compositions for the epitaxial growth (see Fig. 1.5). Furthermore, the growth is typically performed on a selected binary substrate, which further limits the acceptable composition range. In this respect, one of the most convenient materials to work with is AlGaAs. Due to the fact that its constituent binaries AlAs and GaAs have closely matched lattice constants which can be seen from Fig. 1.5, AlGaAs of any aluminum concentration can be grown on GaAs substrate with nearly absolute lattice matching.

Once the epitaxial stacks are ready, the fabrication of integrated optical devices mostly follows a standard top-down approach. This includes the process of mask deposition, patterning, and pattern transfer to the semiconductor material. If necessary, these steps are followed by post-processing. Each of these processes is discussed in the subsequent sections.

An important first step before starting any process is a deep and thorough cleaning of the material. This is done by first cleaning the material in warm acetone, which removes the oil and organic contamination from the material. The next step is cleaning in isopropyl alcohol (IPA). This is necessary because, although acetone cleans all the organics, it leaves its own residue that can contaminate the wafer surface. IPA cleaning removes this residue and dries the surface leaving no contaminants or spots. For some materials, a de-ionized water (DI water) cleaning is also recommended after the IPA cleaning to remove any other contaminants that might still be resting on the material's surface. The last step of cleaning includes blow-drying the surface with nitrogen and heating it on a hot plate to evaporate any water that might be left on the surface after the last cleaning step. The rest of the chapter covers the details of each step schematically shown in Figs. 1.7 and 1.8. We start by introducing the epitaxial growth processes and then continue to the introduction of resists, electron beam lithography, plasma etching, and the processes used for the fault analysis.

Fabrication process development at a university cleanroom facility may appear to one as a redundancy, provided that there are foundry services available for fabricating integrated photonic circuits. However, such foundry services are typically very expensive and have a very slow turnaround. Further, there exist only two open foundries for III-V semiconductor photonic circuits, both of which are situated in Europe. Furthermore, these foundries are highly restrictive with the fabrication tasks which they can carry out, most of which are based on pre-developed epitaxial stacks and pre-established processes, which makes them not suitable for research and development at the component level. It is thus very important to continue developing reliable fabrication processes as part of a research activity at a university facility. To explore newer devices for nonlinear and quantum optics applications, one needs to study different material compositions and structural geometries, and the commercial foundries do not give such flexibility. Therefore developing in-house fabrication processes gives the advantage of developing methods for newer research and creating rapid prototypes for lab testing which

can later be commercialized.

1.5 Key Tools and Processes

As the first step in the integrated component fabrication, the clean wafer is inspected under a microscope for any contaminants or dirt particles, and the defective areas are avoided during the patterning. The epitaxial growth of the wafer structures used in this thesis work was carried out by commercial growers using MOCVD and MBE processes. Some of the important tools used to carry out the top-down fabrication in this thesis are Electron Beam Lithography (E-beam), Plasma Enhanced Chemical Vapor Deposition (PECVD), Scanning Electron Microscopy (SEM), Atomic Force Microscopy (AFM) and ICP-RIE Plasma Etching.

1.5.1 Epitaxial Growth

The process of growing films of semiconductor material on a substrate wafer is called epitaxial growth. Epitaxial growth of III-V semiconductors requires high-quality films with low defect density, which is crucial for nonlinear photonic applications [39]. The trap states associated with the defects act as recombination centers, hampering the device's performance. The substrates also play a crucial role in epitaxial growth. If the substrate is the same as the growth material, the growth is called homoepitaxy. On the other hand, if the growth material is different from the substrate, the growth is called heteroepitaxy [40]. It is challenging to mitigate defects in the heteroepitaxy growth due to the presence of lattice and thermal mismatch between the substrate and the films. Therefore, buffer layers are introduced to optimize the growth of high-quality heteroepitaxial thin films.

MBE [41] is the epitaxial growth technique having precision at angstrom-level thickness. It is a physical deposition technique facilitated under ultra-high vacuum conditions for precise control and monitoring of overgrowth via various in-situ characterization techniques. A molecular beam is focused on a heated substrate and deposits new layers atom-by-atom under controlled growth dynamics. It is capable of growing sharp interfaces and is widely used for electronic and optical devices. However, this growth technique is very costly and offers a slow growth rate which limits its applicability at the commercial scale. MOCVD provides several advantages in this aspect where the growth rate is higher whilst lowering the cost.

MOCVD [42] is a chemical vapor deposition technique using a flow of a gas-phase mixture containing the precursors over a heated substrate for a layer-by-layer deposition. The chamber pressure is slightly lower, and the substrate temperature is higher in comparison to some other techniques like plasma assisted molecular beam epitaxy (PAMBE). This technique is capable of depositing a controlled thin layer with higher wafer throughput. It is widely used for integrated circuit applications.

Liquid phase epitaxy (LPE) [43] technique is a low-cost deposition technique depositing the material from a supersaturated solution. It is not capable of forming sharp junctions between two material layers. All the epitaxial stacks used in this thesis were grown using MBE and MOCVD processes.

Other cost-effective, large-area and faster growth techniques have been explored in the mid-20th century for III–V semiconductors such as hybrid vapor phase epitaxy (HVPE), close-spaced vapor transport (CSV T), and thin-film vapor-liquid-solid (TF-VLS) growth. HVPE is very similar to MOCVD but the former is a non-equilibrium process controlled by the supersaturation of the reactants at the substrate, while the latter features a kinetically controlled growth. A volatile metal chloride is prepared at the atmospheric pressure and flows towards the substrate to mix with the group V material to form III-V-Cl complex on the substrate followed by liberating HCl. The growth rate of the HVPE process is much higher in comparison to that of the MOCVD. CSV T is performed in a closed chamber where the volatile phase is generated from solid materials in situ. This offers high growth rates and improved precursor utilization. The reactions take place under H₂ ambient at the atmospheric pressure. The metal chloride along with a group V dimer is liberated at the source and the substrate. The source is kept at a higher temperature diffusing the vapor phase reactant towards the substrate following the deposition associated with the supersaturation. TF-VLS is a non-epitaxial growth technique maintaining the crystalline and electronic structure. This technique was first reported for the synthesis of InP where a thin layer of In was deposited on the molybdenum foil, which is capped by a layer of SiO₂. Phosphorus in gaseous form diffuses through the capping layer and interacts with the now-liquid In under high temperature to form InP. The technique allows one to utilize a wider variety of substrates. All the growth techniques introduced in this section provide a pathway toward the commercialization of a cost-effective approach for the III-V semiconductors-based photonics industry.

1.5.2 Resists and Spin-Coating

Resists are long-chain polymers dissolved in some solvents that are used to write patterns. These polymers are sensitive to light (photoresist) or electrons (E-beam resists), and their chemical properties change as the beam of light or electrons hits the surface. If the resist bonds weaken by exposure, the development creates a trench, washing the exposed resist portions away. Such resists are known as positive-tone resists. The process of bond-breaking in a positive-tone resist is also known as scission. Some examples of positive-tone resists are ZEP520a, which is a chloromethacrylate and methylstyrene-based polymer, and PMMA (poly methyl methacrylate). In contrast, the chemical bonds of a negative-tone resist become stronger after exposure, and therefore the development process eliminates unexposed parts of the resist while leaving the exposed parts intact. The strengthening of the resist by exposure is associated with cross-linking of polymers. Hydrogen-silsesquioxane (HSQ), ma-N, and SU-8 are common examples of negative-tone resists. Positive and negative tone resists are illustrated in Fig. 1.11.

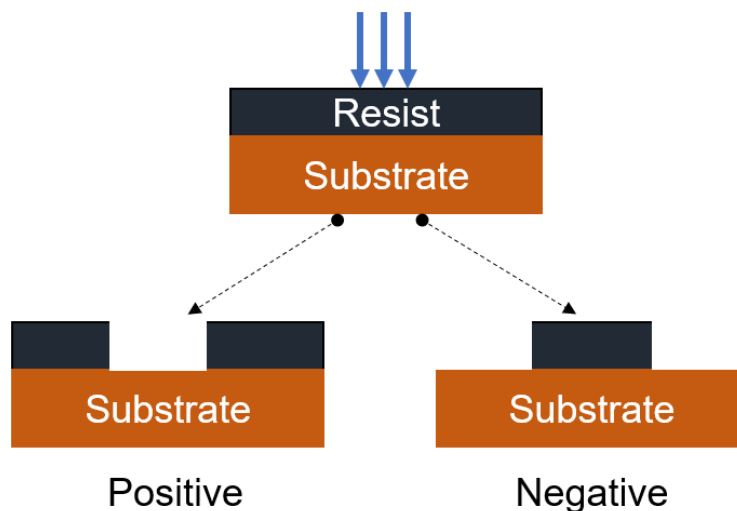


FIGURE 1.11: Positive-tone resist (left) and negative-tone resist (right).

The solvent which is used to dissolve the resists after the E-beam exposure changes its chemical properties and is known as a developer. PMMA is developed in a solvent mixture of Methyl isobutyl ketone (MIBK) and IPA, ZEP520a is developed in n-amyl-acetate, and HSQ can be developed in hydroxide-containing solvents like TMAH, NaOH, KOH. The resists are soluble in some organic solvents, which allows one to change the viscosity of the resists. The viscosity ultimately translates to the maximum resist thickness

at spin-coating and the resolution that can be achieved at exposure. PMMA and ZEP520a can be diluted in Anisole, and HSQ can be diluted in MIBK.

Some important characteristics of resists are adhesion, sensitivity, contrast, resolution, and etch resistance. Adhesion refers to how well the resist sticks to the material's surface during the spin-coating. If the material has been exposed to high moisture, it may have polar $-\text{OH}$ bonds on the surface. This makes the surface hydrophilic, and polar solvents (which is what most E-beam resists are dissolved in) do not stick well to the surface. This is a common case with III-V semiconductors where at times, the resist does not stick well to the material surface because the adhesion is poor. In such cases, a thin layer of HexaMethylDiSilazane (HMDS) that acts as an adhesion promoter is deposited before spinning the resist. The resist resolution is related to the minimum feature dimensions which can be written. Generally speaking, the thinner the resist, the higher the resolution, but this also depends on the chemical structure of the resists. PMMA is known to have the best resolution for the positive-tone resists, and structures with the critical dimension of 10 nm have been demonstrated using PMMA. Similarly, HSQ is also a very high-resolution negative tone resist. Structures with the critical dimension of 7 nm have been produced using this resist. Recently, it has been shown that resist sensitivity can further be improved if used with a lower temperature development process (for positive tone resists) [44].

The sensitivity and contrast are very important resist characteristics. The sensitivity is the minimum dose required for the resist to completely develop at a particular beam energy or acceleration voltage. This is also known as the dose to clear or clearing dose. For instance, the clearing dose for ZEP520a at 30 kV for AlGaAs is around $75 \mu\text{C}/\text{cm}^2$, whereas for PMMA for the same beam acceleration it is $220 \mu\text{C}/\text{cm}^2$. This parameter changes with the beam energy variation. For instance, the sensitivity of PMMA at 100 kV for AlGaAs is around $500 \mu\text{C}/\text{cm}^2$. The contrast is defined as the slope of the development curve. An ideal resist will have a sharp drop at the clearing dose, but this is not the case in actual resists. The development happens at a gradual rate and therefore creates a slope, which mathematically can be defined as

$$\gamma = \frac{1}{\log_{10} D_1 - \log_{10} D_0}, \quad (1.8)$$

where γ is the contrast curve, D_1 is the dose at which the resist is fully developed and D_2 is the dose at which it just starts to develop (as defined in

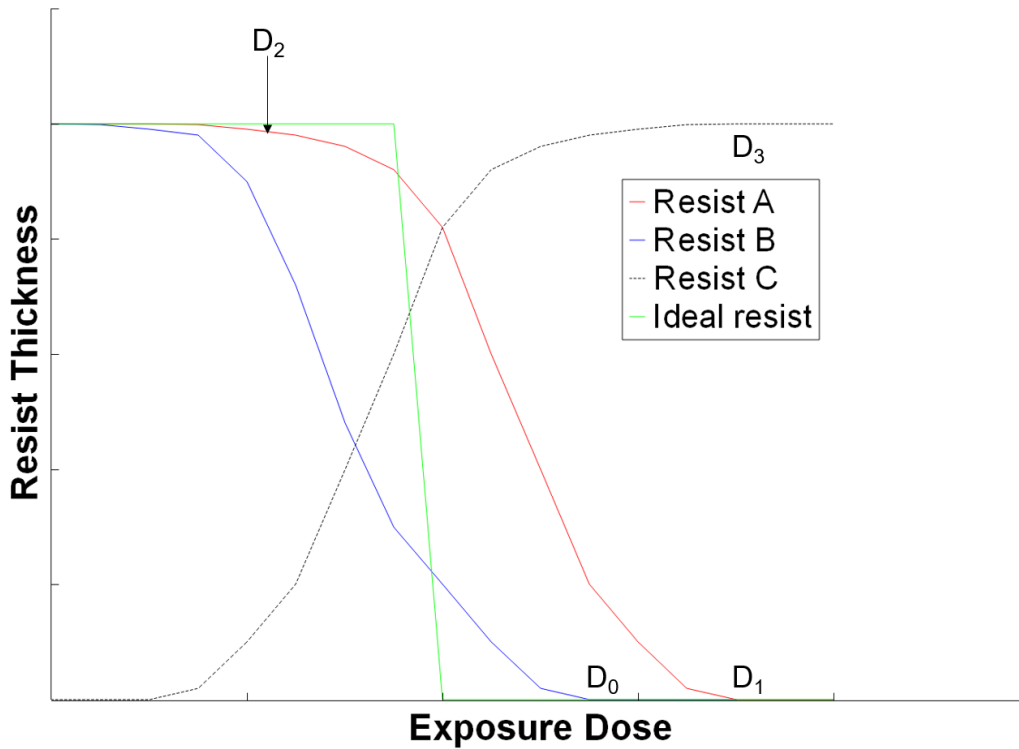


FIGURE 1.12: Graphs representing sensitivity and contrast curves of resists.

Fig. 1.12 for the resist A). For an ideal resist, $D_2 = D_1$, which makes γ infinity. For an ideal resist, both the sensitivity and contrast should be large, meaning a low dose to clear and a sharp drop in the development curve slope, but there is always a trade-off between these two parameters. Fig. 1.12 shows D_1 as the dose to clear for resist A, and D_0 as the dose to clear for resist B. Resist C is a negative-tone resist and therefore the curve goes up as the resist hardens. The green curve shows the characteristics of an ideal resist. The slope of the graphs gives the contrast. The resolution refers to the smallest structure that can be fabricated using the resist. As mentioned earlier, the thinner the resist layer, the smaller the structure that can be resolved, meaning high resolution. The resolution also largely depends on the E-beam properties (beam energy, current), which will be discussed in the coming sections. The type of resist also plays a crucial role in the resolution. And lastly, etch resistance refers to the rate at which the resist erodes during the etching process of the material for which it is acting as a mask.

The choice of the resist depends on the type of the structure to be fabricated. For instance, PMMA is known to have a great resolution but has very poor etch resistance, whereas ZEP520a has lower resolution but a much better etch resistance. HSQ is one of the most widely used E-beam resists. Chemically

it is silsesquioxane (H-SiO_x), and on heating up, it takes up the form of silica (SiO_2), which is known to have an etch resistance of close to 1:10 for most III-Vs. It is also capable of providing a resolution down to a few nanometers (nm) therefore, it makes up for one of the best E-beam resists. ZEP520a and HSQ are the resists that have been used for the fabricated samples in this thesis.

Similarly, for the structures where the trenches are supposed to be created, for example plasmonic metasurfaces, which are metal nanoparticles on a semiconductor/dielectric substrate, it is essential to create an opening to do the metal deposition. In such cases, positive-tone resist is recommended. On the other hand, for waveguides and ring resonators, a negative-tone resist is recommended. This does not mean that waveguides and ring resonators cannot be made using a positive-tone resist, but it is recommended to use negative-tone resists to have lower write times to write the exact transferring structure and not the inverse.

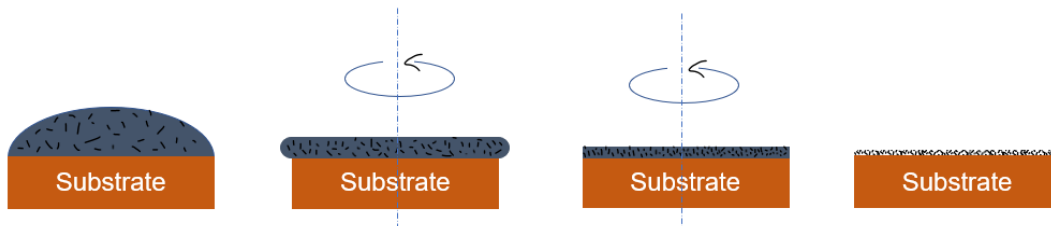


FIGURE 1.13: Spin-Coating.

The process used for depositing uniform thin films of resist on the sample is known as spin-coating [45]. It works based on the principle of centripetal and centrifugal force. A clean sample is placed on a vacuum mount, and an amount of resist sufficient for coating a complete sample is poured onto the sample's surface. The sample is then rotated at some rotation speed (specified in rotations per minute or RPM) to get the required resist thickness. As a result, the poured resist layer starts thinning and eventually turns into a uniform film, as shown in Fig. 1.13. At lower spin speeds, edge beads (or edge effects) are quite common, which results in larger and uneven thickness at the periphery of the wafer. Therefore, these areas around the corner should not be used for patterning. There are two ways to do spin coating: a dynamic way, in which the resist is poured on to a rotating substrate, and a static way, in which the resist is poured on a still sample and the process of spinning follows. In the projects mentioned in this thesis, for the sake of repeatability, we only worked with static spin-coating.

The resist thickness largely depends on the material's viscosity and the spinning speed. The spin curves provide the details for what speeds will lead to what resist thicknesses. These are standard curves which are provided by the resist vendors. Fig. 1.14 shows the experimental results of spin coating ZEP520a at different spin speeds. Another important parameter to know while performing spin-coating is the saturation time, which is defined as the duration for which the resist sits on the sample surface before the spin process is started. This is common in static spin-coating process and the resting of resist for a specified time allows for the films to better stick to the sample surface.

Once the spinning process is finished, the resist is baked at a specified temperature for a given time. This step is performed to ensure that the remaining solvents evaporate and we are only left with the polymer to write on. This process is known as pre-bake. All the above mentioned steps together are known as spin-coating recipe.

Sometimes the resists are also baked at larger temperatures after the exposure and development, and before the process of etching. This is done to interlink the bonds and slow the erosion rate of the resist down during the etching. This bake process is called post-bake. To find out whether the deposited resist has the correct film thickness or not, the measurements of the reflection spectrum or using the profilometer can be performed. Once the patterned mask is transferred into the semiconductor layer and if the resist still remains, the remaining resist can be completely removed. This process is also known as resist stripping. This is done by dissolving the remaining resist in polar solvents like acetone, n-methyl-2-pyrrolidone (NMP, also known as remover PG) or similar solvents. E-beam resists can also be removed using an oxygen plasma.

1.5.3 Electron-Beam Lithography

Lithography literally means “writing on a stone.” In semiconductor lithography, the patterns are written on the semiconductor substrate materials using either light (photolithography), electrons (E-beam lithography), or ions (focused ion beam). Photolithography is the most commonly used method for patterning. It is widely used in the industry due to its speed and high throughput. A resist coated with light-sensitive polymer is kept under a mask with the patterns to be written, and the entire wafer is flooded with

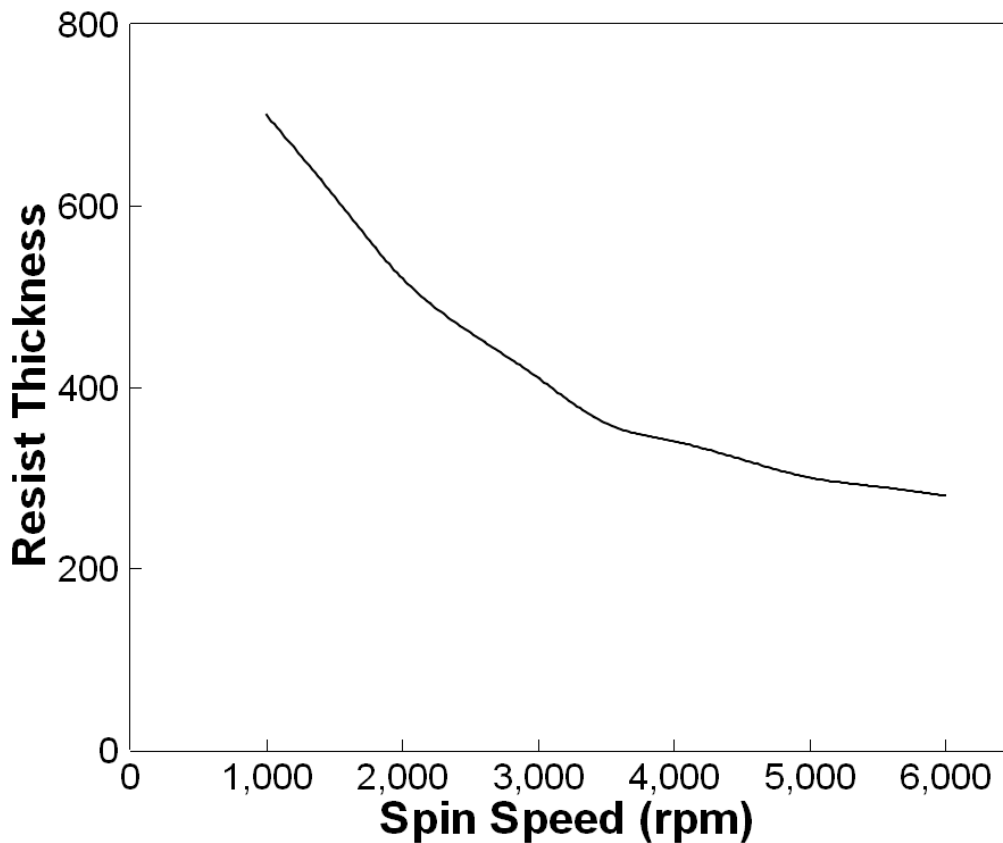


FIGURE 1.14: Experimental spinning curve for undiluted ZEP520a positive-tone resist carried out at uOttawa's clean-room facility. The resist thickness are in nm and spin speeds in rpm

light at the same time, creating chemical changes in the resist. The state-of-the-art optical lithography systems are called extreme ultraviolet (EUV) lithography which uses a radiation source of 13.5 nm, thereby allowing the writing of structures with the resolution down to 10 nm [46], [47].

Another common lithography method is focused ion beam (FIB) [48]. In this method, the exposure is provided by much heavier ions, usually helium or gallium instead of light or electrons. It is a direct write method in which patterns can be defined without the need of resists. This tool allows high resolution imaging (similar to SEM), and can do milling at the same time because of the heavier particles which bombard the material. It is suitable for writing structures with the sizes down to 5 nm.

The most commonly used tool in research and prototyping is electron-beam

lithography (or E-beam) system. These systems are capable of writing structures 5–7 nm in size [49]. In this method, the exposure is provided by electrons accelerated and controlled by the applied voltage. The electrons have extremely small wavelengths associated with them, typically on the order of sub-10-pm. Therefore, there is a very fine limit to the smallest structures that can be written using E-beam. However, the limiting factor preventing sub-10-nm writing is the electron optics that are used inside the E-beam systems and the unavailability of resists capable of writing high-resolution structures. All the samples described in this thesis have been produced using E-beam writing. The section below is dedicated to the working principle and physics behind the E-beam writing process, its control parameters, and the common errors that one might encounter while using the tool.

Working Principle and Control Parameters

In the early 1920s, de Broglie, *et al.*[50] demonstrated that particles such as electrons have an equivalent wavelength, which can be expressed using the relationship

$$\lambda = \frac{h}{p}, \quad (1.9)$$

where h is Plank's constant and p is the momentum of the particle.

Since electrons can behave like waves, all the concepts of wave optics also apply to electrons. Consequently, diffraction of electrons has been demonstrated [51], and imaging systems, such as the scanning electron microscope (SEM) and transmission electron microscope (TEM), were invented. Since the wavelength of an electron is a function of its energy, which depends on the mass of electron (m), voltage (V) and speed of light (c), it can be calculated as

$$\lambda = \frac{1.225 \cdot 10^{-9}}{\sqrt{V}} \cdot \frac{1}{\sqrt{1 + \frac{eV}{2mc^2}}} \quad (1.10)$$

Using this relation, one can obtain the electron wavelengths (in pm) for some common acceleration voltages:

1kV= 38.7; 10kV= 12.2; 20kV= 8.58; 30kV= 6.97; 100kV= 3.7.

Large energies can be generated by an electron generation source, which can be either a thermionic or a field-emission source.

Typical E-beam systems consist of the source at the top, some radiofrequency

(RF) coils to direct the electron beam, a series of focusing lenses, beam blanking system, a motorized stage, and a computer that controls all of the above and hosts the software used for pattern writing [52]. The electron beam is deflected using RF coils and electromagnetic lens systems (commonly known as electron optics). All the electron optics is housed in a stable vacuum environment also known as the E-beam column. This electron beam can be modelled as a Gaussian function [53]. The accelerated electrons generate the energy which eventually translates into some current value. This electron beam passes through the focusing lenses, and creates a spot size on the order of a few nanometers (depending on the beam energy), which is eventually used for writing. There are several important control parameters that manipulate the E-beam. We are going to describe them briefly below.

1. *Acceleration Voltage*: This is the most important parameter characterizing an E-beam, which is related to the acceleration of the electrons as they move from the gun towards the anode. Generally speaking, increasing the accelerating voltage results in a smaller beam spot, which typically improves the resolution. However, a smaller spot is not always recommended.

The smallest structure which can be written is defined as critical dimension or CD. Ideally, a smaller spot is only recommended when the critical dimension (CD) is on the order of the spot size (for example, to write structures that are 7–10 nm in size). For larger structures, a larger spot size is better as it leads to a better line-edge roughness (ler) and line-width roughness (lwr), a better positional accuracy, and faster write times. The write times can be calculated as the product of the dose and the write area divided by the current:

$$\text{Write Time} = \frac{\text{Dose} \cdot \text{Exposure Area}}{\text{Beam Current}}. \quad (1.11)$$

To put things into perspective, an exposure of a 1 cm×1 cm area with a clearing dose of 80 $\mu\text{C}/\text{cm}^2$ will take 30 days on a 30-kV system with the beam current of 30 pA, whereas the same exposure will take 4 days on a system with a larger beam current of 200 pA. If the same write was to be performed on a much more powerful 100-kV system, with 50 nA of current, the same expose can be performed in 1.5 hours (given that the exposure dose for a 100 kV system is roughly 3 times higher, that is, 250 $\mu\text{C}/\text{cm}^2$). This is the reason why high-acceleration-voltage E-beam systems are preferred.

2. *Aperture:* Apertures are the standard openings of varying hole diameters, controlling the electron flux that can pass through the openings to the optics, which eventually determines the value of the beam current. Therefore, these apertures are also called beam-limiting apertures. Beam-limiting apertures also decide the convergence angle of the electron beam, which is described by the forward scattering parameter α . The larger the aperture, the higher the electron-electron interaction in the column, and therefore the larger the current and the spot size. There is also another beam blanking aperture, which is usually situated very close to the filament which is used to blank the electrons when the exposure is not needed.
3. *Beam current:* As discussed previously, the acceleration voltage and the aperture determine the total energy flowing through the column, which eventually determines the E-beam current. Smaller beam currents lead to smaller spot sizes, and therefore smaller CD values and larger resolution. But this also means that the writing speeds are slower, leading to lower throughput, as it was discussed in the previous Section. 1.
4. *Step size (or shot pitch) and Dwell time:* The way E-beam writes the structures is as follows: the Gaussian beam hits the resist at one point and stays at that place for some time such that the exposure of the resist occurs, and then the beam hops on to another spot and repeats the same process. The time for which the beam stays at one spot is called the dwell time, and the distance between the centre of the two Gaussian beam spot positions is called the step size or shot pitch. Ideally, the shot pitch should always be an integer multiple of the structure size; if it is not, there is a common occurrence called grid snapping which leads to a snapped structure at the edges. Fig. 1.15 (a) shows a 5 nm line written on a 1 nm grid, in this case the exposure will lead to a perfect dimension structure. Fig. 1.15 (b) shows the detrimental results of grid snapping: the structure to be written is not an integer multiple of the grid size and therefore the grid snaps and leads to a larger structure size.

All these control parameters lead to the most important process parameter of E-beam writing - the base dose. The base dose varies depending of the pattern density, which means that isolated features would require a larger dose compared to densely packed structures. Therefore, a base dose is selected for a standard feature size, and then a dose sweep is performed or dose matrix

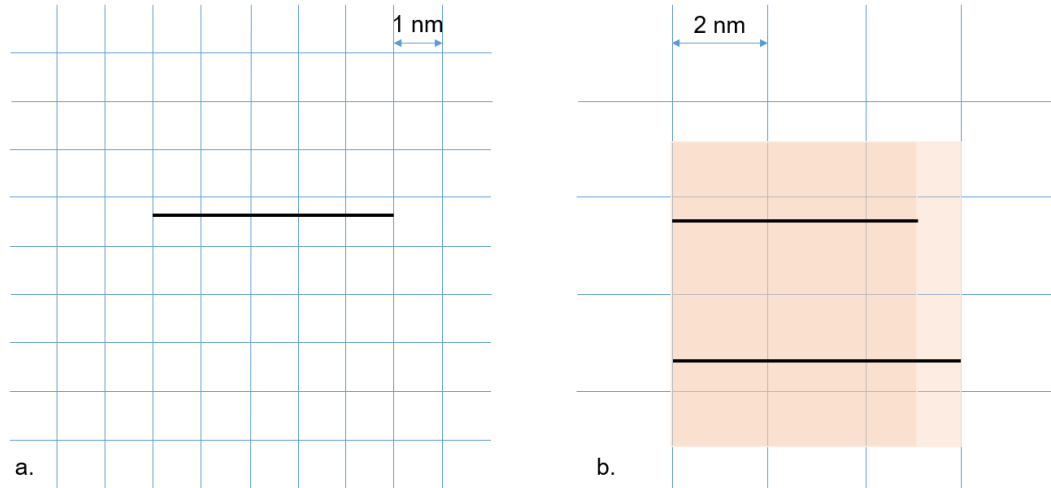


FIGURE 1.15: (a) A 5 nm line written on a 1-nm grid; (b) A 5 nm line written on a 2-nm grid. Grid snapped which results in a 6-nm structure.

is created. Specifically, we create a matrix of 5×5 and sweep across various dose factors, for example, from $0.5\times$ to $2.0\times$, and then check which dose factor leads to the correct CD target after the development.

Gaussian Beam and Proximity Effect

The spread of the electrons once they hit the resist surface can be modelled based on how the electrons penetrate the resist. When the electron beam hits the resist surface, many different reactions can happen, such as the generation of secondary electrons, back-scattered electrons, x-rays, auger electrons and visible light. Of all these effects, secondary electrons and back-scattered electrons are the two most important contributors affecting the variation in the dose. Forward scattering happens because the electrons hit other electrons from the resist, and the molecular chain breaks eventually. This forward scattering parameter depends of the acceleration voltage (V_{acc} in kilovolts) and the resist thickness (R_t in nanometers), and it can be described using the following equation:

$$d_f = 0.9 \cdot (R_t / V_{acc})^{1.5}, \quad (1.12)$$

which shows that forward scattering is the least when the acceleration voltage is the highest and the resist thickness is minimum.

The spread of the beam is usually modelled by a 2-Gaussian-beams model, where the first Gaussian function describes the spread from the secondary

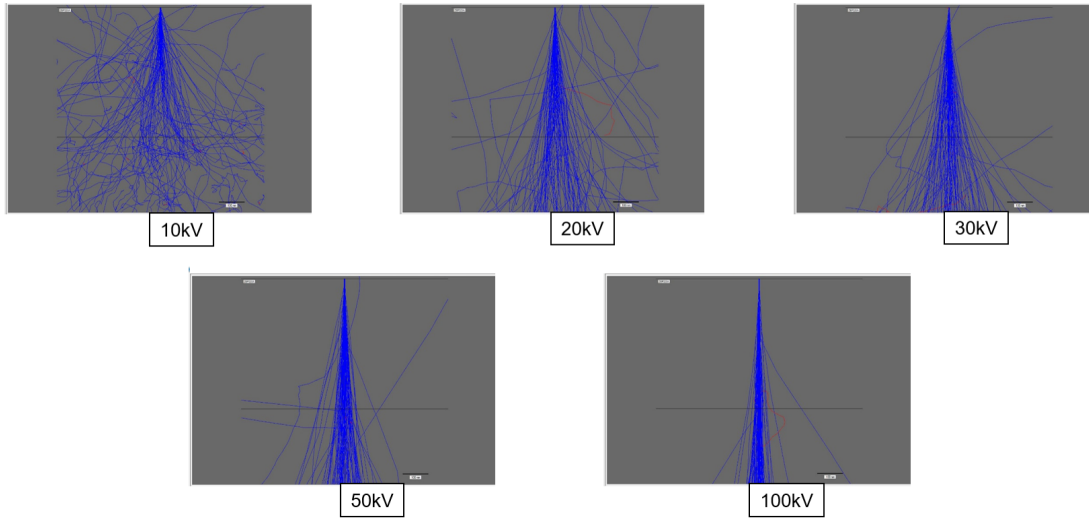


FIGURE 1.16: Monte-Carlo simulations showing how the electron scattering changes with the acceleration voltage.

electron (SE), while the second Gaussian represents the back-scattered electrons (BSE). This is known as point-spread function (PSF)[53], which gives the energy as a function of the radial distance from the centre where the beam hits. The equation below shows the mathematical representation for the proximity function of the 2-Gaussian-beams model:

$$f(r) = D_0 = \frac{1}{\pi(1 + \eta)} \left[\frac{1}{\alpha^2} \exp\left(-\frac{r^2}{\alpha^2}\right) + \frac{\eta}{\pi\beta^2} \exp\left(-\frac{r^2}{\beta^2}\right) \right], \quad (1.13)$$

where D_0 is the clearing dose, α represents the forward-scattering electrons (or short-range scattering in μm), β represents the back-scattering electrons (or long-range scattering in μm), and η is the ratio between the back-scattered electrons and the forward-scattered electrons.

The 2-Gaussian-beam function for the electron beam can be modelled using Monte-Carlo simulations [54], and fairly accurate results can be obtained by simulating the beam energy using millions of electrons. Fig. 1.16 shows the simulation results for 500 nm of ZEP520a on GaAs for different acceleration voltages. The electron-beam width narrows as we move towards larger acceleration voltages, but the backscattering range also increases because the electrons have more energy and therefore can travel larger distances through the resist to create exposures microns away. This simulation was performed using Raith e_Line software by simulating 1 million electrons. The inputs from Monte-Carlo simulations are fed to create the PSF. PSF is another fairly complex relation and depending on the material stack, the model can include

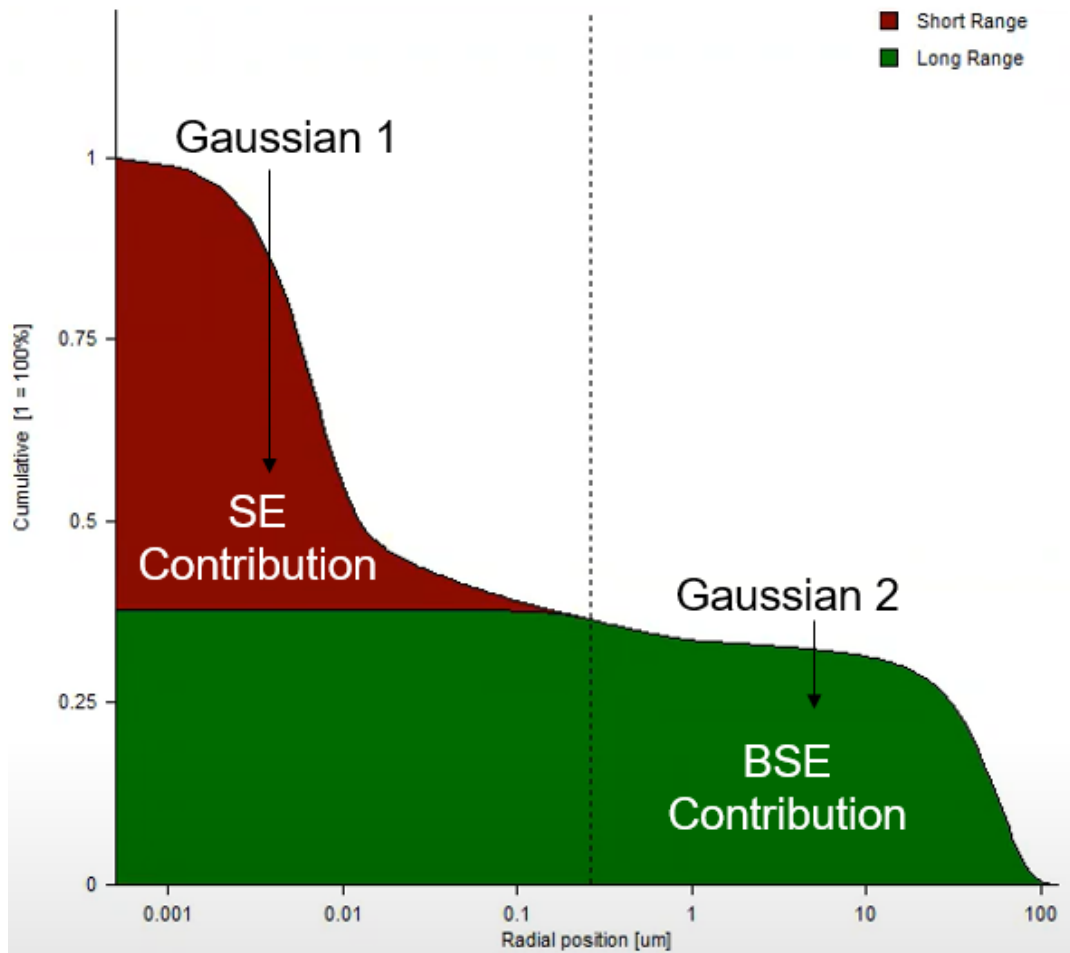


FIGURE 1.17: PSF simulated using BEAMER.

not just two but multiple Gaussian functions. However, two Gaussian functions (SE and BSE) are usually enough to obtain the PSF. Fig. 1.17 shows a PSF simulated using BEAMER software. The convolution of PSF with the designed structure leads to different dose factors at different locations based on the spread of the beam energy through the resist. This varying dose factor is used to correct for the proximity effects, and therefore known as proximity effect correction (PEC). The PSF largely depends on the material density. III-V materials typically have larger densities, and therefore it is very important to perform PEC when doing E-beam writing on III-V semiconductor substrates. Fig. 1.18 shows two PSF simulated at 100 kV acceleration voltage and for 500 nm PMMA resist. The black curve represents the corresponding PSF for GaAs whereas the red represents silicon. As we can see from this figure, the effect of backscattered electrons, also known as range, is slightly higher for silicon, which means that the proximity effect can create more dramatic changes in the structure's shape (particularly the edges and corners) for silicon as compared to III-Vs. However, the background energy is significantly

higher in GaAs because III-V materials are generally more dense than silicon. This means that the BSE creates a sea of electrons in the middle, thereby contributing more energy in the middle for GaAs than for silicon. Therefore, the clearing dose for III-V semiconductors is usually 27% less than that for silicon. It is extremely important to do proximity-effect correction before patterning devices.

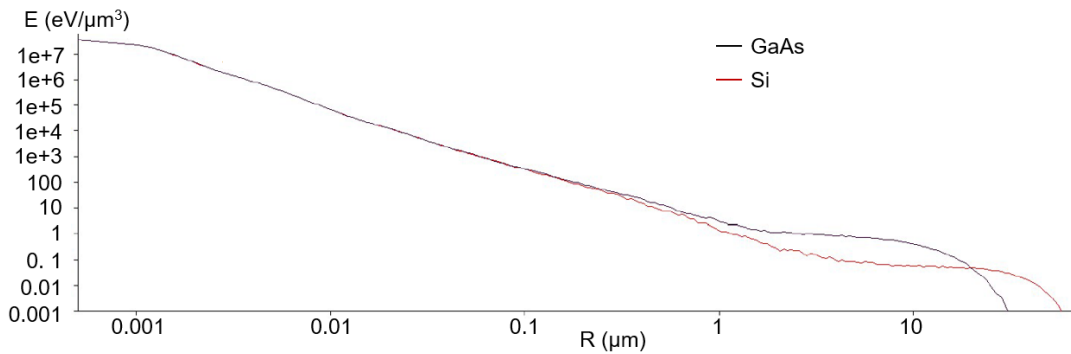


FIGURE 1.18: PSF for GaAs compared with Silicon for 50 nm PMMA at 100 kV [55].

Common Errors and Potential Solutions

There are multiple things that can go wrong during the E-beam exposure. Two of the most common errors are the proximity effect and writefield alignment. As briefly discussed earlier, the proximity effect is caused by a sea of back-scattered electrons that create an exposure of unintended regions. The back-scattering happens because a few of the electrons hit the much heavier nuclei of the resist or the substrate. As a result, the electrons keep their energies, but they are scattered at large angles and travel all the way up through the resist, exposing unintended regions. This back-scattering event causes the proximity effect, which can be corrected by tweaking the dose values where necessary. The proximity-effect correction can be accomplished using the software correction tools like BEAMER, or by manually altering the dose and structure size in the layout file.

Writefield error is another very common error. In order to understand this effect, it is important to understand how the E-beam performs the pattern writing. The beam deflection can happen only up to a few hundred microns, after which the beam starts distorting and changing the shape, as shown in Fig. 1.19 (b). Therefore, the complete structure is divided into smaller parts or areas, called subfields or writefields (WF) (Fig. 1.19 (a)). The E-beam remains centered with respect to the column position, and it can deflect by only a

few micrometers with respect to the centre (in any direction). In order to write the entire pattern, the stage keeps moving from left to right and top to bottom, in the steps of the WF size. For example, if a 1-mm structure is to be written, and the WF size used is $100\ \mu\text{m}$, the structure will be divided into 10 writefields, and the stage will move 100 microns from left to right 10 times for the write process to complete, while the electron beam will remain centered, deflecting by only 100 micrometers to complete each WF. Even for $100\ \mu\text{m}$ of deflection, the beam changes its shape and size because there are higher-order aberrations distorting the beam. However, most E-beam tools have a built-in stigmation correction to eliminate this undesired effect.

Since the structure gets divided into these smaller writefields, and there is a mechanical stage that moves the wafer from side to side (or up and down), this means that the overall structure faces some nanometer-scale errors as the stage moves from one position to another; this is what causes the writefield error. The writefield alignment is the procedure of correcting for the writefield error. It is completed by training the system to align to the centre of the stage at all times. On most of the 100-kV systems, this is an automated process, but this function is not built in for 30-kV systems. The way this is done in the latter systems is manually, by choosing a few-nm-size particle (usually a contamination spot), and going from a higher magnification to a lower while the stage moves to train the beam to always hit the center of the chosen spot. This procedure allows one to make sure that the bigger structure is “stitched” properly without seeing any writefield boundaries called stitchfield errors or WF errors.

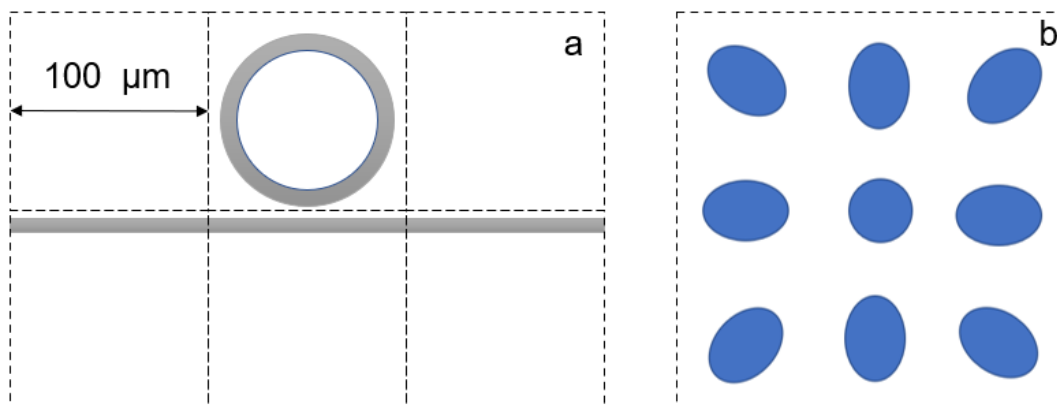


FIGURE 1.19: (a) A bigger structure being divided into smaller $100\ \mu\text{m}$ writefields; (b) The beam shape change inside one writefield.

Drift is also a common error in E-beam lithography. This happens because

the electron beams changes its position slightly with time. This is usually more visible when longer writes are performed over the course of 24-48 hours, where the beam drifts a few nanometers. To avoid this, pneumatic vibration isolation tables are installed, which can absorb the micro-vibrations that can cause these drifts. Sometimes a drift can also be caused by the material's charging (while using non-conductive samples), and therefore, gold sputtering is usually performed to create a thin film of metal which can dissipate the excess charge allowing for easier imaging. Very rarely, some unexpected and unusual beam movements due to a part failure can also cause beam drift, therefore, it is also recommended to keep drift scales/markers, which is discussed in detail in the next paragraph.

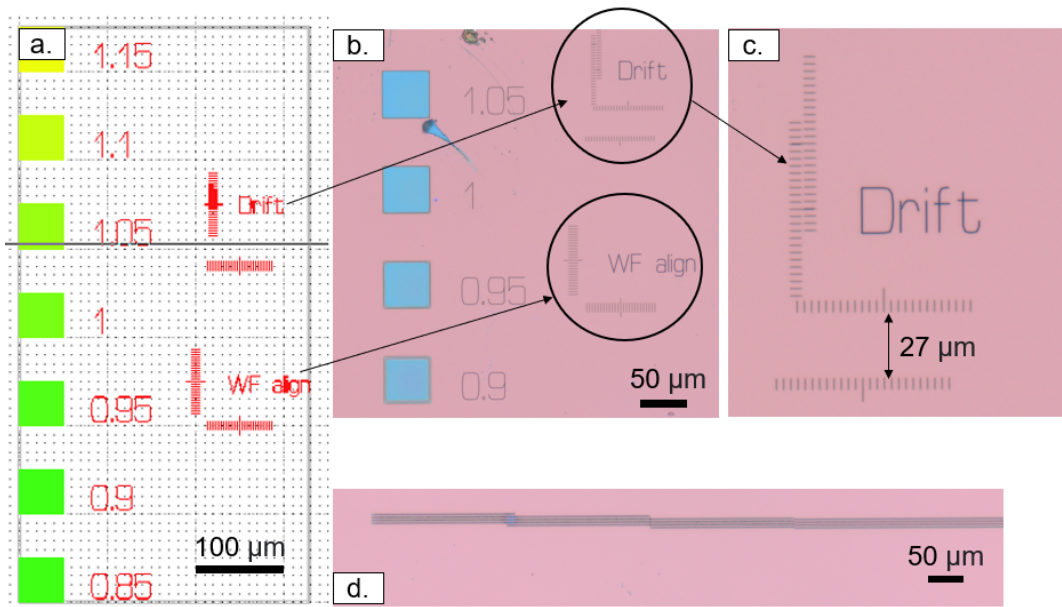


FIGURE 1.20: (a) GDS file showing $50\ \mu\text{m} \times 50\ \mu\text{m}$ Dose pads; (b) Dose pads, writefield alignment markers, and drift markers after development; (c) Large drift error caused by a system failure; (d) Resulting effect of drift failure showing a waveguide split.

Fig. 1.20 shows the structures that are always recommended to have on a GDS file. Fig. 1.20 (a) shows the GDS file; the writing area is divided into smaller $100\text{-}\mu\text{m}$ writefields. $50\ \mu\text{m} \times 50\ \mu\text{m}$ squares are drawn on the GDS file, and they have different doses (the numbers 0.85 to 1.15 represent the dose factors). This is done to find the correct clearing dose. There are also two vernier scales, one representing WFA and the other the drift. As can be seen from the GDS file, the WFA scale is placed exactly in the middle of two writefields in both x - and y -directions. This way, if the WFA is incorrect in any of the direction, it can later be analysed using these markers. The drift

scale is split into two separate layers and written such that the first half of the marker is written before the start of the write, and the remaining half is written at the end of the write. This way, if the beam drifts, the drift scale will be able to show the amount of the beam movement. Fig. 1.20 (b) shows the image after the patterning and development. From this image, the dose factor of 1 looks to be the correct clearing dose. WFA markers are also perfect, but the drift markers are not aligned. This was a rare occasion of a mechanical failure of the system that caused around 27 nm of drift in the y -direction following which the E-beam gun/filament failed. Fig. 1.20 (c) shows the zoomed in image for the drift marker showing a huge drift in the y -direction. Fig. 1.20 (d) shows the impact of this drift on the actual waveguides that were written during that patterning. It is evident from the figure that the drift led to a broken waveguide structure, unsuitable for optical characterization. Therefore such structures are always recommended to be added on every E-beam write. This way, fault analysis can be carried out on the chips even before testing the structures in the lab.

1.5.4 Etching

Etching is the process of transferring the design pattern into the underlying semiconductor material by removal of excess material around the desired feature. There are two types of etching processes as represented in Fig. 1.21: wet chemical etching and dry etching (also known as plasma etching). Wet etching uses chemicals or solvents to eat away the material. This process is generally isotropic in nature (it occurs in all directions evenly), and therefore it is not recommended when vertical sidewalls are desired; however, wet chemical etching leads to a significantly smoother etch surface.



FIGURE 1.21: Schematic representation of dry- and wet-etching processes.

Plasma etching, on the other hand, uses plasma generated using different gaseous reactants in a controlled environment to remove the materials [56]. This is the method which is most commonly used to create integrated nanophotonic devices. There are different types of plasma etching systems

based on the way the plasma gets generated and accelerated towards the material. The most widely used plasma etching system is based on the combination of an inductively-coupled plasma and reactive-ion etching (ICP-RIE). This type of plasma etching has been used for almost all the samples demonstrated in this thesis work. The advantage that such a system provides is that it has two separate RF coils, one for the generation of plasma (ICP) and the other one for its acceleration towards the substrate (RIE), which explains the system name ICP-RIE. There are three main mechanisms or processes occurring in plasma etching: sputtering (or physical etching), chemical etching, and ion-enhanced chemical etching (a combination of the two).

Sputtering: The etching happens merely by physical bombardment of the material with inert atoms (*e.g.*, argon plasma is the major contributor to the physical etching). Argon, being an inert gas, does not chemically interact with other materials. Because of the large atomic mass, it physically bombards the substrate under etching to chisel off the material. That is why, if physical etching (ICP) is the only etching mechanism, the etched sidewalls tend to exhibit a lot of roughness.

Chemical etching: This is similar to the wet chemical etching where acids/solvents are used; the only difference being that a plasma is used instead of the solvent. In chemical etching, the plasma chemically reacts with the material, etching it away while creating etching byproducts that are typically volatile and therefore do not remain on the material's surface. For example, chlorine plasma reacts with GaAs to create highly volatile gallium chloride and arsenic chloride.

Ion-enhanced chemical etching: In this process, the combination of both the chemical etching and physical sputtering is used to remove the excess material, thereby yielding the advantage of a smoother facet and highly anisotropic profile (which is good for vertical sidewalls required in most waveguide structures). The chemical plasma weakens the material bonds, while the argon plasma hits the weakened bonds, thereby increasing the etching rate of the process.

Plasma etching has a number of variables to use as the process controls; some of them are described below.

Gases and gas flow: Different gas chemistries are used to etch different materials. The materials such as silicon, silica, silicon nitride are known to be etched in fluorine-based gases such as CF_4 , SF_6 , whereas III-V semiconductors are known to be etched in chlorine-based gases like Cl_2 , BCl_3 , CCl_4 , SiCl_4 . These

gases chemically combine with the material to be etched to release byproducts in the form of other solids or gases. As mentioned earlier, there are also inert etchants such as argon, contributing to the process physically, which, in combination with the aforementioned gases, can aid the etching process. Some of the gas plasmas have a particular characteristic color. For example, argon plasma is bluish-pink, and chlorine plasma is grey. The flow of the gases is typically quantified in the units of standard cubic centimeter (sccm).

ICP power: This variable controls the amount of plasma which is generated by the top coil in the chamber; the power is measured in watts.

Bias power: This variable controls the acceleration at which the plasma comes towards the material to be etched. As a rule of thumb, the larger the bias, the larger is the etch rate.

Chamber pressure: The pressure inside the chamber is also an important variable in the etching process. The energy of the particles and ions in the chamber, and their movement and direction is controlled by the chamber pressure. The typical chamber pressure values range from 1 mTorr to a few hundred mTorr.

The choice of the substrate/carrier wafer: All the etching systems have a tray which holds the wafer or material to be etched; this is called the backing wafer or carrier wafer/tray. Depending on the system in use, the two common trays are either undoped silicon or quartz. The tray should be such that it does not react with the process gases in any way to hamper the etching process.

Two more important terms related to etching which have extensively been used in this thesis are the etch rate and selectivity. The etch rate can be defined as the amount of material/resist etched per unit time, and the selectivity is defined as the thickness ratio of the mask etched to the material etched:

$$\text{Etch Rate} = \frac{\text{Material Etched}}{\text{Time}}; \quad \text{Selectivity} = \frac{\text{Amount of Resist Etched}}{\text{Amount of Material Etched}}.$$

In this thesis, different plasma etching recipe development have been performed to etch the materials like PECVD silica, AlGaAs and InP.

1.5.5 Fault Analysis Tools

Fault analysis is imperative in fabricating any optical device. It is performed to determine how much the fabricated structures deviate from the design. Fault analysis is further used to find the root cause of possible errors after

the testing. The two main tools used for the fault analysis in this thesis are scanning electron microscope (SEM) and atomic force microscope (AFM). Below we briefly describe these tools.

Scanning Electron Microscope

SEM is the most used tool for all the work done in this thesis. An SEM is used to image the surface of any structure with the resolution up to a few nanometers. The way an SEM works is by scanning an electron beam and detecting the reflected electrons. When the electrons hit the surface of the sample under test, different physical processes can occur, causing the electrons' reflection off the sample's surface or from deeper layers. Most of the SEM systems have an in-lens detector that detects the SE1 electrons (generated from the place where the primary electron hits the material surface) and a secondary electron detector which is placed on the side and detects the SE2 electrons (generated from the backscattered electrons). Therefore, an in-lens provides more detail about the surface morphology, while SE2 is used for cross-section imaging or for better depth-of-field and contrast.

Atomic Force Microscope

AFM is a nondestructive process of fault analysis [57]. This process falls under the umbrella of scanning probe microscopy. The principle of operation is based on using a fine tip which remains in touch with the material's surface and can be swept across the surface to create a 3D topological structure of the surface. An AFM tool has a long cantilever and a pyramid-shaped tip attached to the end. The tip's height is usually a few micrometers, and the tip diameter is a few nanometers wide. The tip is used to raster-scan the surface to be imaged, which results in a high-resolution surface topography. In this thesis, this tool was largely used in Chapter 5 to measure the surface roughness after etching.

1.6 Contribution to knowledge and thesis layout

Since this thesis is majorly focused on fabrication, in Chapter 1 we started by introducing the basic concepts and tools used in fabrication of optical micro and nanostructures. Moreover, we provided the introduction and the details of the physics behind the tools used, the control variables of the tools, and some of the best practices.

In Chapter 2, we describe our developed recipe of silica hard masks for III-V semiconductor etching which were etched using SAMCO ICP-RIE plasma etcher. We developed a turnkey recipe to etch silica using ZEP520a e-beam resist negating the effect of RIE-lag. This recipe is now being used as a standard process by the uOttawa nanofab facility to etch silica. We also demonstrate that this process can work well with other photoresists to etch any type of silica layer. The process shared in this chapter can also be used by cleanrooms around the world to create repeatable silica masks using any soft mask.

Chapter 3 focuses on developing the fabrication processes for large-aspect-ratio structures and densely packed structures based on III-V semiconductor AlGaAs. The fabrication process development for these structures represents a number of challenges because the layers with different AlGaAs concentration are etched at different etch rates with different smoothness, and the etch rate varies drastically from place to place in the samples with variable feature densities. The latter effect is highly undesirable as it creates features etched to a different depth, leading to undesired results. We also demonstrated a selectivity of roughly 1:3 for etching AlGaAs using a soft mask ZEP520a. In Chapter 3, we demonstrate our effort at fabricating various passive AlGaAs components such as waveguides, photonic crystals, and ring resonators, and successfully address the challenges associated with fabricating the large-aspect-ratio structures and the structures with variable feature density. The fabrication processes introduced in this chapter provides a thorough study of fabricating passive structure of various critical dimensions using AlGaAs platform. Additionally, the etch process introduced in this chapter to etch AlGaAs using a soft mask ZEP520a was optimized resulting in an etch selectivity improvement to 1:2.9.

Chapter 4 is our first effort at designing, fabricating and testing deeply etched photonic-crystal (PhC) line-defect waveguides operating in the second bandgap lying above the light line. The optical modes below the light line are known to be guided by TIR, whereas the modes above the light line are either reflected or radiated in the continuum. This was one of the first demonstrations of guided modes lying above the light line in an AlGaAs PhC waveguide. We designed and fabricated different lengths of photonic-crystal waveguides, and we provide a detailed study of estimation of loss as the length of the photonic crystal changes.

In Chapter 5, we describe our efforts at fabricating InP waveguides using a 3-layer InP/InGaAsP heterostructure. We developed a repeatable etch process for creating large-aspect-ratio (with the value of 1:10) structures in InP with heated substrate using silica mask. The challenges associated with etching InP (the heated etching requirement), discussed in the chapter, are properly addressed in the process of the sample fabrication. There are very few nonlinear optics studies performed using InP/InGaAsP platform. Further, there is no detailed study on plasma etching of InP-based nonlinear photonic devices. This work serves as one of the first such studies reporting on plasma etching of InP/InGaAsP half-core and nanowire waveguides. The fabricated waveguides were used to measure two-photon absorption coefficient (TPA) of 19 cm/GW and nonlinear refractive index coefficient n_2 value of 1.9×10^{13} cm²/W for InGaAsP/InP at 1550 nm. The latter was the first accurately measured value of n_2 coefficient in InP waveguides.

In Chapter 6, we completed a theoretical study of the third-harmonic generation in suspended AlGaAs photonic crystal waveguides. We also describe the process of creating suspended structures (surrounded by the air) in AlGaAs using a combination of plasma etching and wet chemical etching. The PhC waveguide was dispersion-engineered to have a flat group index for a 10 nm bandwidth centered near 1596 nm with the aim to generate the THG at 532 nm. We also demonstrate an optimized coupler design which enhances the coupling efficiency for the PhC and fabricate coupling waveguides to have the complete structures suspended. This is the first theoretical study of THG in AlGaAs photonic crystal waveguides.

Chapter 7 is a summary of 3 additional projects that I undertook in the course of this PhD. In the first work, we fabricated kagome-lattice photonic-crystal waveguides in silicon. Such structure can exhibit very high group index values (around 10^4) [58]. In the second project, we performed the experimental characterization of third-harmonic generation in silicon nitride waveguides. Finally, in the last work, we came up with a solution to the problem of tracing back the index-guided modes existing in photonic crystal waveguides. Our proposed method takes one order of magnitude less time and is extremely accurate compared to obtaining the same results using the more rigorous (yet time- and resource-consuming) 3D-FDTD. This novel method can be of significant importance in studying interesting effects in photonic crystal lattices such as bound states in continuum (BICs), residing in the higher-frequency regions on the band diagram.

Chapter 8 is the concluding chapter presenting the summary of all the work performed in this thesis and detailing the next steps in the projects. The chapter also presents the future outlook of the field.

Chapter 2

Developing Silica Masks for III-V Etching

In this chapter, we discuss the results for creating a repeatable and turnkey plasma etching recipe for etching silica. Integrated III-V semiconductor devices based on multilayer heterostructures generally require large etching depths [59]–[61]. Common photoresists and E-beam resists offer a very poor etch resistance, and therefore deeply etched structures are unachievable with the resists alone as etching masks. To obtain deeply etched structures, we need a mask that erodes at a much lower rate compared to the etching rate of the actual semiconductor. Such masks are called hard masks. Silica is known to be a durable hard mask for all types of III-V materials. The etching process of III-V semiconductors masked with silica exhibits the selectivity of almost 1:10; that is, for every 1 nm of silica etched, there is 10 nm of III-V semiconductor etched. The benefit of large selectivity makes it possible to etch structures with microns of etch depth. Therefore, silica hard masks are a preferred mask option when large etch depths are required.

The rest of the chapter is organized as follows. We first provide a description of the standard process flow associated with the fabrication of III-V photonic devices (in more specifics than we described it in Chapter 1). After that, we describe the modifications that we proposed to this standard process, and show the results achieved with the simplified procedure that we developed.

2.1 Standard Process Flow

The most common process flow that has traditionally been used [59], [60], [62], [63] to fabricate III-V semiconductor devices is shown in Fig. 2.1. The first step in this process is silica deposition on top of the III-V wafer; this

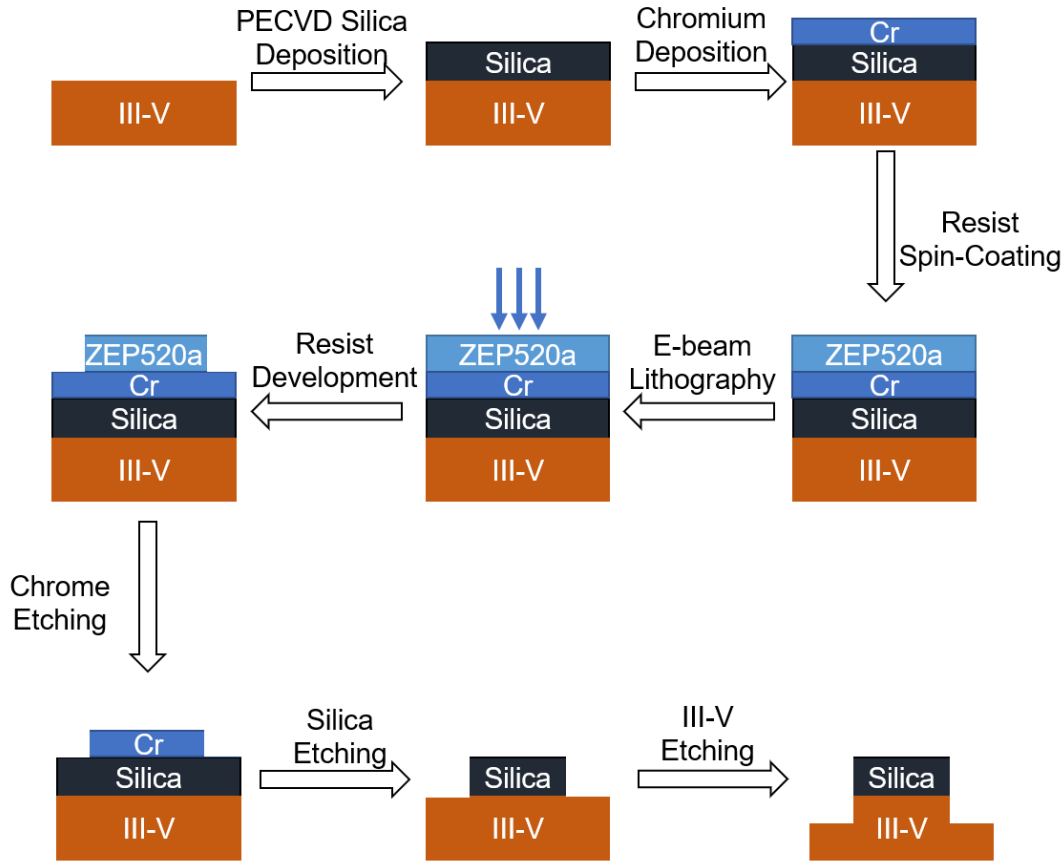


FIGURE 2.1: Standard process flow for III-V semiconductor integrated photonic device fabrication.

layer will serve as a hard mask at the final etching step. Then a layer of chromium is deposited, which is used to etch the silica layer. Once both the silica and chromium are deposited, an E-beam resist is spin-coated on top of the chromium layer, and the desired structures are written in it. The E-beam mask is then used to etch the chromium layer, and the chromium mask is used to etch the silica layer, which eventually creates the required etching mask for a III-V semiconductor. For the facilities where multiple etchers are readily available with turnkey processes for etching chromium and silica, this process works well. Although this process flow is widely used, it includes multiple deposition and etching steps requiring different chemistries [60], [62], thereby adding complexity to the fabrication process. Also, if the CD has very tight tolerances (that is, a small change in the structure dimensions can lead to a large change in the device properties), multiple etch steps are not recommended as there are always a few nanometers of bias between the mask layout and the structure dimension after etching. Consequently, the larger the number of etching steps, the larger would be the bias variable.

One way to eliminate the complexity is by using certain new E-beam resists such as HSQ [64] that provide great etch resistance and can serve as a solo mask in the etching process, allowing one to bypass additional steps. However, these resists come at an exceptionally high price, and they have a very low shelf life (typically around 6 months). It is thus necessary to explore possible alternative scenarios allowing one to affordably reduce the process complexity.

The University of Ottawa's cleanroom facility has only one ICP-RIE system. In addition, the rules do not permit the etching of chromium (or other metals) on the tool. Moreover, it is a shared tool that stays in fluorine-based chemistry for half a year for etching silicon and silica-based materials, and the other half a year in chlorine-based chemistry for III-V etching. To make the best use of the tool, we performed a recipe development for etching silica using E-beam resist ZEP520a, which is readily available at the in-house facility. The etched silica mask can then be used to transfer the pattern to the underlying III-V layers.

Silica can be deposited using different physical processes, the most common of which are spin-coating (for HSQ which turns silica-like), E-beam evaporation, chemical vapor deposition, and physical vapor deposition. The mask resistance varies drastically for each of these methods because of the different physical characteristics and interlinking bonds of the resulting silica films. We experimentally determined the etch rates of different types of silica which can be used as masks, and the etch resistance in increasing order is as follows:

Evaporated Silica $\rightarrow$ PECVD Silica $\rightarrow$ Thermally grown silica

For this work, initial trials were done using evaporated silica but the etch resistance was very poor. Therefore we decided to deposit silica using the LPCVD system available at Carleton University. LPCVD deposited silica is known to have etch resistance similar to that of PECVD silica because both are chemical vapor deposition based methods.

2.2 Proposed Process Flow

Fig. 2.2 shows the new process flow that we propose. In this flow, as we mentioned, we attempt to remove the additional steps of chromium deposition and etching. The samples were cleaved in $2\text{ cm} \times 2\text{ cm}$ pieces, cleaned

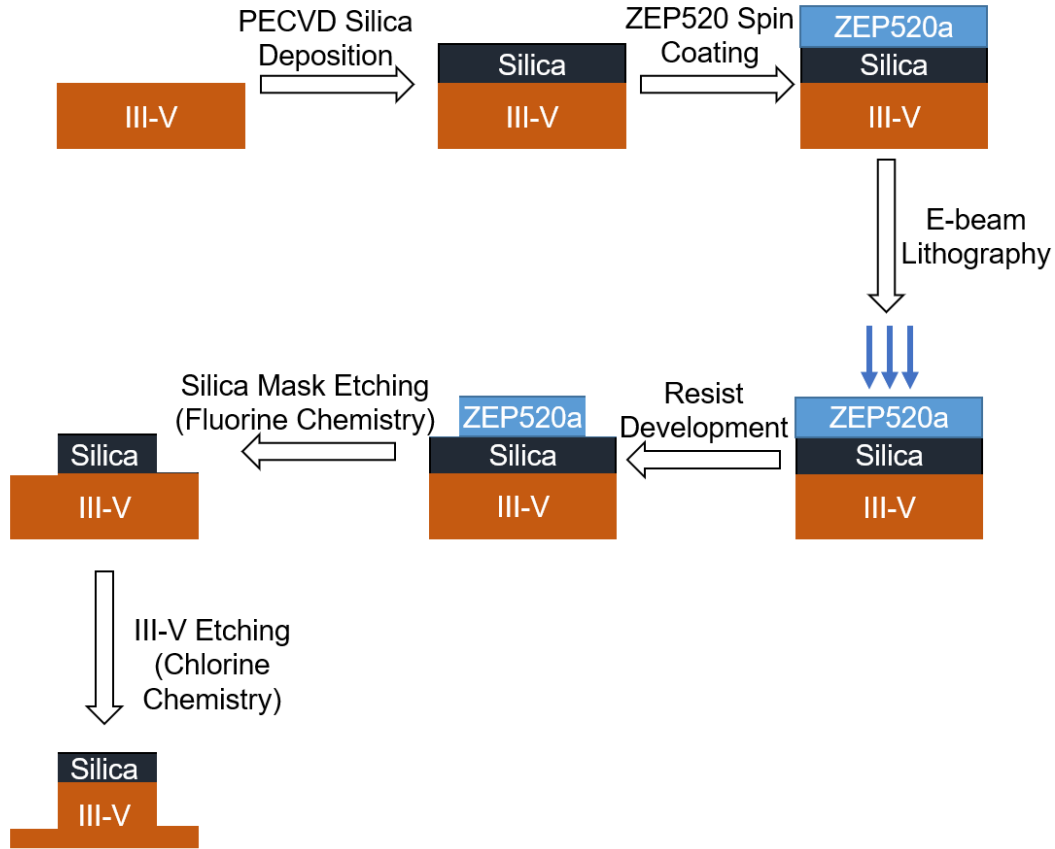


FIGURE 2.2: Proposed process flow for creating silica masks for III-V etching.

in acetone and IPA, and blow-dried with nitrogen afterwards. A silica layer with the thickness of 360 nm was then deposited using the LPCVD tool at Carleton University.

The samples with deposited silica were cleaned again and spin-coated at 2000 rpm using fresh ZEP520a to get an approximately 500-nm-thick resist layer. This process was followed by 3 minutes of prebake at 180 °C to evaporate all the solvent. The patterns with the gaps varying from 100 nm to 1 μm were written using a 30-kV Raith E-beam system at an acceleration voltage of 30 kV and a 10-micron aperture with a base dose of 80 $\mu\text{C}/\text{cm}^2$, and then developed in n-amyl acetate for 90 seconds. After that, they were rinsed in IPA to stop the development process. Fig. 2.3 shows the structures for an etch test sample. The GDS file had waveguide structures with varying gaps spanning across the entire chip in the x -direction, and long-length chains of holes in 2D triangular lattice patterns covering the entire space on the chip in the x -direction. The same pattern was repeated in the y -direction with 2000 μm gaps to leave cleaving space. This large chip was

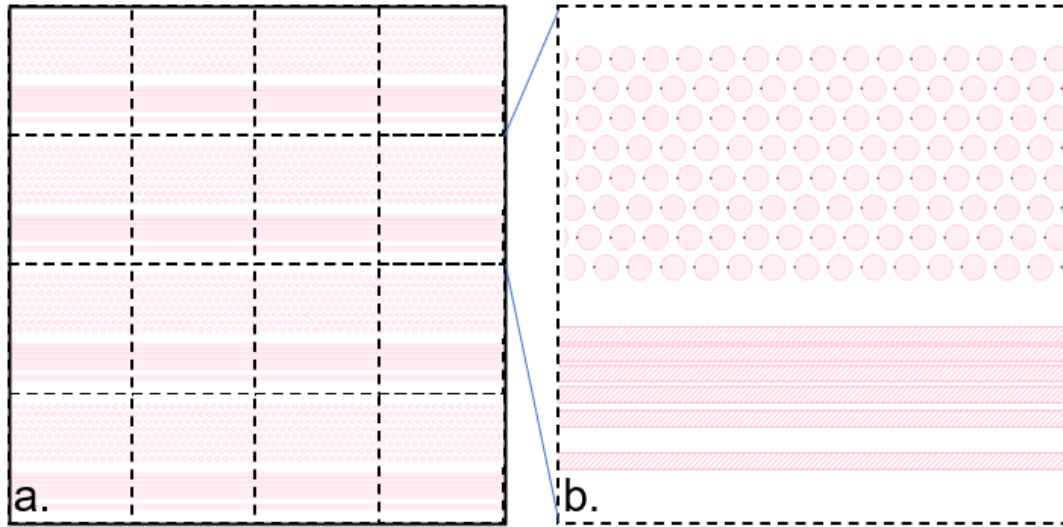


FIGURE 2.3: GDS file of etch test structures- (a) Dotted lines show the points for cleaving the structures to make smaller etch-test samples; (b) Zoomed-in image of the structures placed on a single etch test sample.

further cleaved to make even smaller ($3\text{ mm} \times 3\text{ mm}$) etch-test samples such that every single etch test sample had the exact same structures. Fig. 2.3 (a) shows the largest chip, and the dashed lines represent the cleave boundaries. Fig. 2.3 (b) shows a zoomed-in image of the features on one small etch test sample ($3\text{ mm} \times 3\text{ mm}$), which is further cleaved in the middle for cross-section imaging. Fig 2.4 shows the cross-section SEM image of the developed 550 nm ZEP on silica mask.

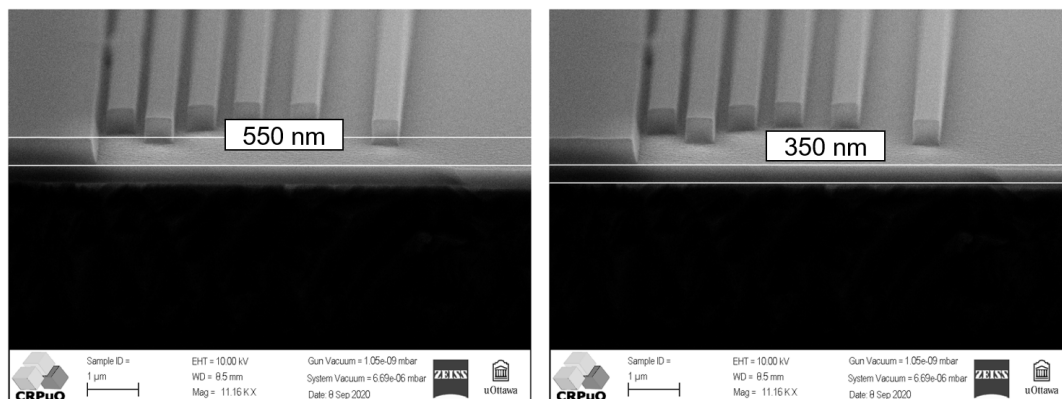


FIGURE 2.4: Cross-section SEM image of ZEP on Silica after the development (a) ZEP thickness was measured to be 550 nm, and (b) silica thickness was measured to be 350 nm.

As seen in the process flow above, we were able to get rid of one additional deposition and etching step (chromium). Etching trials were then performed

starting with CF_4 and oxygen plasma, but the results revealed the etch rate of ZEP as 508 nm/min and for silica as 146 nm/min, giving a selectivity of 3.47, which was too low to etch the entire silica layer. Next, etching trials were performed using CH_4 and Argon. Argon ions do not chemically react with any materials; they are only used for physical bombardment and result in a faster etch rate. Systematic trials were performed by first keeping fixed concentrations of argon and CF_4 at 2 sccm and 15 sccm, respectively. The ICP was fixed at 150 W; the pressure and etch duration were kept fixed at 0.2 Pa and 50 seconds, and 3 tests were performed by setting the bias power to 25 W, 50 W and 75 W. This led to a ZEP:Silica selectivity of 1:0.23, 1:0.37, and 1:0.38, respectively and really slow etch rates. Clearly, this was not good enough because these selectivity values mean that we would need at least 900 nm of ZEP to etch the 360 nm of silica, which is not possible. Next, some etch tests were performed where we varied the concentration of argon and tuned the ICP values. However, no results led to the desired selectivity. We later concluded that the reason for the lower etch rate was the backing wafer (carrier wafer) used to hold the etch test samples, which was made of quartz. Having quartz as the backing wafer contributes to the etching process as CF_4 and Argon ions react with quartz to releases more oxygen ions in the chamber, which leads to a lower etch rate of silica, hence the lower selectivity. Therefore, we tried some etch tests by changing the wafer tray to undoped silicon.

2.3 Results

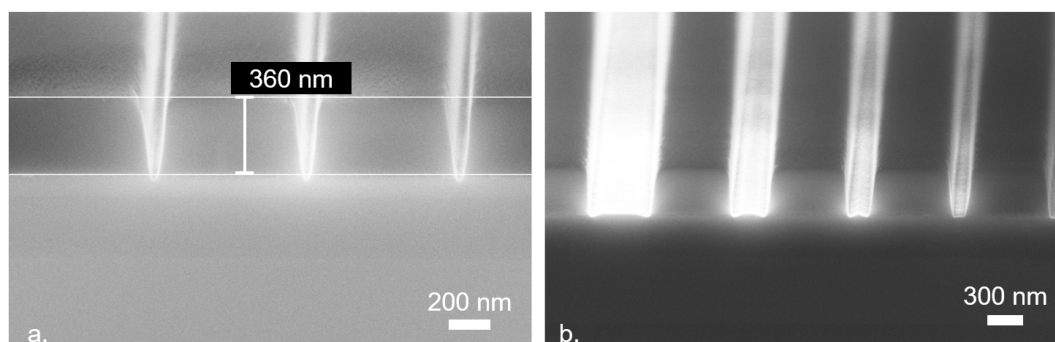


FIGURE 2.5: (a) Cross-section SEM image of silica etched completely; (b) All the gaps being etched at the same rate.

Systematic etch trials were repeated while varying gas concentrations and changing the ICP with silicon tray to hold the etch test samples, and changing the backing wafer, indeed, improved the selectivity from the previous best of

1:0.38 to 1:0.57 in the very first trial. We further fine-tuned the recipe by tuning the bias values and were able to etch the silica layer completely with nearly vertical sidewalls, as shown in Fig. 2.5 (a). Not only this, by playing with the pressure and bias values, we were able to etch all the dimensions at the same etch rate, which is uncommon in plasma etching. The result is demonstrated in Fig 2.5 (b). The optimized etch recipe is as follows:

$$\text{Ar:CF}_4=(2:15) \text{ sccm, ICP} = 150 \text{ W, Bias} = 75 \text{ W, P} = 0.2 \text{ Pa} \quad (2.1)$$

With this process, we obtained an etch rate of ZEP as 391 nm/min, and that of silica as 270 nm/min, which yields a selectivity of 1:0.68 (ZEP:silica).

2.3.1 RIE Lag

RIE lag is a common phenomenon in plasma etching which means that smaller trenches are etched at lower rate as compared to larger gaps [65] as shown in Fig. 2.6. This is also valid for the structures which are densely packed and therefore etch slower compared to isolated structures which etch faster. This will be further discussed in the next chapter. RIE lag happens because of the plasma acceleration which is controlled by the reactive ion etching. The RIE parameter depends on the total area that the plasma sees. When making masks, it is crucial to minimize this effect. This is usually done by overetching the wider gaps until the narrower gaps just have their mask completely etched through, but this comes with a compromise of overetching the larger gaps to the point that we reach the semiconductor, or changing the shape of the larger trenches at the bottom. In the method that we propose, by controlling the RIE and chamber pressure values, we were also able to get rid of the deleterious RIE lag and to etch all the gaps at the same rate. This is extremely important when making multiple structures with different dimensions on the same chip.

As mentioned previously, the etch rate of silica for this process was 270 nm/min, therefore, 1 minute 20 seconds were needed to etch the 360 nm of silica completely. To compare how drastic the effect of changing the backing wafer is, we did another test with the exact same recipe and duration but by changing the backing wafer to quartz, and this resulted in only 84 nm of silica etching as shown in Fig. 2.7 (a), whereas using the silicon backing wafer, we were able to completely etch the silica layer as shown in Fig. 2.7 (b). This means that due to the additional oxygen ions in the chamber, the etch

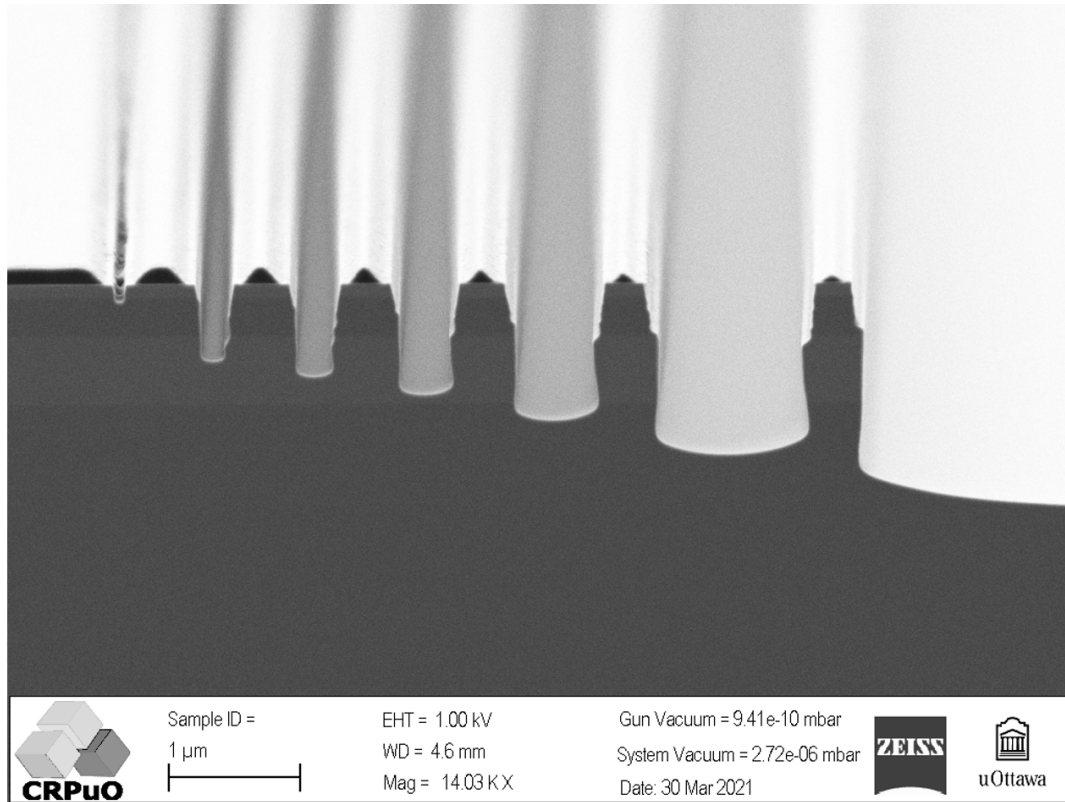


FIGURE 2.6: Cross section SEM imaging showing RIE lag.

rate reduces by almost three times. In Fig. 2.5 (a), we can see that 150 nm gaps written on AlGaAs heterostructure are etched to the bottom of the substrate, whereas image (b) shows the same etch recipe performed with a silica backing wafer. Clearly, for Fig. 2.5 (b), we can see the reduced etch rate due to the additional oxygen ions in the chamber which slows down the etch rate.

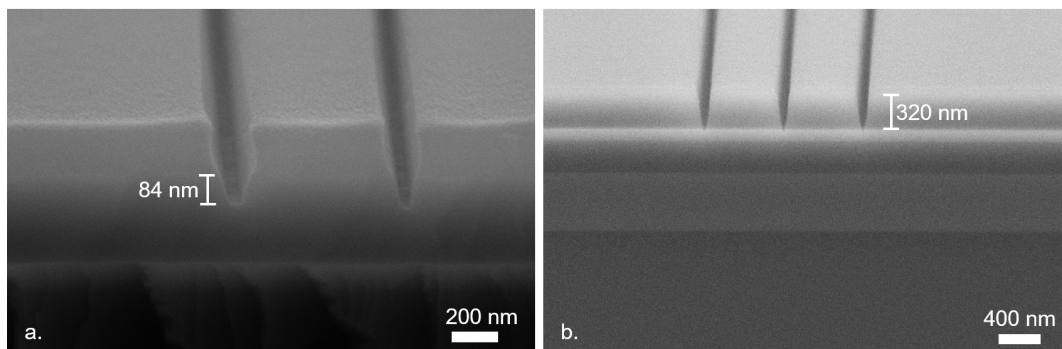


FIGURE 2.7: Cross-section imaging of etched silica using (a) silicon backing wafer; (b) silica backing wafer.

2.4 Conclusion

In summary, we were able to develop a highly repeatable and reliable recipe to etch silica using ZEP mask. Since we wanted to develop a recipe which can be used as a turnkey process by multiple users, not only with ebeam resist but also with photoresists (PRs) for the structures written by photolithography, we tried some more tests using the same recipe as introduces earlier (2.1) but by patterning larger structures using optical lithography on a photomask. We spin-coated 10 μm of SPR-220 on a silicon wafer covered with 1 μm of thermally grown silica. Large vias ranging 50-100 microns in diameter were patterned and the etching trials were performed using the previously developed etch process. The results were as expected. Fig. 2.8 (left) shows the vias patterned and etched and the image on the right shows the zoomed-in image of the vias. We can see that 7 μm of PR was left while 540 nm of silica has been etched. The selectivity is very different in this case because PRs are known to have poorer etch resistance, and this was a thermally grown silica which is known to be more etch-resistant. In conclusion, we were able to develop a highly repeatable etch process for etching silica, in-house, which is being used as a turnkey recipe to etch all kinds of silica by multiple users. This silica mask etching process was used in most of other projects discussed in the next few chapters.

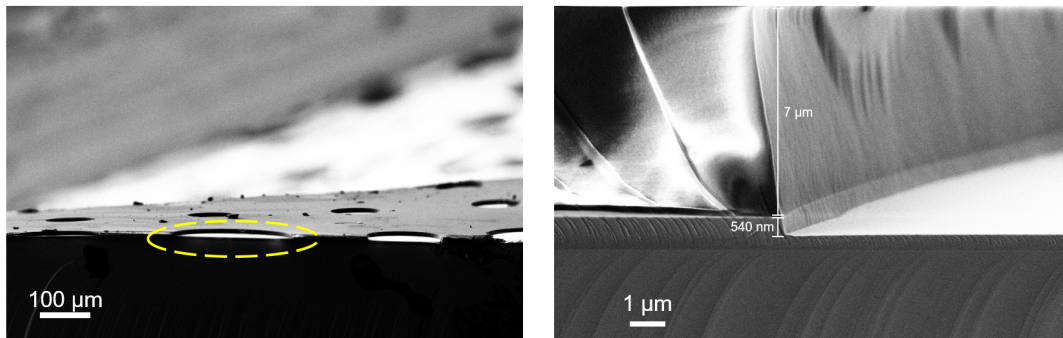


FIGURE 2.8: Cross-section SEM image of patterned and etched holes using photoresist SPR-220 (left). The encircled area is zoomed in and shown on the right; 540 nm of silica etched and 7 μm of photoresist remaining (right).

Chapter 3

Fabrication of Densely Packed and High-Aspect-Ratio AlGaAs Nanostructures

AlGaAs is one of the most extensively studied III-V semiconductor materials in nonlinear optics [63], [66]–[69]. Like most III-V semiconductors, it has a direct bandgap for aluminum concentrations of less than 45%. Therefore, laser sources and detectors can be made using this material [70], [71]. It has a high linear refractive index in the telecommunication regime, tunable from 2.9 to 3.4 depending on the aluminum concentration (changeable from 100% to 0%, respectively) [72]. Further, AlGaAs features a high nonlinear refractive index and second- and third- order nonlinear susceptibilities [66]. It also has a large transparency window (0.9 to 17 μm). AlGaAs is considered to be a suitable material platform for the nonlinear optical applications in the telecommunications C-band due to low two-photon absorption near 1550 nm, which can be accomplished by tailoring the energy gap of AlGaAs through varying the aluminum concentration. Specifically, it has been demonstrated that $\text{Al}_{0.18}\text{Ga}_{0.82}\text{As}$ exhibits a negligible two-photon absorption and a small three-photon absorption at 1550 nm [73]. Thanks to the favorable nonlinear optical properties of AlGaAs, the nonlinear optical processes such as SHG, THG, FWM, supercontinuum generation, self- and cross-phase modulation have been demonstrated in this platform [61], [63], [74]–[76].

Another important advantage this material offers is defect-free growth. AlGaAs, for almost all the concentrations of aluminum, is perfectly lattice matched to GaAs (AlAs and GaAs have closely matched lattice constants, as evident from Fig. 1.5), which means that epitaxial films of any concentrations $\text{Al}_x\text{Ga}_{1-x}\text{As}$ can be grown on GaAs without any defects or stress in the films.

Lattice matching is a very important property for the consistent production of low-loss optical devices.

There have been several well developed processes for plasma etching of AlGaAs [60], [62], [77]. The majority of these studies were performed in standalone waveguides with low aspect ratios (*structure width : etch depth*). While fabricating these passive structures based on AlGaAs, we realized that one single fabrication process does not serve all the designs. Variation in design features and etch depth requirements necessitates widely different parameter tuning. The E-beam and etching processes vary drastically as the structure density or aspect ratio requirements change. In this chapter, we describe our efforts at fabricating AlGaAs photonic-crystals waveguides, ring resonators and high-aspect-ratio waveguides. We discuss the challenges associated with the defect-free fabrication of each type of these devices, and describe how we mitigated these issues.

E-beam lithography was used for patterning all the aforementioned structures. E-beam is a fairly standard process, and for a fixed resist thickness, the patterning recipes do not vary much for structures with similar sizes. However, the processes change significantly when the structure's size and density change. This is primarily because of the additional doses at undesired locations caused by the back-scattered electrons causing the proximity effects, as it was discussed in Chapter 1. It becomes extremely important to make use of the proximity-effect correction (PEC) to prepare the lithography files, especially for densely packed structures and structures requiring narrow gaps (*e.g.*, the gaps between the ring and the bus waveguide). For the structures that will be discussed in the upcoming sections of the chapter, although the base dose remained the same for all the exposures, PEC was performed before the patterning. This was confirmed by doing a dose test before starting the E-beam writing.

Fig. 3.1 shows an optical microscope image of a dose-test sample. The image on the left shows larger squares with 50- μm side that provide a coarse estimation of the clearing dose. A dose value is set, and the dose factors are varied in the GDS file from $0.85 \times$ the base dose to $1.15 \times$ the base dose. For example, if the base dose is set to $100 \mu\text{C}/\text{cm}^2$, the dose values at the top and the bottom of the set are 115 and $85 \mu\text{C}/\text{cm}^2$, respectively. The square which comes out the cleanest (looking at the edges and corners) is known to be the correct “clearing dose”. As we can see from the particular example shown in Fig. 3.1 (a), the dose structure with a dose factor of 0.85 clearly

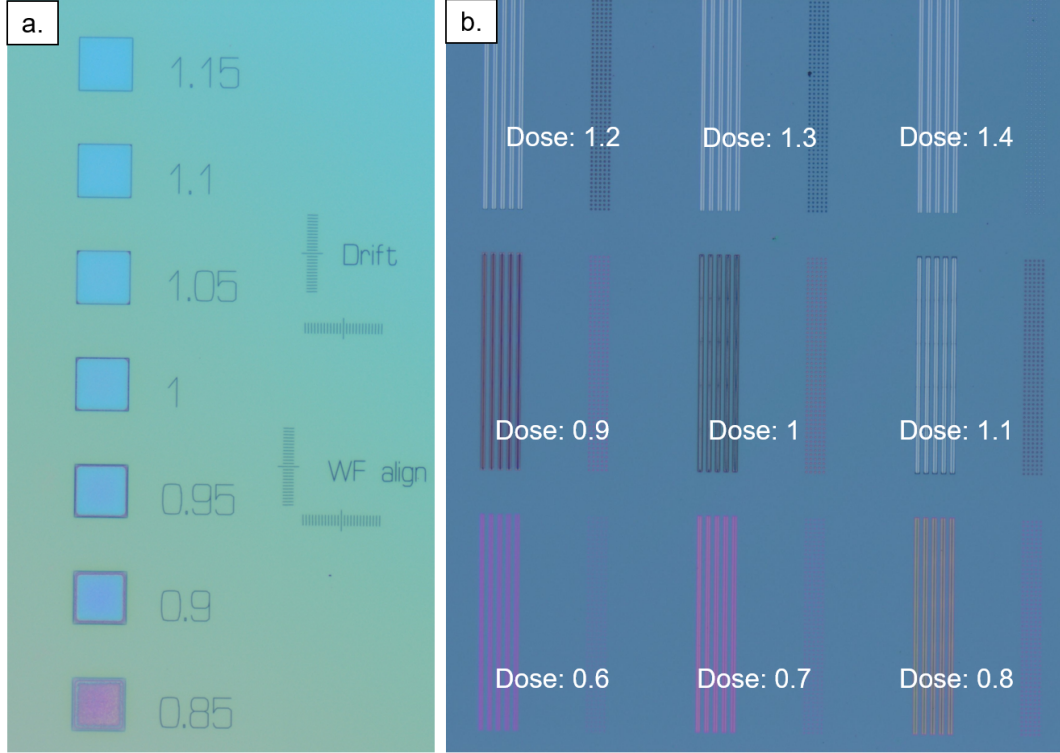


FIGURE 3.1: Optical microscope image for a dose test: (a) A coarse dose test using 50-micron test structures; (b) A finer dose-test array using the actual designed structures.

seems to not have developed. Similarly, 0.9, and 0.95 are also not fully developed. The dose factors of 1 and 1.05 appear to have cleared in the middle. However we can see that they are not fully developed at the corners. The dose factors of 1.1 and 1.15 seem to clean the squares completely. This means that 1.1 is a good starting dose factor for a finer dose test. If the base dose is $100 \mu\text{C}/\text{cm}^2$, a dose factor of 1.1 indicates that the clearing dose for the structures is $110 \mu\text{C}/\text{cm}^2$.

Once a coarse dose is determined, a copy of the exact structures (waveguides, gaps, or rings) is patterned, and a dose matrix is created to determine the correct clearing dose for the individual elements. As we can see from Fig. 3.1 (b), a base dose of 1.2 works better for the waveguides but a base dose of 1 is enough to clear the holes. Once this dose factor is confirmed, the next step is performing PEC.

Another important consideration while patterning structures using E-beam is the writefield alignment (WFA) which was also briefly discussed in Chapter 1. Whenever longer structures are written that span across more than one writefield, WFA becomes crucial. For the waveguides that span across a few

100s of writefields, if WFA is not performed correctly, discontinuities along the waveguides will be visible, which can act as points of optical leakage or loss. Similarly, for the ring resonators or photonic crystals, the position of the structures on the GDS file becomes crucial. If the length of the critical structure is under $100\text{ }\mu\text{m}$ (which is the size of the writefield window), the structures should be placed such that they fall under a single WF instead of crossing multiple WFs. All these individual considerations for every single device will be discussed in the next few sections.

The plasma etching process changes drastically when the structures are densely packed. This happens because the total surface area from which the material needs to be removed is increased. Also, RIE lag is very common in plasma etching, which means that the larger the gaps/trenches, the deeper would be the etch depth.

Selectivity in plasma etching also largely depends on the resist or the mask being used. For the majority of the devices fabricated in this chapter, the processes were developed using 500 nm of ZEP520a as a resist, which is known to have a selectivity of 1:1 for etching most III-V semiconductors. As a result, there have not been any in-depth studies of etching AlGaAs using ZEP as a mask because its selectivity is known to be fairly low. By adjusting the etching parameters, we were able to etch close to $1.5\text{ }\mu\text{m}$ of AlGaAs using ZEP as a mask for stand-alone structures, obtaining a selectivity of 1:3. This result indicates that waveguide-like structures (which are not densely packed, or do not have small gaps) can be etched to this etch depth without the need for a hard mask, thereby eliminating the steps of silica deposition and etching. However, densely packed structures and the structures with small gaps are usually not etched at the same rate as stand-alone structures. Therefore there is a need to develop separate etch recipes subject to the design constraints.

There are several steps that precede the fabrication process. The first step is finalizing an epitaxial stack. Since we are looking at fabricating light-guiding devices, we need to make sure that the epitaxial stack is appropriate for supporting TIR. The minimum requirement for the light to be guided through any medium is having a high-index core and low-index surrounding claddings. Therefore, to create an epitaxial stack using AlGaAs, the aluminum concentration must be adjusted such that the core layer has the maximum refractive index whereas the claddings have relatively low refractive indices. The next step is to design the actual integrated optical components

using numerical mode solvers. The majority of the design work was carried out using Ansys Lumerical's MODE and FDTD solvers, and some open-source software such as MPB and MEEP [78]. Once the epitaxial stacks and designs are finalized, the devices are ready for fabrication. In this chapter, we explore the fabrication processes for different passive optical structures based on an AlGaAs platform.

For the devices described in this chapter, we determined one common epitaxial stack that should accommodate for all these structures. It has been demonstrated that AlGaAs with 18% aluminum works best for nonlinear optical applications in the telecom C-band frequency range as it has low linear, two-photon and three-photon absorption at these frequencies [73]. Therefore, we selected Al_{18%}Ga_{82%}As as the core layer, which exhibits a refractive index of 3.28 at 1550 nm. Fig. 3.2 (a) shows how the refractive index of Al_xGa_{1-x}As changes with the variation of the aluminum concentration. To create the refractive-index contrast, the concentration of Al in the claddings must be higher than 18%. Ideally, to achieve the maximum refractive index contrast, one can use AlAs as the claddings. However, it has been observed that for AlGaAs layers with the Al concentration higher than 70% the aluminum starts to oxidize. This process is accompanied with an uncontrolled change in the refractive index and with the formation of the scattering centres, which leads to undesired shifts in the output spectrum and scattering losses. Taking this into consideration, we kept the cladding composition at Al_{70%}Ga_{30%}As with the refractive index of 3.05 at 1550 nm. Since we have a high-aluminum-concentration layer at the top, to prevent the stack from oxidizing, we capped it with a 100-nm GaAs layer. This epitaxial layer arrangement was grown on top of a GaAs substrate with lattice-matching fulfilled. Fig. 3.2 (b) shows the schematic representation of the resulting cross-section for the designed epitaxial stack (as described above) used in all the AlGaAs projects in this thesis.

In nonlinear optics, the ratio

$$\frac{1}{T} = \frac{n_2}{\lambda_0 \alpha_2} \quad (3.1)$$

is introduced as the nonlinear figure of merit for evaluating the nonlinear optical performance of a material [79]. The T -parameter depends on the nonlinear refractive index n_2 , two-photon absorption (TPA) coefficient α_2 and the wavelength of operation λ_0 . For a material to be considered suitable for nonlinear optical applications, the T -parameter should be less than 1.

For $\text{Al}_{18\%}\text{Ga}_{82\%}\text{As}$, $T = 0.6$ at 1550 nm, which is a lot lower compared to the corresponding values for silicon ($T = 1.9$) and GaAs ($T = 14.5$) [80]. This is because the TPA coefficient of $\text{Al}_{18\%}\text{Ga}_{82\%}\text{As}$ at 1550 nm is 0.05 cm/GW, which is one order of magnitude smaller compared to that of silicon and almost 2 orders of magnitude less than that of GaAs. This was the primary reason we selected this epitaxial stack with the core-layer composition $\text{Al}_{18\%}\text{Ga}_{82\%}\text{As}$.

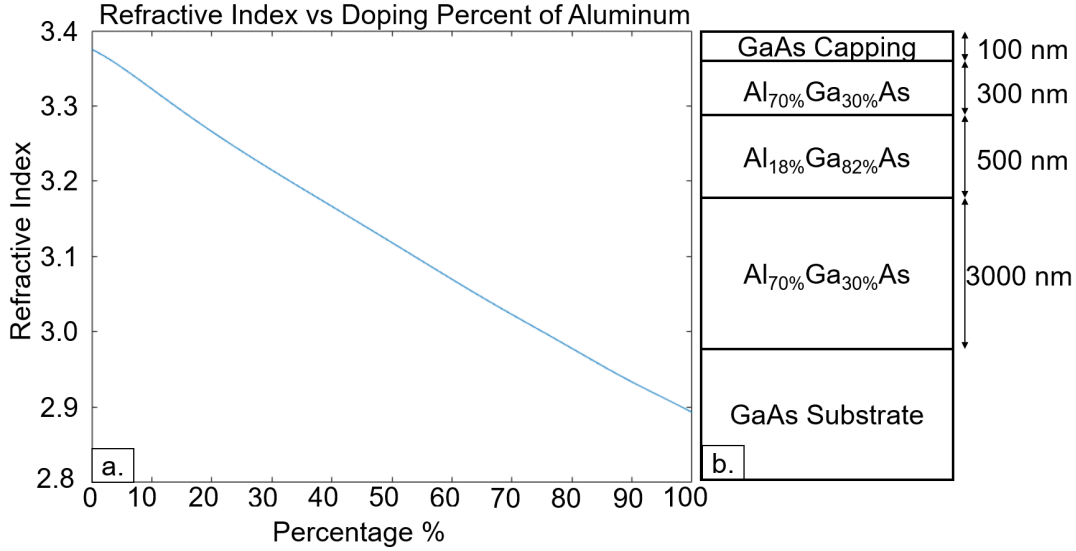


FIGURE 3.2: (a) The refractive index of AlGaAs as a function of the Al concentration expressed in percents [72]; (b) The finalized AlGaAs epitaxial stack used for all the devices described in this chapter.

3.1 Fabrication of Waveguides

Waveguides are the most basic building block of an optical chip. Recently, Espinosa, *et. al.* [63] demonstrated FWM in three different waveguide geometries using the epitaxial stack shown in Fig. 3.2 (b). These structures were produced using the process flow shown in Fig. 2.1. In this section, we describe our results of fabricating similar waveguides with large etch depths using only ZEP520 as a mask, thereby bypassing the need for a hard mask. Since ZEP520a is known to have a selectivity of 1:1 for III-V etching, theoretically, it can resist the etching process up to a maximum of 500 nm of AlGaAs only. This is because after depositing 500 nm of ZEP520a the resist starts to crack and it cannot be deposited at a spinning speed slower than 2000 rpm.

We started the fabrication process by first cleaving the wafers using a diamond scribe into small $1.5\text{ cm} \times 1.5\text{ cm}$ pieces. These pieces were cleaned using acetone, IPA and DI water, and then blow-dried with nitrogen. ZEP520a was spin-coated at a spinning speed of 2000 rpm, and then the samples were pre-baked at 180°C for three minutes, which resulted in a 500-nm-thick resist layer. Waveguide patterns with varying gaps were written using the Raith Pioneer E-beam system at CRPuO's cleanroom facility. The structures were written at 30 kV acceleration voltage with a clearing dose of $75\text{ }\mu\text{C}/\text{cm}^2$. After the patterning, the structures were developed in n-amyl-acetate for 90 seconds to reveal the waveguide patterns in ZEP. Since ZEP is a positive-tone resist, the inverse of the structures was written, that is, $2\text{-}\mu\text{m}$ -wide trenches on either side of the waveguides were written, leaving the waveguides standing out as islands surrounded by the trenches. The trench width was chosen to be $2\text{ }\mu\text{m}$ because anything less than that would have created a problem of light coupling into the side slabs. The coupling objectives used in the experimental setup for the characterization focus light down to a spot size of around $5\text{ }\mu\text{m}$ in diameter, and $2\text{ }\mu\text{m}$ is a safe width for the trenches to prevent the coupling problem. Fig. 3.3 (a) illustrates this problem. The circle in this figure represents the smallest spot that the coupling objectives allow one to achieve at the input facet of the waveguide. Since the space between the waveguide and the slab is less than $2\text{ }\mu\text{m}$ in this example, some part of the light gets coupled to the side slab modes. Fig. 3.3 (b) shows larger trenches that allow one to avoid the slab-coupling problem. Ideally, the larger the gap between the device and the slab, the easier is the coupling to the desired waveguide mode. However, this solution would result in a much longer writing time on the E-beam system. Therefore, $2\text{-}\mu\text{m}$ gaps are optimal for most of the devices.

The etch-test samples, having the exact replicas of the waveguides, were fabricated and cleaved into smaller $3\text{ mm} \times 3\text{ mm}$ pieces for the etch tests. The etch tests in different gas chemistries and under different etching parameters were performed to establish an optimum etching recipe for the ultimate waveguide structures. Since AlGaAs can be etched in chlorine-based chemistry, and we had Cl_2 and BCl_3 gases available, we attempted the etching with different combinations of the two gases (as well as using them one-by-one). There have been existing etching recipes where nitrogen was introduced along with the chlorine-based gases to passivate the sidewalls of the etched waveguides [60], [81]. Introducing nitrogen has been shown to lead to a faster etching process with more vertical sidewalls of the final structures. However, in our trials with ZEP as the resist, we were unable to recreate these

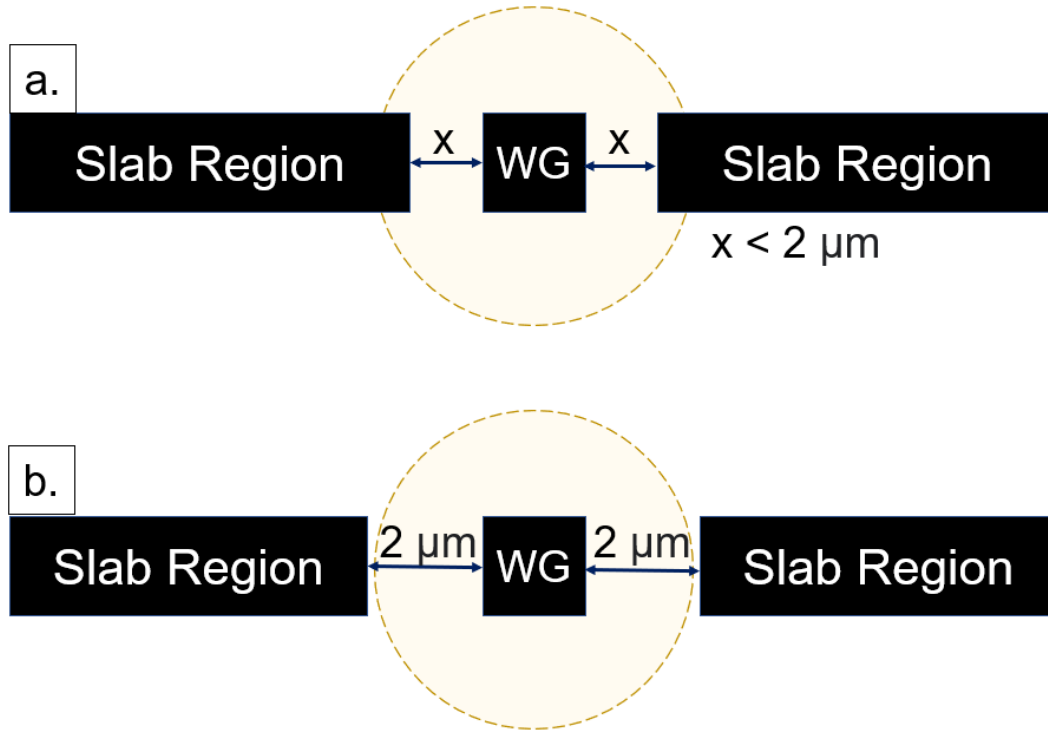


FIGURE 3.3: (a) The waveguide structure surrounded by the trenches of less than $2\ \mu\text{m}$ in width, exhibiting the problem of light coupling to the slab region; (b) The solution to the problem by creating wider trenches between the slab and the waveguide.

results [60], [81]. This is because all those recipes had silica (or HSQ) as the pattern-transferring mask, which also assisted in creation of the passivation layer. This is, unfortunately, not feasible with a ZEP mask alone. Below we describe our efforts at etching AlGaAs using a ZEP mask in different etching chemistries with the advantages and disadvantages of using each process.

1. Etching using Chlorine (Cl_2)-based chemistry only: Chlorine plasma has widely been used to etch GaAs, and the initial few trials were carried out using chlorine gas only. Later some argon was also added to increase the etch rate. The observation from using the chlorine-based etching chemistry only was that the etching selectivity for the AlGaAs layers with different aluminum concentrations is very high. This means that the etch rate, sidewall roughness, and sidewall angle will be different for the three layers with different AlGaAs compositions. The best results obtained after optimizing all the parameters and using only Cl_2 and Ar gases for etching the 3-layer heterostructure are shown in Fig. 3.4. It is clearly visible that there is more chemical etching for the core and less for the claddings. We can also see that the roughness on the sidewalls is higher for the core layer compared to that for

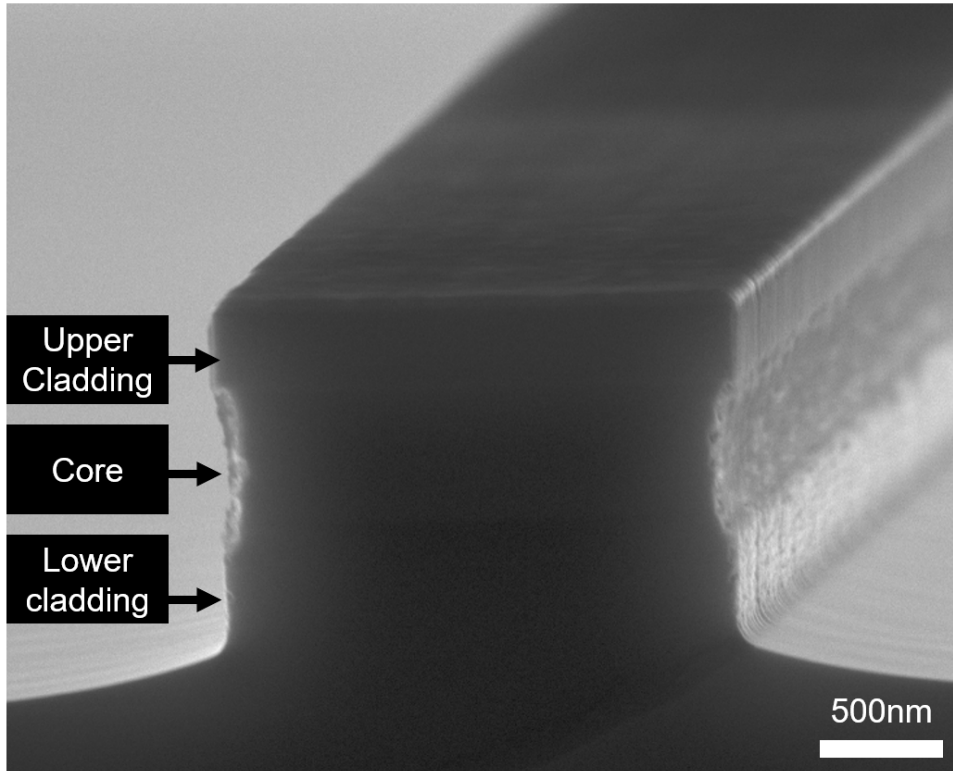


FIGURE 3.4: Plasma etching of a 3-layer AlGaAs stack using chlorine-based chemistry only (no BCl_3 gas).

the claddings. In addition, since in most of our designs the majority of the light confinement is in the core, this recipe is expected to lead to greater scattering losses. Below are the parameters for the most optimized etch recipe:

$\text{Cl}_2:\text{Ar} = 16:2$ sccm; Pressure = 0.6 Pa; ICP = 200 W; Bias = 120 W

This etch was run for 30 seconds and resulted in an etch rate of 40 nm/sec for isolated waveguide features. All of the ZEP was eroded in 30 seconds corresponding to selectivity of 1:2.4 (ZEP:AlGaAs). As mentioned previously, ZEP is commonly known to have a selectivity of 1:1 with respect to III-Vs, but we were able to optimise the process to get a higher selectivity compared to the previous works [77].

In conclusion, the chlorine-based recipe yields acceptable results for higher aluminum concentration layers but leads to more isotropic etch for the core layer with a lower aluminum concentration. As a result, it is not a recommended process for etching AlGaAs heterostructures with layers of different compositions.

2. Etching using BCl_3 -based chemistry only: Since Cl_2 plasma yields different etching results for different layers, we tried several etch tests using

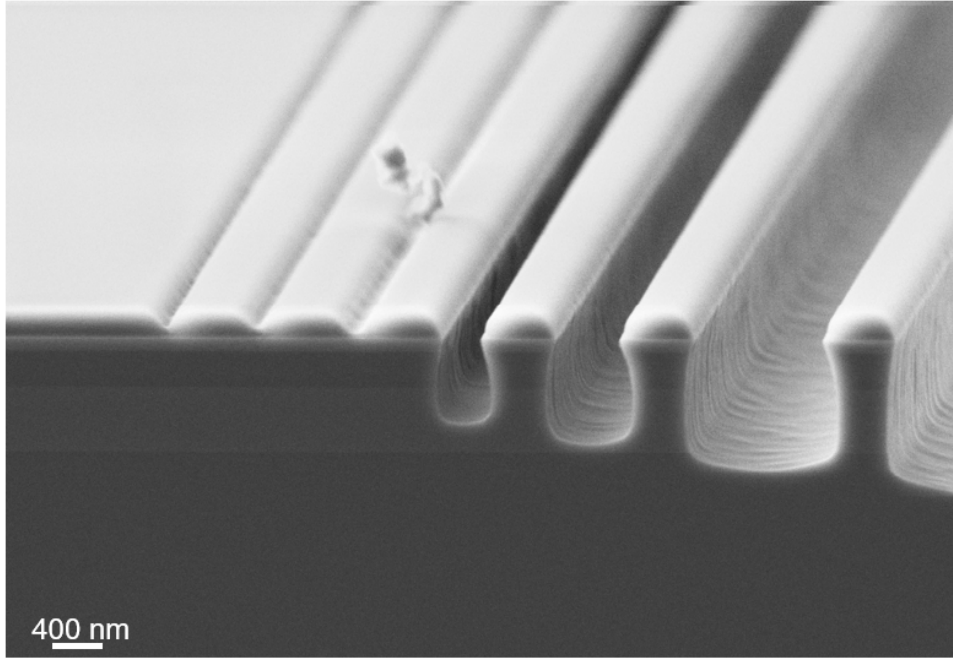


FIGURE 3.5: Plasma etching of a 3-layer AlGaAs stack using BCl_3 -based chemistry only.

BCl_3 only, which is known to be less selective to the layers with different aluminum concentrations. After several iterations, the best results were achieved using the following parameters:

$\text{BCl}_3:\text{Ar} = 10 \text{ sccm}$; Pressure = 0.6 Pa; ICP = 250 W; Bias = 150 W

This test was run for 35 seconds, and the results were more isotropic even with a large bias. However, having BCl_3 plasma only definitely led to a less selective process. As can be seen from Fig. 3.5, all the layers were etched at the same rate. The most isolated waveguide was etched down to a $1.05 \mu\text{m}$ depth in 35 seconds while 145 nm of resist was still left, corresponding to an etch rate of 30 nm/sec and selectivity of 1:2.1 (ZEP:AlGaAs). It can also be seen that, since the process is largely isotropic, it does not allow the etching of smaller gaps, so the first three gaps on the left in Fig. 3.5, having 100-, 150-, and 200-nm widths, were not etched at all. In conclusion, using BCl_3 only results in a less selective process for the different aluminum concentration layers, but the process is largely isotropic and therefore results in a poorer verticality.

Comparing the two recipes shown above, we realized that, to have the most optimized result in terms of smooth and nearly vertical sidewalls, we needed a mixture of both Cl_2 and BCl_3 gases, along with some argon that aids the

process of physical etching. Consequently, the next series of tests was performed using a mixture of both gases.

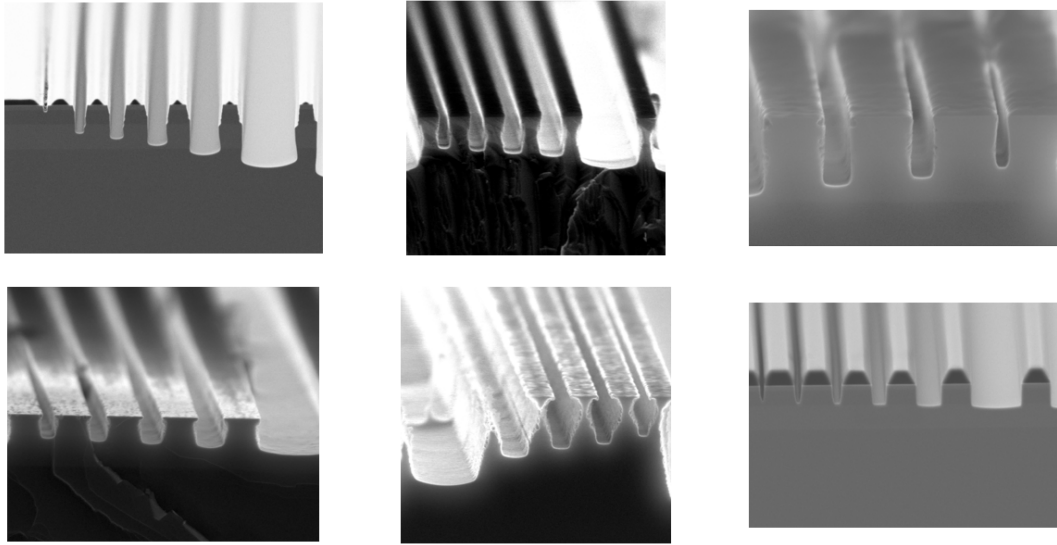


FIGURE 3.6: The etch-test results obtained using varying concentrations of Cl_2 and BCl_3 .

3. Etching using a mixture of BCl_3 , Cl_2 , and Ar: Several etch tests were performed using this process by varying the concentrations of the three gases to optimize the result based on the etching selectivity, sidewall angle, and roughness. Some examples of the iterations are shown in Fig. 3.6.

The etching procedure relying on all three gases resulted in two optimal etch recipes. The first one was a faster process with a lower argon concentration, which is desirable for isolated features requiring faster etching times and less control over the etch depth. The other recipe is a very slow and controlled process, which is preferable for situations where a high level of precision is required. Both the etching processes were developed based on the etching requirements of the different projects. Below we provide the parameters for both the processes together with some additional detail.

Fast process:

$\text{Cl}_2:\text{BCl}_3:\text{Ar}= 12 : 4 : 2$ sccm; Pressure= 0.6 Pa; ICP= 100 W; Bias= 75 W

The fast process was developed for the high-aspect-ratio structures without small gaps. The high ICP and bias values do not allow enough plasma to flow into the smaller trenches. Argon was added in this process as it contributes to the physical etching, offering two advantages: faster etch rate and more vertical sidewalls. The developed fast etching process offers sidewall verticality and works well for trenches wider than 220 nm. As can be seen from Fig. 3.7,

the gaps smaller than 250 nm were etched at a very small rate. An etch time of 30 seconds resulted in etching a 1-micron-wide trench down to the depth of $1.44\ \mu\text{m}$, while a 250-nm-wide gap was etched down to 988 nm only. The corresponding etch rate was 48 nm/s for the widest trench and around 33 nm/s for the 250-nm trench, as shown in Fig. 3.7. Almost all of the resist eroded in 30 seconds, yielding a selectivity of around 1:2.9 (ZEP:AlGaAs).

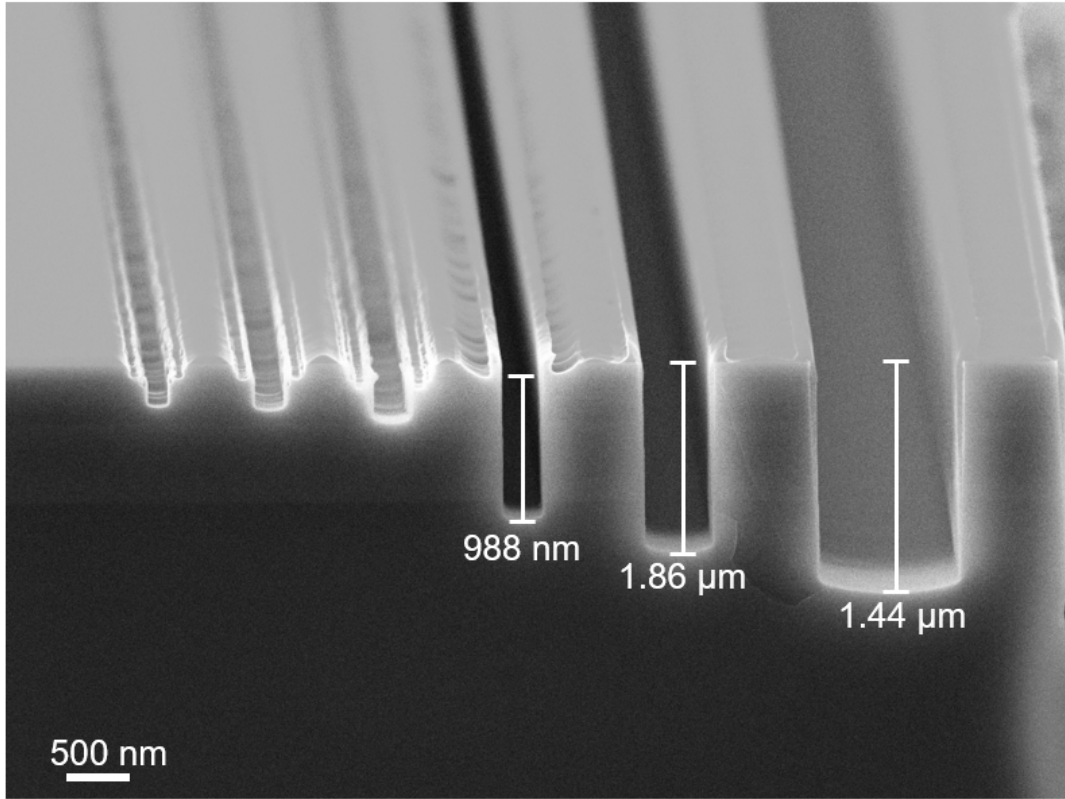


FIGURE 3.7: The results of AlGaAs etching obtained with the fast etching process.

Slow process:

$\text{Cl}_2:\text{BCl}_3 = 0.5 : 1.3\ \text{sccm}$; Pressure= 0.1 Pa; ICP= 20 W; Bias= 12 W

The slow process also resulted in very smooth side profiles and a high verticality. The major motivation behind the slow process was to develop a process that can work well with smaller gaps and trenches. Therefore, low gas flows, low pressure values, and low values of ICP and bias were chosen for this process. The etch tests were performed for the samples with varying gaps, but since the motivation for this recipe was etching smaller gaps (smaller than 250 nm wide), 150 nm wide trenches were also added as a separate patterned on the same etch test sample to see if they can be properly etched. As can be seen from Fig. 3.8 (a), all the gaps starting from 100 nm

to 1 μm are being etched properly using this process. The etch test was run for 30 minutes, and the resulting AlGaAs etch depth was 474 nm for a gap of 150 nm while around half the resist was still left, as shown in Fig. 3.8 (b). The selectivity of around 1:1.8 and the etch rate of 0.26 nm/s for the critical features (150 nm gaps) were demonstrated. This process works well for etching high-density structures such as photonic crystals and ring resonators with small gaps between the bus and the ring waveguides.

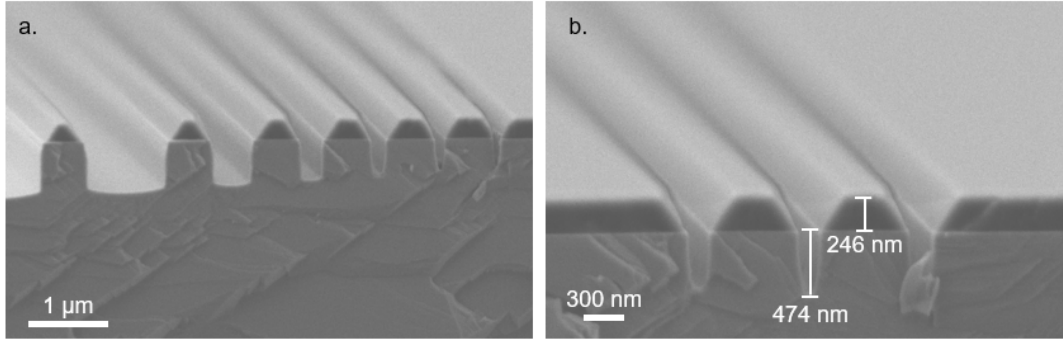


FIGURE 3.8: The results of AlGaAs etching with a slow etching process.

Both the fast and slow etching processes were tested several times with different structures, and the results were found to be satisfactory and repeatable. Fig. 3.9 shows the achievable etch depth as a function of the trench width. It can be clearly seen from the figure that, for the gaps smaller than 200 nm, the slower etch process works better because it has a slightly larger etch rate under these circumstances. On the other hand, for structures wider than 200 nm, the fast process is well suited. Also, the effect of RIE lag is relatively smaller in the slower process as compared to the fast process as can be seen from the slope of the curves. In conclusion, we developed two different etch recipes for plasma etching of AlGaAs using chlorine-based gases that can yield perfectly vertical sidewalls, low sidewall roughness, and low selectivity with respect to different aluminum concentrations.

3.2 Fabrication of Photonic Crystals

Photonic crystals (PhC) are periodic structures with an ability to control the propagation of light in unprecedented ways [82], [83] owing to the property of engineered photonic bandgap [84]. As a results, PhC structures allow for observation of interesting physical phenomena such as slow light [85], [86],

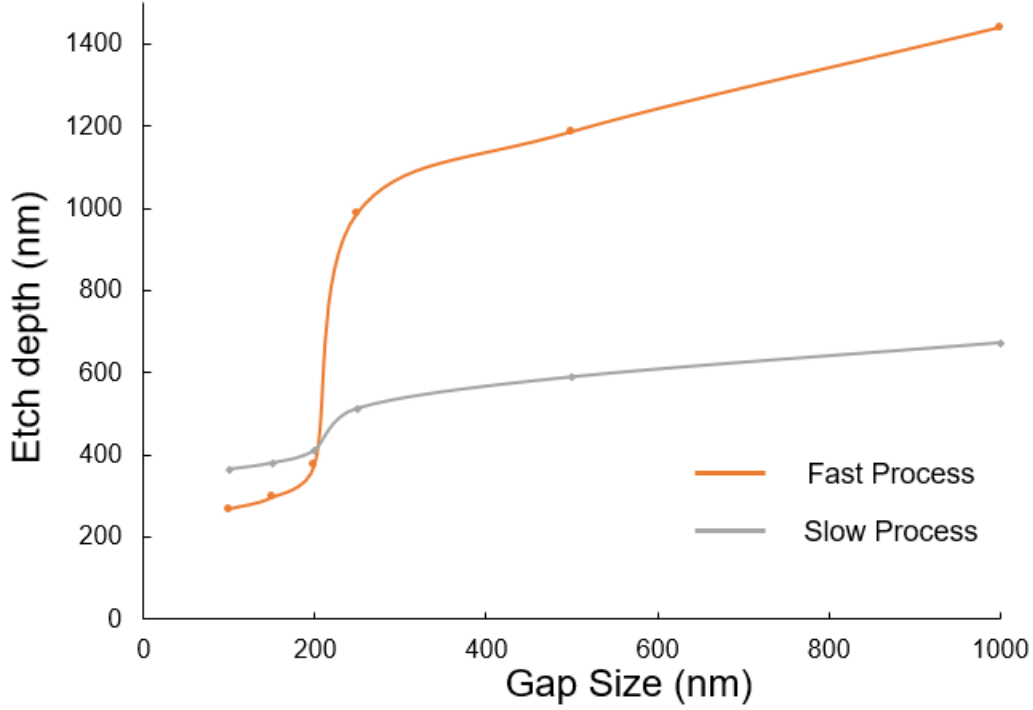


FIGURE 3.9: Graphical comparison of the fast and slow etch processes.

superprism effect [87], and negative refraction [88]. In terms of physical dimensions, integrated photonic crystal devices are typically comprised of 2D arrays of cylinders with circular cross-sections arranged in a geometric lattice (triangular, square, etc), etched into a semiconductor slab such that they create air holes. In this thesis, we will discuss the fabrication of photonic-crystal waveguides which are created by removing one row of holes from the middle of the 2D photonic crystal (also known as W1 waveguides). Such PhC waveguides allow certain frequencies falling within the bandgap of the PhC structure (and therefore forbidden or rejected by the structure) to pass through the created defect waveguide. A more detailed introduction to photonic crystal structures and waveguides is provided in Chapter 4, which is fully dedicated to PhC waveguides.

Based on the epitaxial stack thicknesses and index contrast, photonic crystal structures are categorised into *membrane-type PhC* and *substrate-type PhC*. Membrane-type PhC are the ones which have holes etched in a thin slab

(200 nm – 300 nm) surrounded by the air and therefore have large index contrast. Substrate-type PhC, on the other hand, are created using heterostructures (similar to the epitaxial stack defined in Fig. 3.2 (right)), and therefore they have lower index contrast between the core and the cladding layers. Photonic crystals are fairly complex structures to fabricate primarily because of the enhanced proximity effects owing to the structure density. The membrane-type PhC are even more complicated because of the large etch depth requirements in addition to the pronounced proximity effect. There are three major complexities in fabricating photonic crystal structures that we discuss below.

1. **Proximity effect and lithography:** As discussed in Chapter 1, the proximity effect comes into play due to backscattering electrons (BSE) and becomes dominant in densely packed structures. Fig. 3.10 shows a proximity-effect-corrected photonic crystal waveguide structure. The color temperatures represent different dose factors with blue corresponding to lower dose factors and red representing higher dose factors. We can clearly see that the center looks cooler (blue) and becomes hotter at the corners (red). This corresponds to a larger dose requirement at the edges and a lower dose in the central region. This difference is caused by the BSE. The backscattering events accumulate large background energy, therefore, causing additional doses in the middle and lower doses at the corners (refer to Fig. 1.18). Therefore, there is a need to perform the proximity-effect correction. This correction was performed using GenISys' BEAMER software that has a built-in PEC module. The software fractures the area into smaller segments, and, based on the input data from the point-spread function of the epitaxial stack, creates a dose matrix and assigns the correct dose fractions to different regions of the designed structure.

Fig. 3.11 shows a pattern similar to that shown on the GDS file in Fig. 3.10, written and developed: (a) with PEC performed, and (b) without PEC. The deteriorating effect of BSE is evident in figure (b) where the holes near the waveguide look larger than the ones at the edges. This happens because plenty of backscattered electrons already exist in the central region creating an additional, unintended, E-beam dose. For instance, this effect may contribute a dose factor of 0.2 of the base dose in addition to the latter. To facilitate further discussion, let us call this factor of 0.2 as *BSE – dose*. When the whole pattern is written with a

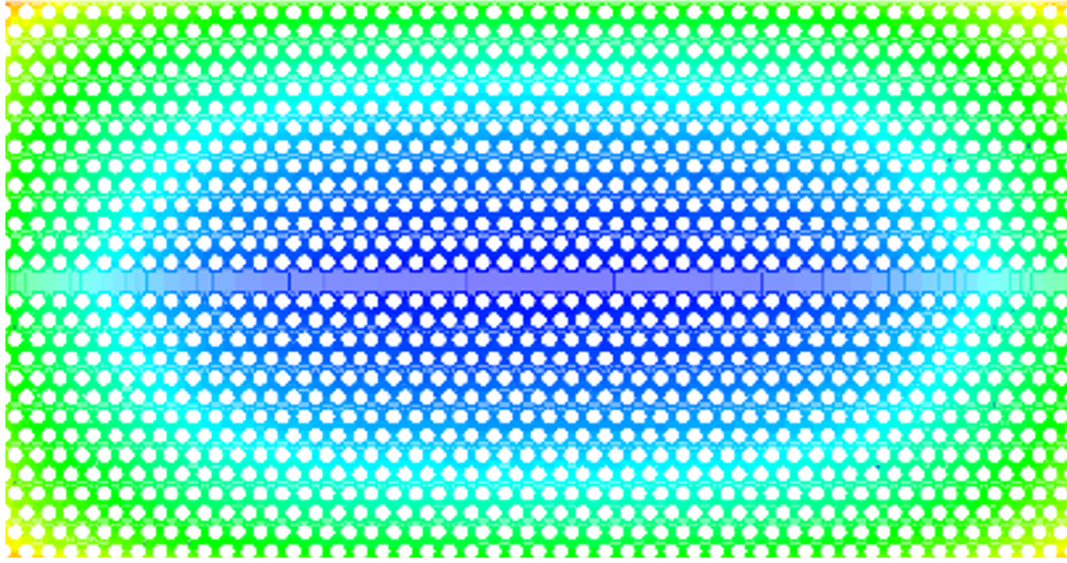


FIGURE 3.10: Photonic crystal waveguide GDS file corrected for the proximity effects. The simulation was done using BEAMER's PEC module.

dose of unity, the area in the centre “sees” an effective dose equivalent to $1 \times BSE - dose$. This corresponds to an effective dose of 1.2, and therefore the structures come out to be larger than what is drawn on the GDS file. In the PEC structure, all the holes come out to be of the correct dimension because this dose factor is already taken into consideration. This illustrates the reason why PEC is necessary for densely packed structures.

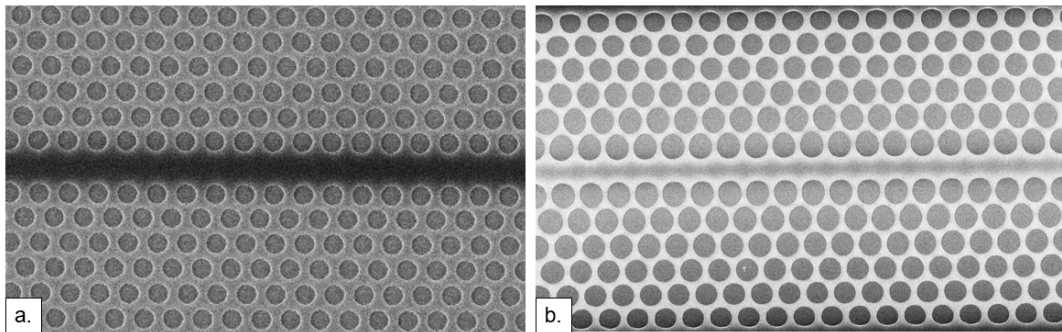


FIGURE 3.11: SEM top-view image of PhC after patterning: (a) with PEC, (b) without PEC.

2. **Large etch area:** The fabrication process of substrate-type photonic crystals experiences further complications because of the large etch depth requirements in such structures. Since the area to be etched is

a lot denser, the plasma flow causes the etch rates to slow down drastically. The flow of plasma largely depends on the gap/trench size:

$$\text{Etch rate} \propto \frac{1}{\text{Gap size}} \quad (3.2)$$

Fig. 3.12 shows a cross-section SEM image after etching of densely packed PhC structures and waveguides with large side trenches written adjacent to each other on an etch test pattern. It can be seen that the holes are etched at almost half the rate as compared to the large gaps. Because of the large density of structures, the rate of erosion of the mask is much larger in PhC as compared to sparsely spaced waveguide-like structures. Therefore, etching holes requiring larger etch depths using a low-selectivity soft mask (electron beam resist) is fairly challenging. For the samples fabricated in this thesis, the etch-depth requirement for PhC designs was 500 nm for suspended AlGaAs PhC (these designs are reported in Chapter 6), and 900 nm for substrate-type PhC (which be described in Chapter. 4).

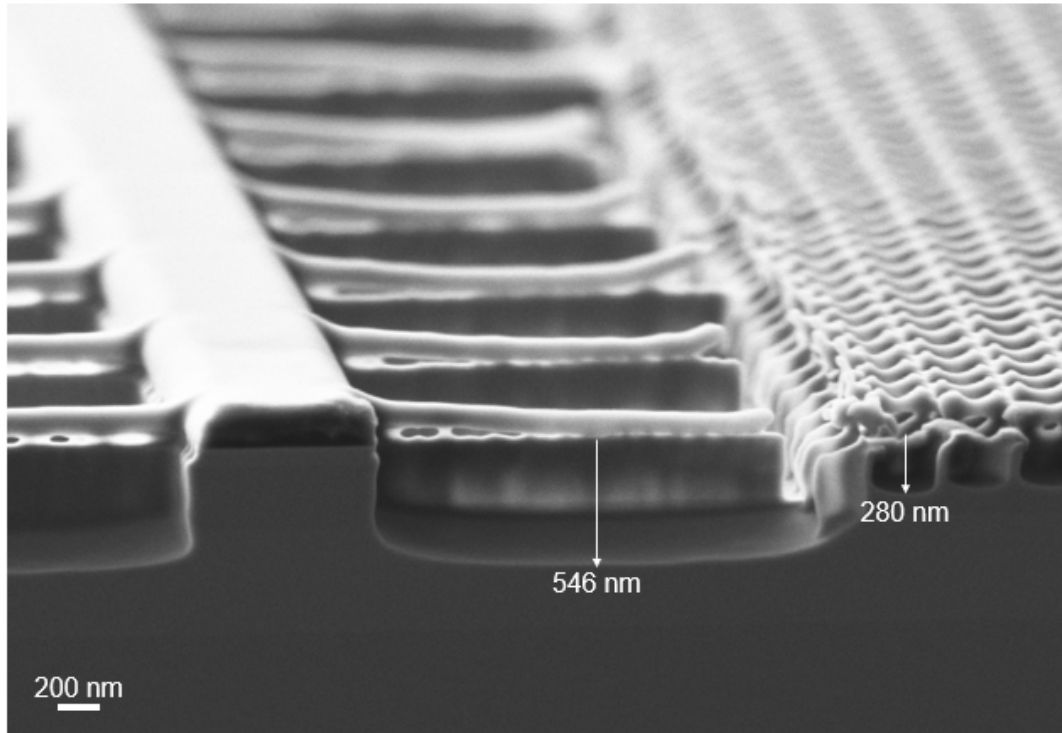


FIGURE 3.12: SEM cross-section image showing a comparison of etching large trenches and densely packed holes patterned next to each other.

3. Sidewall verticality: Two characteristic features of photonic crystals are the distance between their centers, also known as the pitch, or lattice constant (a), and the radius of the holes r . The pitch depends on the size of the bandgap and the operation wavelength. The fabrication tolerances in PhC require the pitch dimensions such that the remaining distance between the two holes ($a - 2r$) is sufficient to separate the holes even if the etching becomes slightly isotropic. This is demonstrated in Fig. 3.13. Part (a) of the figure shows perfectly vertical holes with an etch depth of H and distance between the centers $a - 2r$. Fig. 3.13 (b) indicates the problems associated with non-vertical sidewall etching in PhC. It is evident that if the sidewalls are not perfectly vertical, the holes will not be able to reach the target etch requirements of H , and will join at the height h . Therefore, sidewall verticality plays a crucial role in fabricating photonic crystal structures, particularly the ones requiring large etch depths.

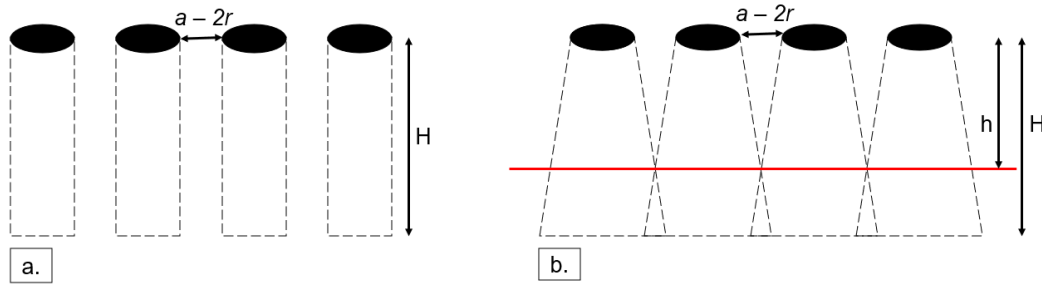


FIGURE 3.13: Schematic representation of (a) perfectly vertical etched holes, (b) holes with non-vertical sidewalls.

Fig. 3.14 shows different problems which might occur while creating deeply etched photonic crystal structures. The first image (a) shows more isotropic etching which causes the nearby holes to join. The second image (b) shows the variation in the etch selectivity because different epitaxial layers have different aluminum concentrations. Lastly, part (c) of the figure shows the results of a slight over-etch when the resist gets completely eroded. As a result, we were tasked with creating a process which is not selective to the aluminum concentration but has a high selectivity (ZEP:AlGaAs) and etch rate, and creates perfectly vertical sidewalls. Thankfully, the fast etch process mentioned in the previous section works perfectly well for the photonic-crystal holes. The only difference is that the etch rate for the holes is fairly

different compared to the large trenches, as shown in the previous section. Fig. 3.15 shows the cross-section image of the etch results revealing perfectly vertical sidewalls. The image on the right is the zoomed-in version showing the etch depth of 900 nm, which yields the etch rate of 30 nm/sec. Very little resist is still left on top of the holes. We can clearly see that the sample was etched down to the end of the core, which was the minimum requirement for the etch depth of the structures (more details to follow in Chapter 4), and there appears to be no roughness on the sidewalls.

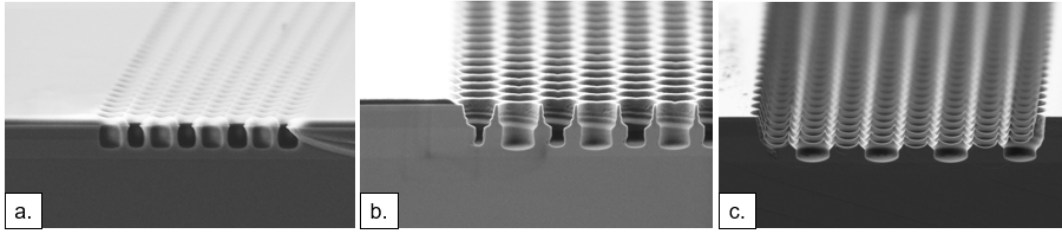


FIGURE 3.14: SEM cross-section image of common problems that occur while etching PhC structures to a large depth.

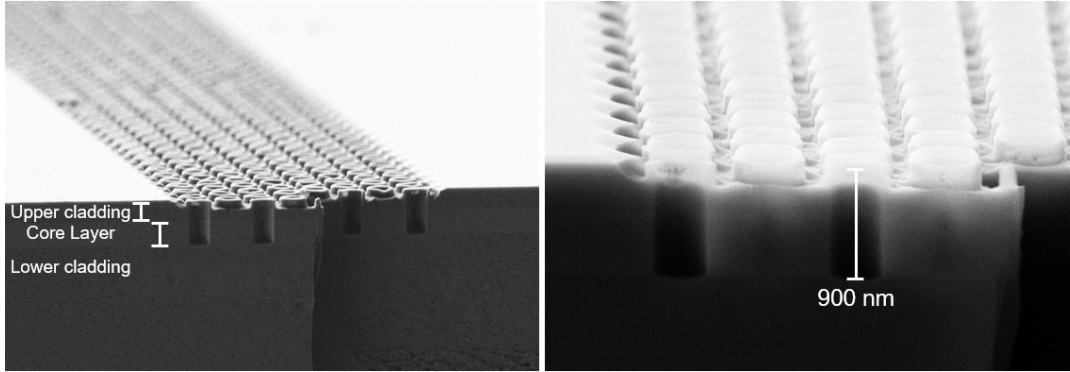


FIGURE 3.15: Cross-section image of perfectly vertical sidewalls of the holes revealing the etching down to the bottom of the core layer (left); Zoomed-in image showing a vertical profile and a 900-nm etch depth (right).

3.3 Fabrication of Ring Resonators

Ring resonators are widely explored optical structures which find applications in high-Q filters, frequency-comb generation, and photonic sensing [89]–[93]. Such structures have been commonly fabricated on waveguide platforms such as silicon, silicon nitride, and GaAs for nonlinear frequency conversion-based processes. However, the previously demonstrated structures required relatively low aspect ratios because of thin membrane/films

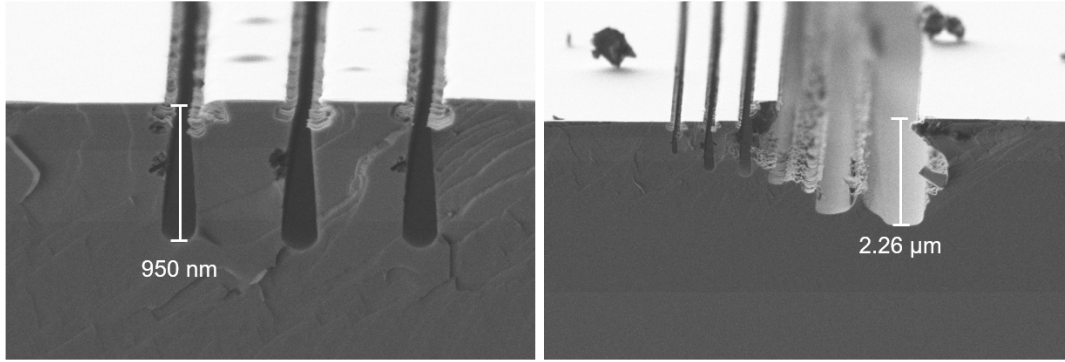


FIGURE 3.16: Etching of 150-nm-wide gaps (left); Etching of gaps of varying sizes (right).

as guiding layers. In this work, we aim to create ring resonators using the 3-layer AlGaAs heterostructure introduced in the previous sections. The simulations were carried out by Ehsan Mobini, another Ph.D. student in the group, and the designed structures required a gap of 150 nm to be etched down to 1000 nm. The two major processes requiring optimization for fabricating ring resonators are lithography and plasma etching. Similar to the previous sections, the PEC was applied to the designed structures to make sure that all the places on the GDS file receive the correct dose factor. For the etch-test samples, the critical dimensions were written along with varying trenches, as shown in some previous examples. This was done to compare the etch rate of the gap versus the coupling waveguide (which sees more opening on one side). The reason why it is important to write both the structures together on the etch-test sample and not just the critical dimension (gap) is demonstrated in Fig. 3.16. As explained in the previous sections, as the gap size becomes smaller, the amount of plasma flow into the trenches also lowers, thereby lowering the etch rate. As a result, the mask erodes too fast before the required etch depth is achieved.

Initially, the etch tests were performed while keeping in mind the etching of critical dimensions only. As can be seen from Fig. 3.16, the 150-nm gaps were etched down to 950 nm. Although the etch seems fairly good for the smaller gaps (except for the more isotropic etching which leads to non-vertical side-walls), the effect of this etch is a lot more dramatic compared to the etching of different gaps. The image on the right shows the gaps of varying sizes: 100 nm, 150 nm, 200 nm, 250 nm, 500 nm, and 1 μm (from left to right). We can see that the smaller gaps (up to 200 nm) are etched fairly well, yielding an aspect ratio of almost 1:7 for the critical dimension. But for the gaps 250 nm and larger, the gaps did not survive after etching. This clearly shows

the dominant effect of chemical etching, and therefore this process cannot be utilized for etching ring resonators.

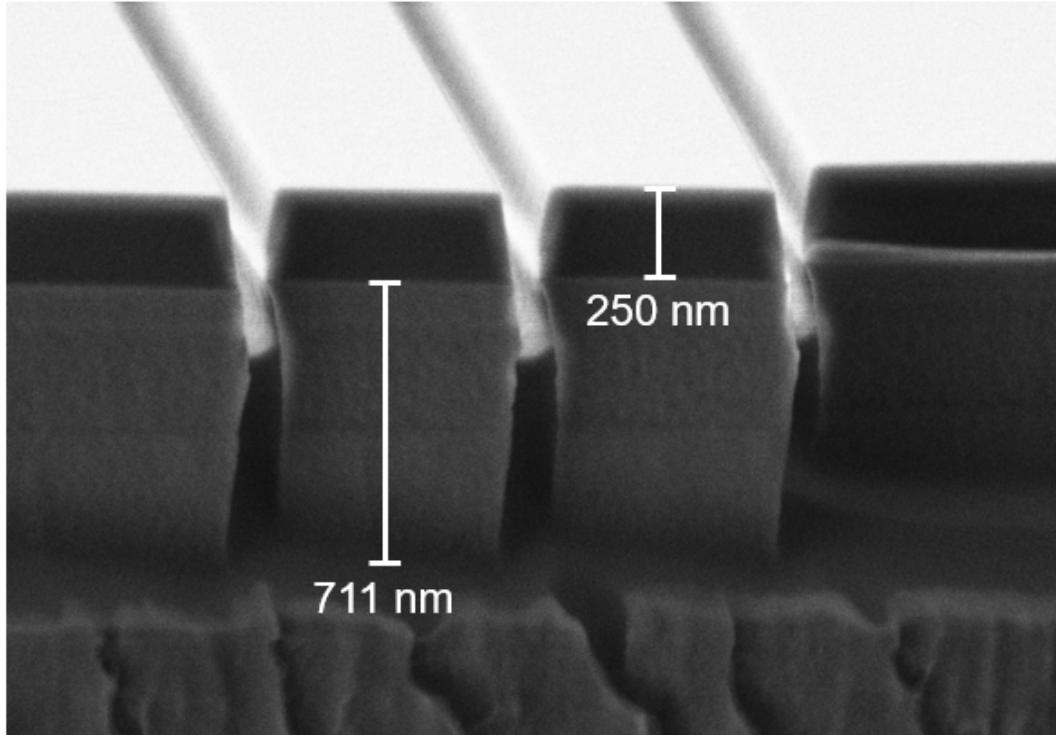


FIGURE 3.17: Silica mask used for etching smaller gaps yielding the selectivity of 1:10.

Based on the observations from the previous etch tests as shown in Fig. 3.16, we concluded that a hard mask is necessary for reaching the required etch depth and aspect ratios. The etch-test samples were created using the silica hard mask recipe introduced in Chapter 2. Fig. 3.17 shows the etch-test results for etching 150-nm gaps. By optimizing the etch recipe, we were able to achieve an etch depth of 711 nm while 250 nm of silica mask still remained on top of the structures. We started with 320 nm of mask, which means that only 70 nm of mask was used to etch 711 nm material, giving a selectivity for silica:AlGaAs slightly greater than 1:10. The following is the optimized recipe that was used for this etching:

$\text{Cl}_2:\text{BCl}_3:\text{Ar} = 5 : 5 : 2$ sccm; Pressure = 0.65 Pa; ICP = 250 W; Bias = 30 W

3.4 Fabrication of Cylindrical Pillars (using positive-tone resist)

Bound states in the continuum (BIC) [94], [95] is a concept originating from quantum mechanics that is now well adapted in optics. BIC is defined as a state which stays highly confined in the continuum region and does not get radiated out. Because of this, it has widely been used to enhance light confinement. Recently, Mobini, *et. al* [96] theoretically demonstrated an asymmetric SHG in $\text{Al}_{18\%}\text{Ga}_{82\%}\text{As}$ metasurfaces and showed a four-orders-of-magnitude increase in the second-harmonic power achieved with quasi-BIC.

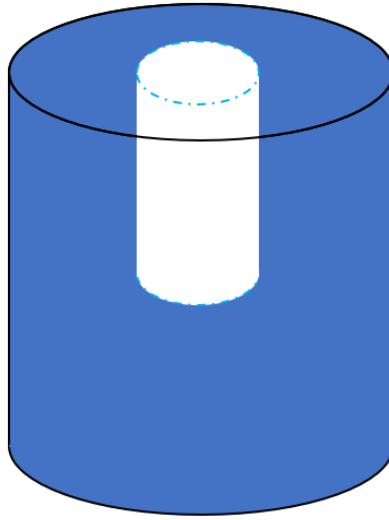


FIGURE 3.18: Schematic representation of standing cylinders with etched cylindrical holes (shown in white).

The geometric structures were cylindrical structures made of $\text{Al}_{18\%}\text{Ga}_{82\%}\text{As}$, with a hole etched inside the cylindrical pillars, as shown in Fig. 3.18. In this work, we demonstrate our initial tests for fabricating such structures using a positive-tone resist.

The next step in this project [96] was to fabricate the designed structures. The 3-layer epitaxial stack discussed at the beginning of this thesis was used for the fabrication trials of the designed structures. Since we only wanted the $\text{Al}_{18\%}\text{Ga}_{82\%}\text{As}$ layer, we used wet chemical etching to remove the first two layers (100 nm GaAs and 300 nm $\text{Al}_{70\%}\text{Ga}_{30\%}\text{As}$). A detailed discussion of the wet etching recipes and how to selectively remove individual layers will be provided in Chapter 6. Two-step wet-chemical etching was performed on

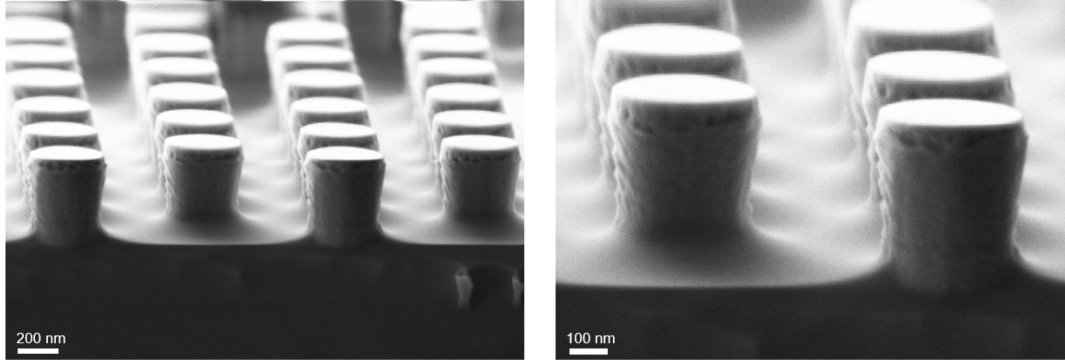


FIGURE 3.19: Plasma etching of cylindrical pillars written using positive-tone resist.

the bare wafer to get rid of the top GaAs capping layer and the top cladding layer of $\text{Al}_{70\%}\text{Ga}_{30\%}\text{As}$. Then the wafer was spin-coated with ZEP520a, and the inverse of the holes was patterned, as shown in Fig. 3.20 (b). This was the challenging part because, in this case, since we are using positive-tone resist, the requirement was for the patterned holes to stay while removing everything else. Therefore, the holes were written on a GDS file and subtracted from a slab to create the inverse of the design. This resulted in the regions without holes. Fig. 3.20 (a) shows the designs if written using a negative-tone resist, whereas (b) shows the designs for a positive-tone resist. For the first batch of tests, we wanted to test writing the cylindrical pillars only (and not the holes inside them). The structures were corrected for PEC and written using E-beam lithography at 30 kV acceleration voltage. After the lithography, the structures were developed in n-amyl acetate.

The pattern was then transferred into the underlying $\text{Al}_{18\%}\text{Ga}_{82\%}\text{As}$ layer by plasma etching. Several tests were tried but the best results were obtained using the slow etching process discussed in the previous sections. The etch resulted in 410 nm of etched AlGaAs layer when the resist ran out. As we can see from the cross-section images in Fig. 3.19, the structures are not perfectly vertical. This is because the E-beam was patterning the areas around the holes (as shown in Fig. 3.20 (b)). Consequently, the development process did not lead to perfectly vertical structures, and therefore, the mask created did not have vertical sidewalls. As a result, the pattern transferred into the underlying AlGaAs layer also witnessed similar non-verticality. Additionally, the roughness on the sidewalls is very evident, which means that this etching process does not work perfectly for this sample and there is still room for improvement.

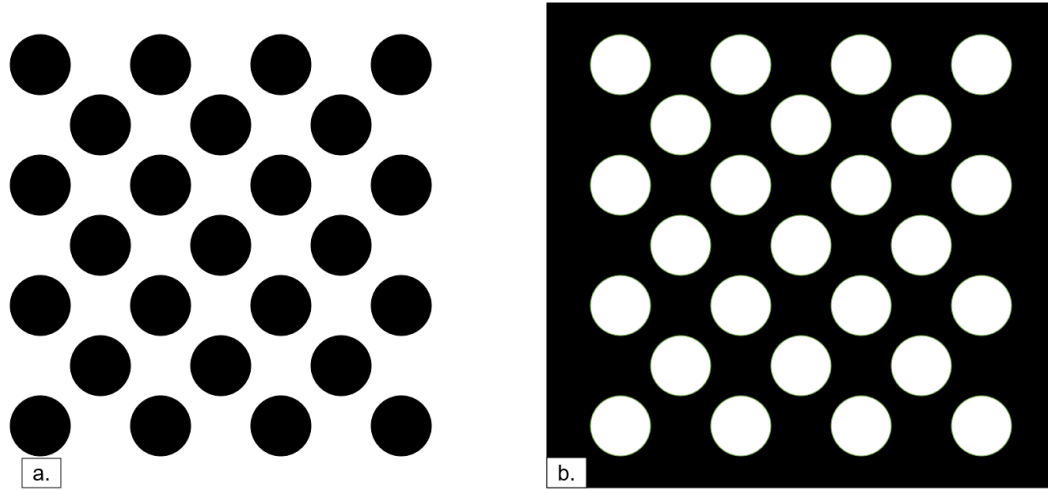


FIGURE 3.20: Schematic representation of GDS file for the designed structures (a) using negative-tone resist; (b) using positive-tone resist. The dark region represents the area where E-beam patterning will occur.

As a next step, some tests will be performed with the smaller holes inside the patterned cylinders. In addition, a controlled etch process needs to be developed by making use of the RIE lag such that it etches the cylinders more and the holes less as required by the design. Such designs are always challenging to implement, but this was our first effort to fabricate metasurfaces using $\text{Al}_{18\%}\text{Ga}_{82\%}\text{As}$ and the results from this can be built upon to modify the existing recipes to fabricate the final device in the future.

Chapter 4

Design, Fabrication and Characterization of AlGaAs Photonic Crystal Waveguides Operating in Second Bandgap

As introduced in Chapter 3, photonic crystals (PhC) are periodic structures exhibiting the property of photonic bandgap [84]. Numerous devices such as optical filters, photonic crystal-based waveguides, small-volume and high-Q cavities, *etc.* [86], [97], [98], rely on the fundamental concept of bandgap. Depending on the periodicity, photonic crystals can be defined as 1D, 2D, or 3D structures, as shown in Fig. 4.1. It was demonstrated by Yablonovitch *et al.* [82] that one of the most effective ways to confine light is to have an electronic bandgap overlap with the band-edge for a structure having periodicity in three dimensions. There have been a few studies where 3D photonic crystal structures have been demonstrated [99]–[101], but these structures are extremely difficult to fabricate, and are not practical to be integrated with the current planar CMOS-compatible processes.

In this project, we worked with a 2D photonic crystal waveguide created by inducing a line defect in the photonic crystal lattice. In photonic crystal waveguides, a defect breaks the periodicity of the lattice, which allows certain frequencies in the bandgap to pass. This defect can be a line defect (leading to waveguide-like structures), or point defect (leading to cavities). Photonic crystal line-defect waveguides can support slow-light modes [103], [104]. The velocity of light in vacuum (c_0) is approximately $3 \times 10^8 \text{ m s}^{-1}$. When light is guided in a medium with the refractive index n , the velocity

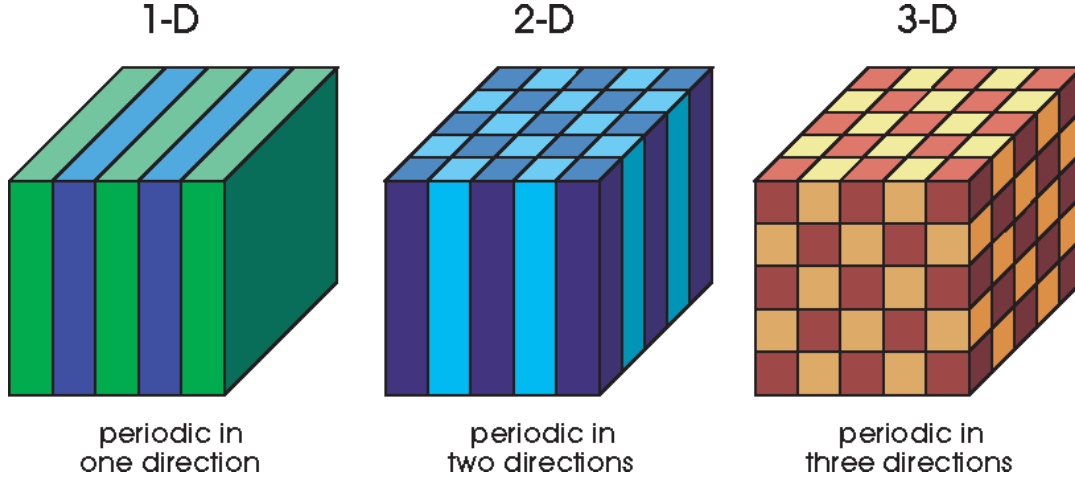


FIGURE 4.1: 1D, 2D and 3D photonic crystal structures. The figure is adapted from [102].

becomes c_0/n . It is this high speed which allows high-speed data transmission possible in fiber optics. However, such large speeds are not easy to control in the time domain. This is where the concept of slow light comes in. Slow light allows the group velocity (v_g), or the wave envelop to travel at the speeds lower than c_0 . The concept of slow light has a great potential in optical buffers, optical memories, and optical signal compression [105], and it also helps to better understand light-matter interaction mechanisms. The way a defect-guided mode transitions into a slow-light mode can be considered by thinking of the holes on either side of the waveguide as Bragg mirrors. The light inside the device is scattered coherently by these Bragg-mirror-like structures. The interaction of the incoming light with this scattered light forms an interference pattern, which tends to move at a slower group velocity forming the “slow-light mode”.

In particular, the dispersion engineered slow-light regime that can be established in a photonic crystal waveguide is of massive interest, especially in the field of nonlinear optics. Furthermore, its ability to enhance linear phase changes makes such regime even more interesting. Therefore, it has attracted a lot of attention from the research community. Based on the number of rows being removed to create the line defect, the photonic crystal waveguides can be defined as a W1, in which one row of holes is removed, or W2, meaning 2 rows of missing holes, and so on. The waveguides with line defects such as W1 waveguides can exhibit slow light at the frequency range near the band edge. These waveguide structures can operate on a single transverse mode, but they also exhibit limitations due to high intrinsic back-scattering and high group-velocity dispersion (GVD) near the band edge [106]. This

high GVD can cause the group index, n_g , (which is inversely proportional to the group velocity) to increase parabolically near the band edge, thereby making such structures non-suitable for any applications. Although it is desirable to have large group index, it is equally important to have large n_g values stay constant for a certain finite bandwidth to make the best use of this effect. To resolve the issue of parabolically increasing group index values, dispersion engineering is performed, which allows one to create a small region where one can obtain high group indexes and at the same time have the bandwidth of operation of a few nanometers, therefore making it usable for slow-light applications.

The photonic crystal bandgap region can be obtained by computing definite frequency eigenstates of the Maxwell's equations of the periodic structures. The result can be represented as a plot of the normalized frequency on the y -axis and the normalized k -vector on the x -axis. The parameter "light line" provides an insight into which frequencies can be confined and guided by the photonic crystal structure:

$$\text{Light line: } \omega = ck/n_o,$$

where n_o is the refractive index of the cladding. For air-claddings, $n_o = 1$, which corresponds to the light line of photonic crystal with air-claddings.

Fig. 4.2 shows the band diagram for a typical photonic crystal waveguide. The line $y = x$ on the *frequency – wavevector* curve represents the light line for a photonic crystal with air claddings (since $n_o = 1$ for the air). All the frequencies lying below the light line are known to be guided, and the ones above it are reflected or radiated out of the plane. For a 3-layer heretostructure (a photonic crystal with semiconductor claddings), the refractive indices of the core and claddings are very close, thereby leading to a lower refractive index contrast Δn . This means that the slope of the light line will decrease because of the higher refractive index of the cladding (n_o). As a result, most of the bandgap region will be lying above the light line, and therefore the frequencies will be radiated.

3-layer heterostructures represent an easier arrangement for photonic crystal waveguides that does not require wet etching to achieve air claddings. In this work, we attempted to explore the higher-order bandgaps in a photonic crystal waveguide based on such heterostructures, and to find guided

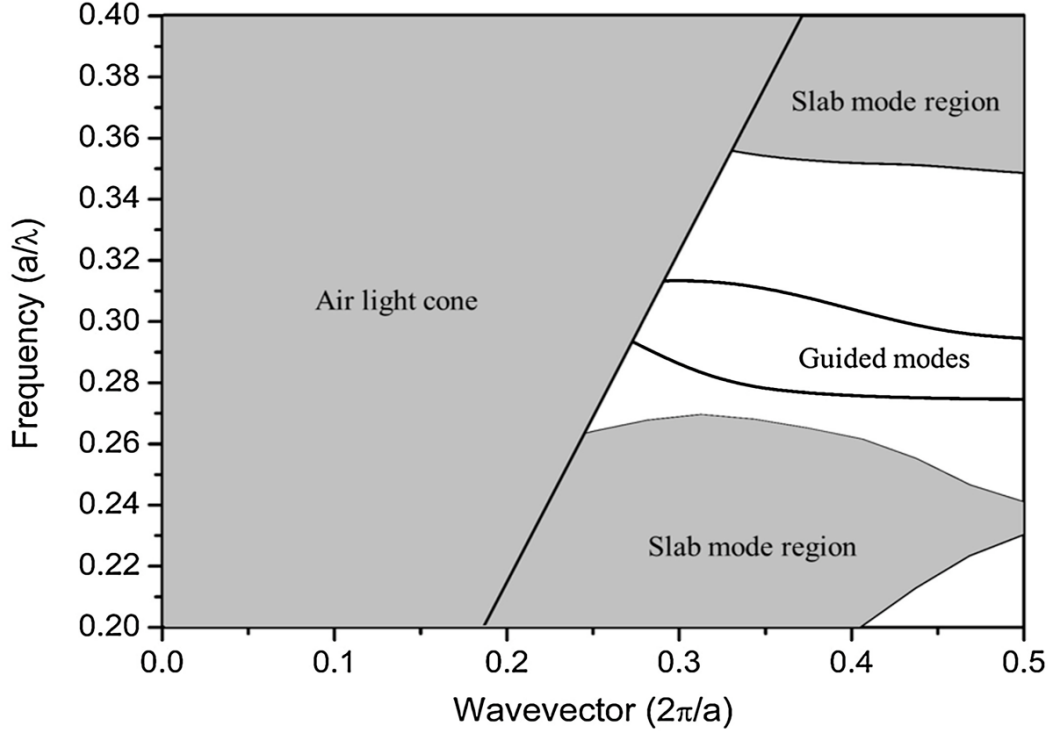


FIGURE 4.2: Representation of light line with air claddings for a photonic crystal waveguide. Figure adapted from [107].

modes residing inside the bandgap region with semi-slow-light-like properties [108]. The bandgap for a triangular photonic crystal lattice usually reduces in size as the frequency increases. This means that the largest bandgap is the first (lowest-frequency) bandgap, which is usually also complete. All other bandgaps following the first one are either incomplete, or occur for a narrower frequency range compared to the first bandgap. In this work, we explore the second bandgap to find guided modes residing in this incomplete bandgap.

4.1 Theory and Waveguide Design

The first step in designing a waveguide based on a ternary or quaternary III-V semiconductor is to identify the composition of the layer stack on a lattice-matched substrate. In this case, we used a previously well-studied AlGaAs layer stack [80], [109] that was introduced in the previous Chapter 3. The epitaxial stack consisted of 18% aluminum concentration core layer ($\text{Al}_{0.18}\text{Ga}_{0.82}\text{As}$), confined between 70% aluminum top and bottom claddings ($\text{Al}_{0.70}\text{Ga}_{0.30}\text{As}$). It has been well established that $\text{Al}_{0.18}\text{Ga}_{0.82}\text{As}$

with 18% aluminum concentration leads to minimum two-photon absorption at 1550 nm [73], [79]. To have lattice matching and low defect densities, the structure was grown by MBE on a GaAs substrate. A 100-nm-thick GaAs film was grown on top of the upper cladding to protect the higher-aluminum-concentration $\text{Al}_{0.70}\text{Ga}_{0.30}\text{As}$ layer from oxidation.

Since PhC waveguides are aimed to be used in optical interconnects and all-optical signal processing applications, it is imperative to have 2D light confinement in both the vertical and lateral directions. The vertical confinement in this case is achieved by the total internal reflection, and the lateral by photonic crystal patterning. The higher the index contrast between the core and the claddings, the more favorable conditions for the TIR are realized. Therefore, the most ideal way is to have a thin membrane or a slab of high refractive index surrounded by the air on both sides to have the maximum Δn . There have been several studies reported using a photonic crystal waveguide with air claddings in silicon, and such a geometry is called a suspended PhC structure. Although such structures offer a lot of promise due to the high index contrast, they still have some drawbacks such as higher scattering losses. In addition, the structures are not mechanically stable and require support structures to be fully suspended.

In this work, we explore a 3-layer AlGaAs heterostructure where the core and claddings have an index contrast of around 0.2. As a result, the light stays confined in the core, as it can be seen from Fig. 4.3 (left). The lateral confinement is achieved by employing photonic crystal patterning as can be seen from Fig. 4.3 (right). In our design, we have formed a “W1” waveguide line defect, which corresponds to one row of missing holes. To achieve maximum confinement, the bandgap region should be large, and the band profile of the guided mode should be as flat as possible for the operation in the slow-light regime.

The well established theory of electron wave in matter can be utilized in photonics as well [82]. The wave equation describing the propagation of light in a medium has a form analogous to Schrödinger’s equation. EM waves in a periodic lattice can be modelled similar to how the electrons are modelled in a periodic potential of a semiconductor lattice. The EM modes can be found by solving Maxwell’s equations with the boundary conditions describing the refractive-index boundaries of the material. For relatively simple geometries, the solutions can be found using simple analytical equations. However, for more complex geometries, like in the case of photonic-crystal

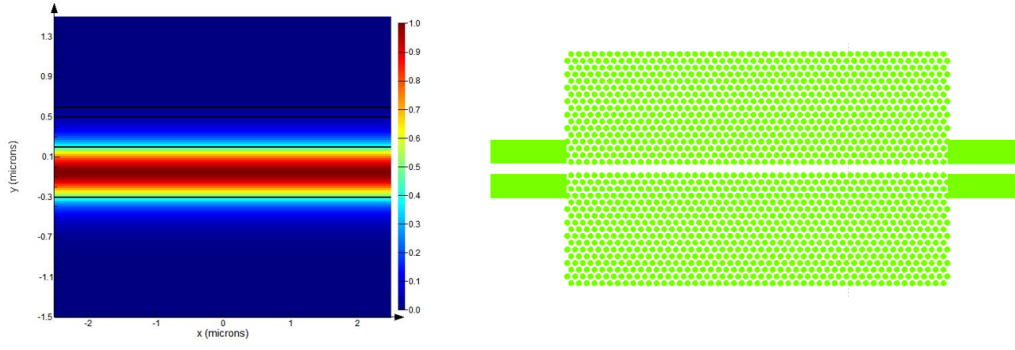


FIGURE 4.3: Side view simulation result depicting vertical confinement in the higher-index $\text{Al}_{0.18}\text{Ga}_{0.82}\text{As}$ core (left), and the GDS file for the photonic crystal line defect pattern representing the top view (right).

structures, numerical-based methods need to be deployed. To understand the behaviour of the modes, the frequency as a function of wave vector (ω vs $\vec{k}$) relation of the EM waves is used, which gives all the necessary information about the behavior of the wave inside the structure. This relation is known as the photonic band diagram or dispersion relation. The wave function of the mode travelling in a photonic crystal can be considered as a plane wave modulated by a periodic function. According to the Bloch theorem, this can be represented using the following equation:

$$\vec{H} = e^{-i(\vec{k}\vec{x} - \omega t)} * \vec{H}_{\vec{k}}(\vec{x}). \quad (4.1)$$

where $\vec{H}$ represents the eigen-state. Using the field equation (4.1), the solution to the Maxwell's equations becomes the following eigenvalue problem:

$$\left[\vec{\nabla} + i\vec{k} \times \frac{1}{\epsilon} (\vec{\nabla} + i\vec{k}) \times \right] \vec{H}_{\vec{k}} = \left(\frac{\omega_n(\vec{k})}{c} \right)^2 \vec{H}_{\vec{k}}. \quad (4.2)$$

.

The solution to Eq. (4.2) gives the eigenvalues for all the values of wave-vectors and frequency points, which yields the photonic band structure also known as ω vs $\vec{k}$ plot. In this work, since we are interested in 2D periodic lattices only, we do not need to consider all three components of $\vec{k}$. We can consider $k_z = 0$, which leaves us with k_x and k_y only.

To simplify the computations further, we can make use of the periodicity of the photonic crystal lattice. Due to the translational symmetry in the x -direction, $\vec{k}$ gets conserved in each lattice period, and because of this, one

can use k_x as a parameter to distinguish the modes within a small region, which is known as the first Brillouin zone. The corresponding frequencies of the x -component of the wave vector also make a periodic function. The range of this periodicity is determined by transforming the lattice vector (in position space) and the reciprocal lattice vector (in frequency, or momentum space). This means that the band diagram can be represented as ω versus k_x , which leads to a 2-dimensional plot of all frequencies corresponding to the x -component of the wave vector k_x .

We used an open-source software MIT Photonic Bands (MPB) [78] for calculating the band structure (or dispersion relation) $\omega(k)$ and MEEP for calculating the transmission spectrum of the guided modes. We also confirmed the results using Lumerical 3D FDTD. MPB is an open-source software which calculates the band diagram by computing the eigenstates of Maxwell's equation by employing plane-wave expansion method. MEEP is also an open-source solver which can perform finite-difference time-domain (FDTD) solutions, and was employed to observe the time evolution of the fields and the transmission spectrum.

As mentioned previously, we performed the calculations for the band structures using MPB. Ideally, the simulations should be performed in 3D, but 3D simulations are very computationally intensive and time-consuming. Since we have a symmetry in the z -direction, we can make use of the effective-index method (EIM) [110], and can run the equivalent 2D simulations, which will still lead to almost the same results as that expected from 3D simulations. For ease of calculation, the effective-index method was deployed, in which the behaviour of a 3D heterostructure stack is mimicked by considering an equivalent 2D structure with an effective index corresponding to that of the heterostructure. For the 3-layer AlGaAs heterostructure that we considered, the effective index was calculated to be 3.16799 at 1550 nm for a heterostructure with the following layer parameters:

300 nm top cladding, 500 nm core, and 3 μm lower cladding.

Recently, a newer approach to calculating effective index, called the effective-period method (EPM), was proposed [111], in which the authors argued that, for a symmetrical mode profile in z -direction (where the confinement is provided by TIR), simulating the heterostructure in 2D with n_{eff} gives wrong results for the propagation loss and group velocity. Therefore, they proposed using the bulk refractive index for 2D simulations and calculating the correct

value of lattice constant from the resulting simulations of the bulk. The major difference in the EPM method is the operating wavelength which largely depends on the vertical dimensions of the slab. The correction that was used in EPM is shown in the equation below:

$$\lambda = \frac{a_{\text{eff}}}{\nu} = \frac{n_{\text{eff}}}{n_{\text{bulk}}} \frac{a}{\nu} \quad (4.3)$$

Here $a_{\text{eff}} = \frac{n_{\text{eff}}}{n_{\text{bulk}}} a$ is the effective period.

Overall, the difference between EPM and EIM for the determination of the band structure is just a shift in the frequency; however, for the loss calculation, it can lead to erroneous results. Therefore, we also ran simulations using EPM to perform a comparison of the fabricated devices using the two different methods.

4.2 Simulation Results

2D band-structure simulations were performed using MPB for lateral confinement in the waveguide. The simulation procedure starts with defining the physical parameters such as effective refractive index of the material, index of the holes, and radius-to-lattice-constant ratio (r/a). The physical structure and geometry is defined, and the r/a value is varied to find the bandgap openings at different frequencies with the aim to maximize the bandgap region. Then a single line defect is created in the geometry, and the simulations are run again with the coarse parameter tuning to find the guided modes inside the bandgap region. It was observed that TM modes were achieved only for large r/a values, which would mean that the structure dimensions would be relatively difficult to fabricate, and such structures will be more prone to damage. As a result, we stick to the TE modes for these simulations. After a few iterations, $r/a = 0.36$ was chosen as the optimized ratio. For this value of r/a , we can see from Fig. 4.4 that there is one complete bandgap with a single guided mode with a flat band profile near the band edge, followed by a second incomplete bandgap with two guided modes.

We initially wanted to work in the first-bandgap region which is complete and hosts a single guided mode with a flat slope near the band edge, meaning that this would lead to high group index values because $\frac{d\omega}{dk}$ would be close to 0. Fig. 4.5 shows the zoomed-in image for the first bandgap region. The

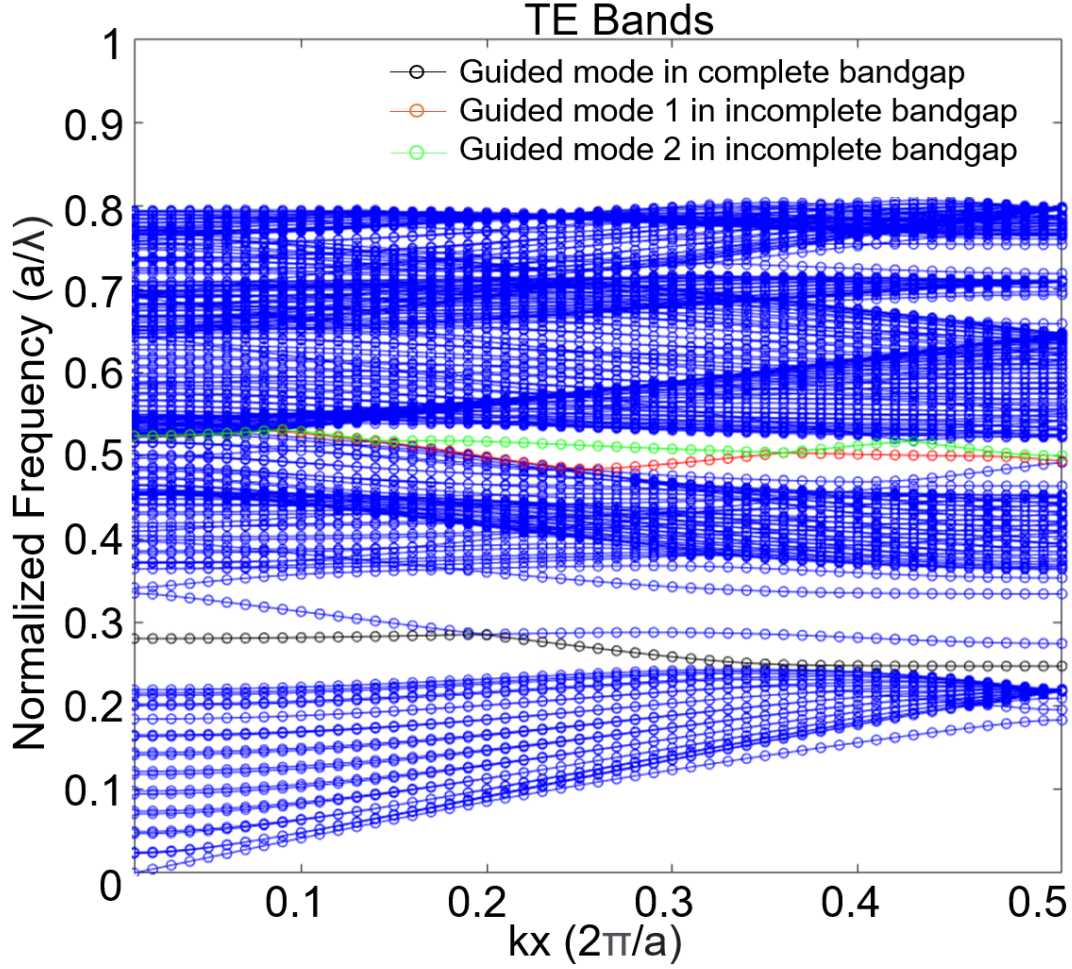


FIGURE 4.4: Band diagram simulated using MPB. The black curve represents the single guided mode inside the complete bandgap region. The red and green curves represent two modes inside the incomplete bandgap.

radius and lattice constant values corresponding to the the guided mode in the first bandgap are as follows:

$$\text{Radius} = 154 \text{ nm}; \text{Lattice Constant} = 427.7 \text{ nm}$$

Next, the transmission spectrum simulations were performed using MEEP and 2.5D FDTD, which point towards a single, line-defect-guided mode within the bandgap region operating in the slow-light regime. Fig. 4.6 represents the transmission spectrum for the given dimensions and the respective mode profile that looks like a typical index-guided mode at 1450 nm (away from the band edge). In Fig. 4.7, we see a sharp drop in the transmission near the band edge (circled in red) and confirm the slow light operation regime from the $H(z)$ field profile. This is the usual field pattern for a slow-light mode [112].

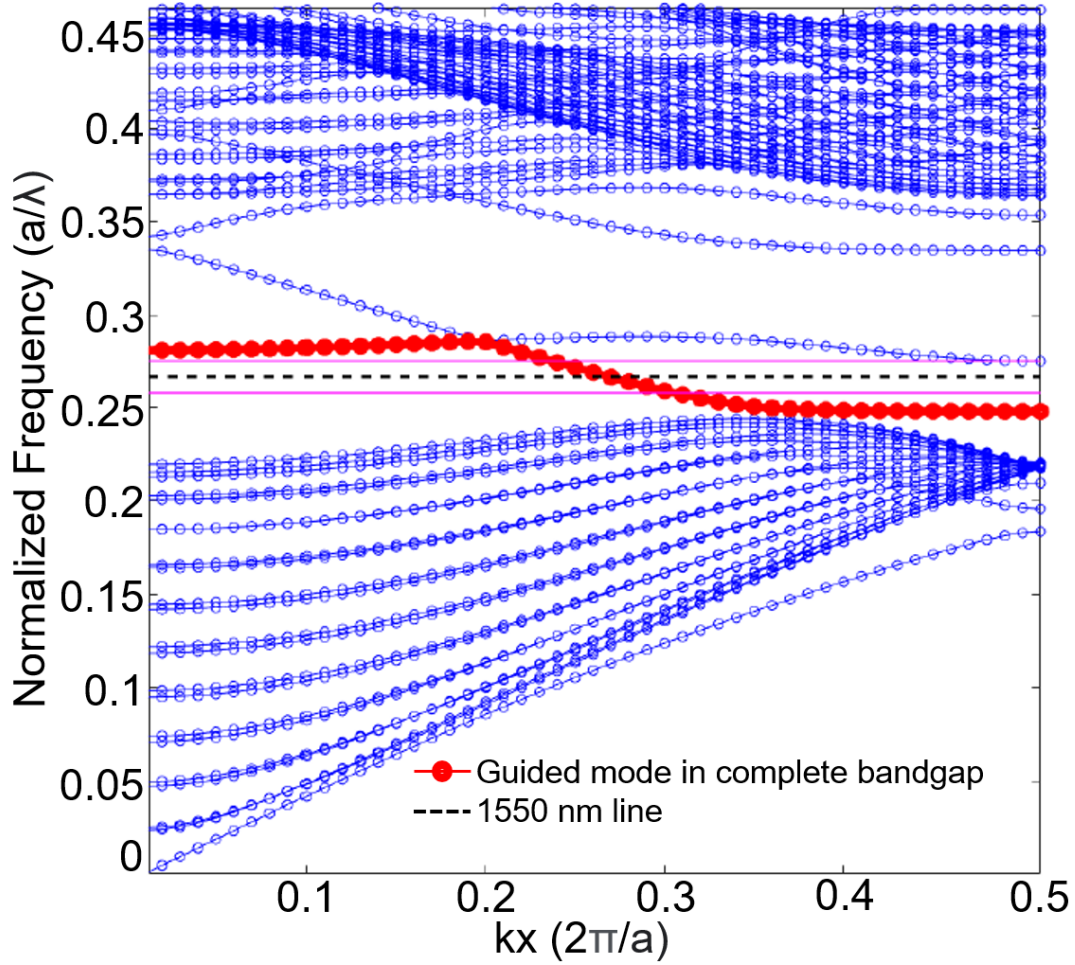


FIGURE 4.5: Band diagram simulated used MPB. The red line represents the guided mode inside the bandgap region.

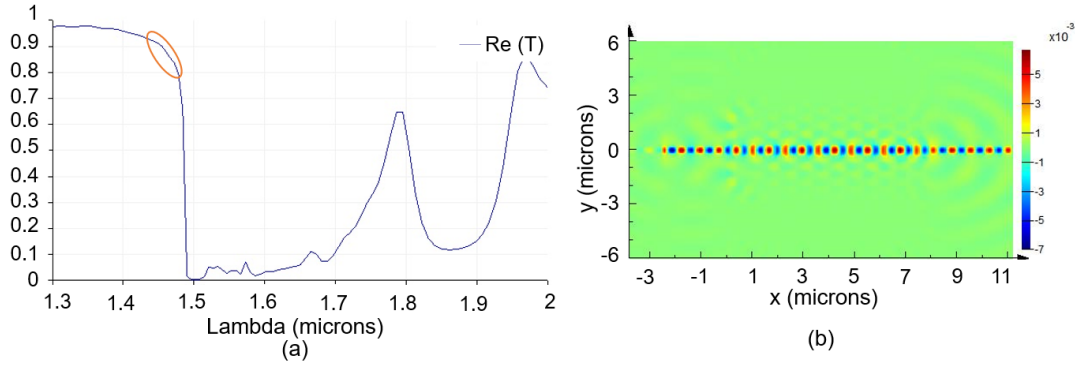


FIGURE 4.6: (a) Simulation results showing the transmission spectrum vs wavelength for a slow-light mode; (b) Field profile showing the top-view for a refractive index-like mode at 1450 nm [circled in red in part (a) of the figure].

The results obtained for radius and lattice constant values from the band diagram of the first bandgap geometry were used for fabrication trials. But the hole dimensions were so small that the resist ran away before the core was

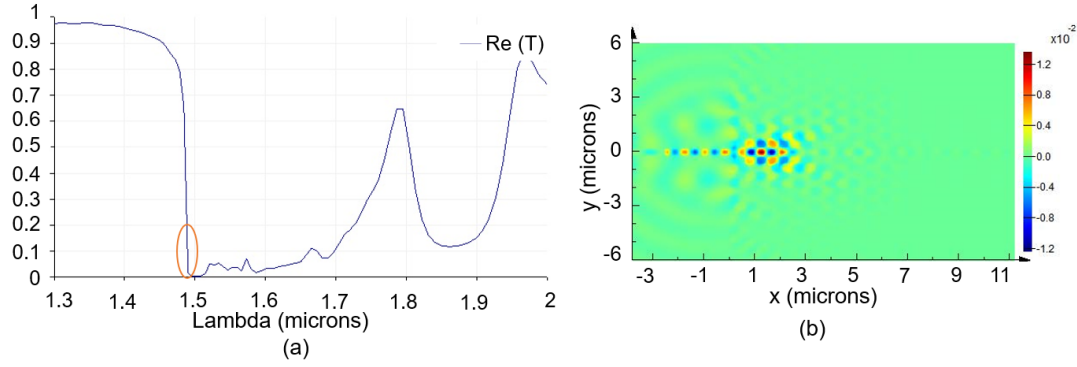


FIGURE 4.7: (a) Simulation results showing the transmission spectrum vs wavelength for a slow-light mode; (b) Field profile showing the top view for a slow-light mode at 1492 nm near the band edge.

completely etched through. This was discussed as one of the challenges in the previous chapter. Following this, some more etch-test trials were performed, and the results gave a clear indication that the resist (500 nm of ZEP520a) could only be used for etching holes with the radius of 250 nm or greater to achieve the required etch depth of 800 nm.

As a next step, higher-order bandgap regions were explored as they provide the dimensions that could lie within our fabrication limitations. Fig. 4.8 shows the second bandgap region. One can see from Fig. 4.8, two guided modes (shown in red and green) exist in the bandgap region. Although these modes do not have a slope as flat as that of the first-bandgap mode, the fact of their existence in the incomplete bandgap is interesting by itself. There have been a few works exploring higher-order photonic-crystal bandgap regions for defect-guided modes. The modes above the light line lie within the continuum of leaky modes and are expected to have very short lifetime due to the out-of-plane radiation losses. Therefore, the transmission of these “quasi-guided” modes (if any) is expected to be very low [113]. As mentioned earlier, although this is not a complete bandgap, nor it is as big in size as the first bandgap region, we still were able to find guided modes lying within this incomplete bandgap. The photonic crystal holes radius was calculated to be 287 nm, and the corresponding lattice constant was 798 nm. The structure dimensions that allow one to obtain guided modes in this region fit within our fabrication tolerances, which stimulated us to fabricate these structures. As a next step, the transmission spectrum simulations were performed, and the results are shown in Fig. 4.8 (a) along with the field profile in Fig. 4.8 (b). We can see from the field profile that these are not complete slow-light modes but

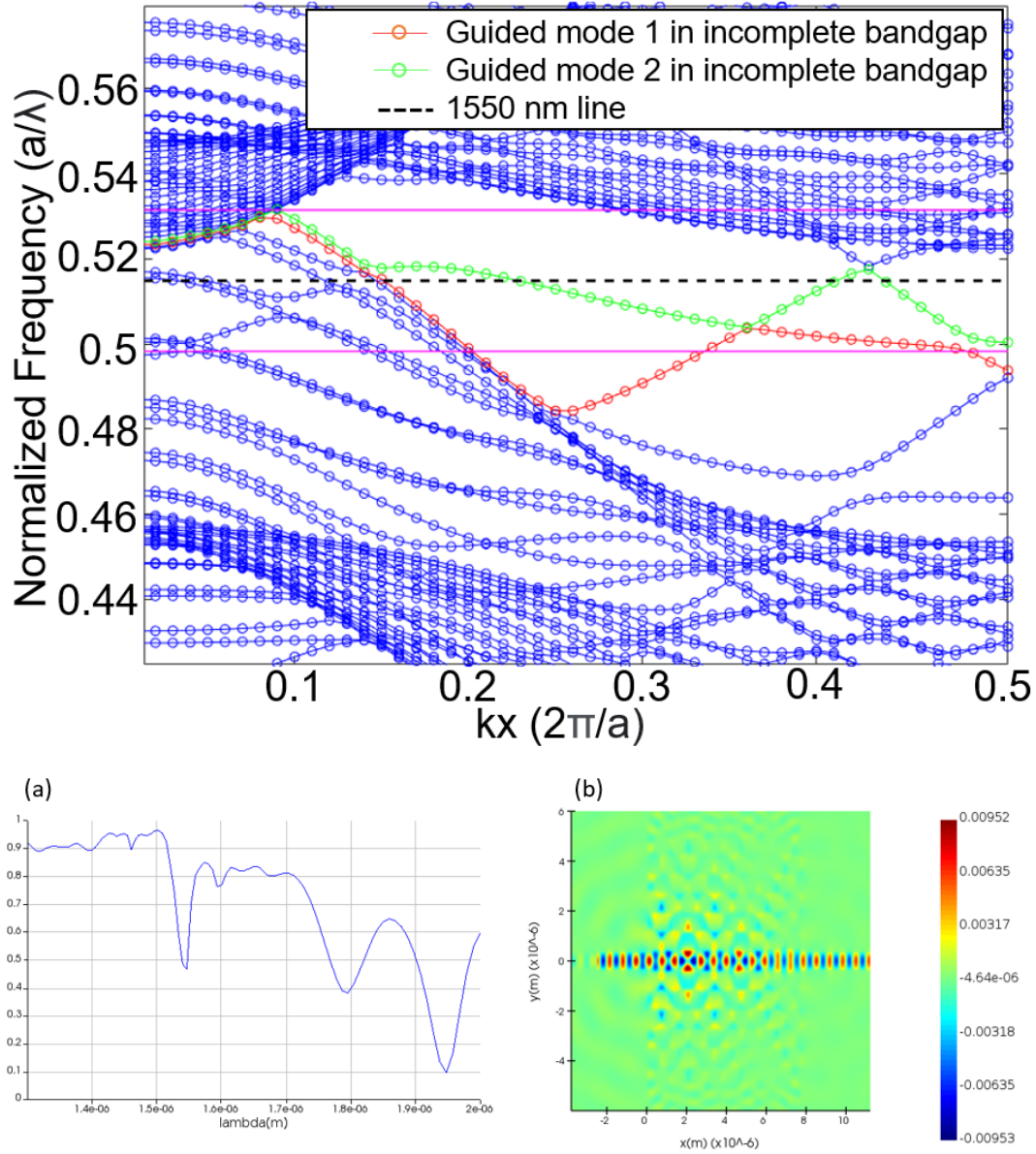


FIGURE 4.8: Top: Band diagram for the second bandgap region showing guided modes inside the higher-order incomplete bandgap. Bottom: (a) Simulated transmission spectrum; (b) Field profile at 1555 nm exhibiting semi-slow-light-like behaviour.

they rather exhibit semi-slow-light-like properties [112], which was expected given that the modes lie in the higher-bandgap regions. As a next step, we fabricated the devices with the dimensions as described above.

4.3 Fabrication

AlGaAs wafers were cleaved into small 1 cm×1 cm pieces, and cleaned in acetone and IPA for 15 minutes. These steps were followed by blow-drying with nitrogen. Fresh E-beam resist ZEP520a was spin-coated at 2000 rpm, resulting in a film thickness of 500 nm, verified using a Dektak profilometer. The pattern was written using the Raith E-beam lithography system at 30 kV acceleration voltage and with a 10- μ m aperture with a base dose of 75 μ C/cm², and developed in n-amyl acetate for 90 seconds, followed by a 30-second rinse in IPA to stop the development process. All the structures were corrected for proximity effects.

700-nm-long straight waveguides were added on both sides of the photonic crystals for in- and out-coupling, as shown in Fig. 4.3 (right). Photonic crystal waveguides of three different lengths (80 μ m, 160 μ m, and 320 μ m) were written so that we can perform cut-back loss measurements. The input and output waveguides widths were 700 nm, which corresponds to the space created after removing one row of holes.

Plasma-etching runs were performed using varying values of ICP power, BIAS, pressure, and gas concentrations of chlorine, BCl₃ and argon, the details of which were already discussed in the previous chapter. The optimized etch recipe results were analysed using cross-section SEM images. Fig. 4.9 (left) shows the SEM image of photonic-crystal hole features after patterning and resist development. The image on the right shows plasma etching test results; some amount of resist can still be seen on top of the structure. The optimised etch recipe was:

$$\text{Cl}_2:\text{BCl}_3 = (0.5 : 1.3) \text{ sccm, ICP} = 25 \text{ W, Bias} = 15 \text{ W, P} = 0.1 \text{ Pa.}$$

Once the final sample was etched, the device was cleaved on both sides using a diamond scribe to open up the edge facets for the light coupling.

4.4 Experimental Results

The linear optical characterization of the fabricated samples was performed using an external-cavity diode laser tunable in the C-band range from 1480 nm to 1640 nm using a free-space coupling setup. Fig. 4.11 shows the experimental setup for the linear transmission measurements. The light from the laser passed through a polarizer, and the TE-polarized light passed through a 50:50 beam splitter. One arm of the splitter went to feed a reference

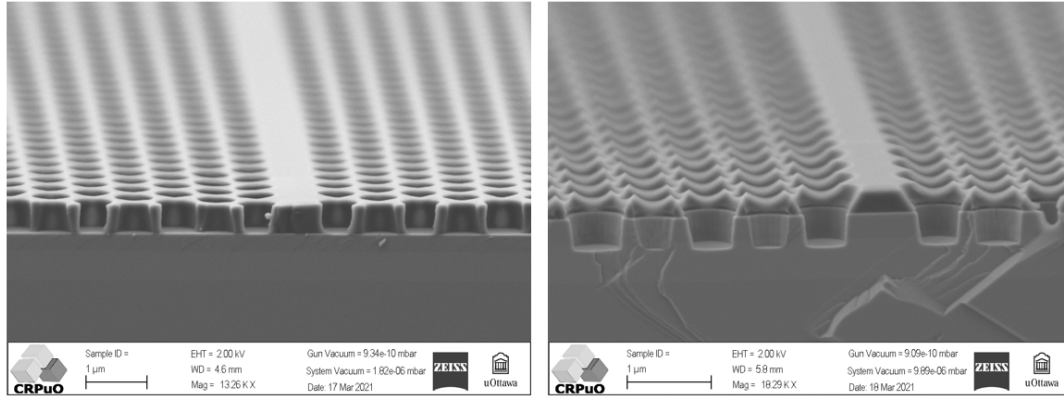


FIGURE 4.9: SEM image of the photonic crystal waveguide cross-section after the development (left); after plasma etching (right).

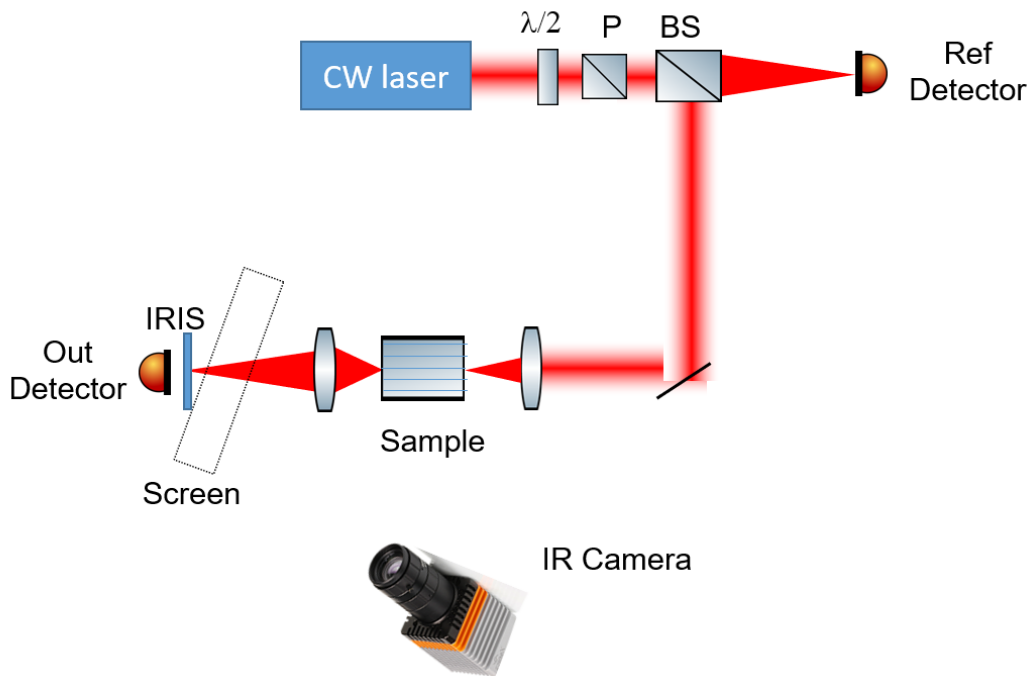


FIGURE 4.10: Experimental setup for transmission spectrum measurement.

detector, and the other arm was reflected from the high-reflectivity mirrors into the coupling lens that formed a spot size small enough to couple the light into the waveguide. A coupling stage with 3D adjustment was used to optimize the light coupling into the photonic crystal waveguide. The light passing through the waveguide was collected at the output facet. Then it traveled to the detector for the output power measurement. Since the light was IR, we used an IR card to make sure that the light alignment was correct. IR cameras were used to look at the mode profile by projecting the output

light onto a screen. To make sure that the light was being coupled to the correct waveguide, an overhead camera was used, which showed the top view of the fabricated device.

The transmission spectrum of the photonic-crystal waveguides with varying lengths (80 μm , 160 μm and 320 μm) were measured, which are shown in Fig. 4.11. The peaks of the curve around 1510 nm and 1620 nm represent the transmittance of the guided modes within the photonic crystal bandgap. The figure on the right shows simulated transmission spectra (black) overlapped with the experimental results (blue) with a slight offset, which occurred due to fabrication imperfections. A 10-nm increase in the hole radius can lead to a wavelength shift greater than 40 nm. Although the observed transmission was low, we were still able to demonstrate guidance in higher-order bandgaps above the light line, which is the first experimental demonstration for observed guided-modes lying above the light line in AlGaAs platform for a substrate-type photonic crystal line defect waveguide.

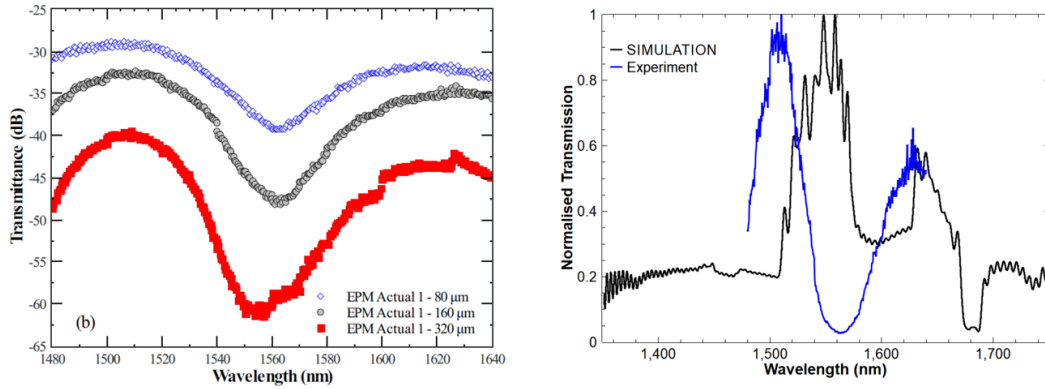


FIGURE 4.11: Experimentally measured transmission spectra of PhC waveguides of varying lengths (left); a comparison of the simulation results and experimental results (right).

4.5 Conclusions and Future Outlook

The work reported in this chapter was one of the first demonstrations of guided modes lying above the light line in a PhC waveguide. We were able to perform the linear transmission experiments but the losses were too high. This was the reason we were not able to witness any nonlinear effects. The biggest challenge was to achieve the light coupling into a 700-nm-wide waveguide, and that is where the majority of the losses occurred. For the newer batch of devices, we fabricated 2- μm -wide coupling waveguides, and

adiabatically tapered them down to 700-nm with a 200-micron length. For the next generation of devices, we also plan to optimize the couplers to have a fairly large transmission. One of the ways to optimize coupling into the PhC lattice is by increasing the lattice period of the first 10 holes by a few nanometers [107], also known as step couplers. Some effort in that direction will be further described in Chapter 6. By making use of the adiabatic waveguide taper, and an optimized photonic crystal taper, we can perform a more efficient mode conversion from fundamental TE mode to the photonic crystal mode as demonstrated in Fig. 4.12. This way, we expect to decrease the coupling loss sufficiently to be able to observe nonlinear optical interactions in the PhC waveguides.

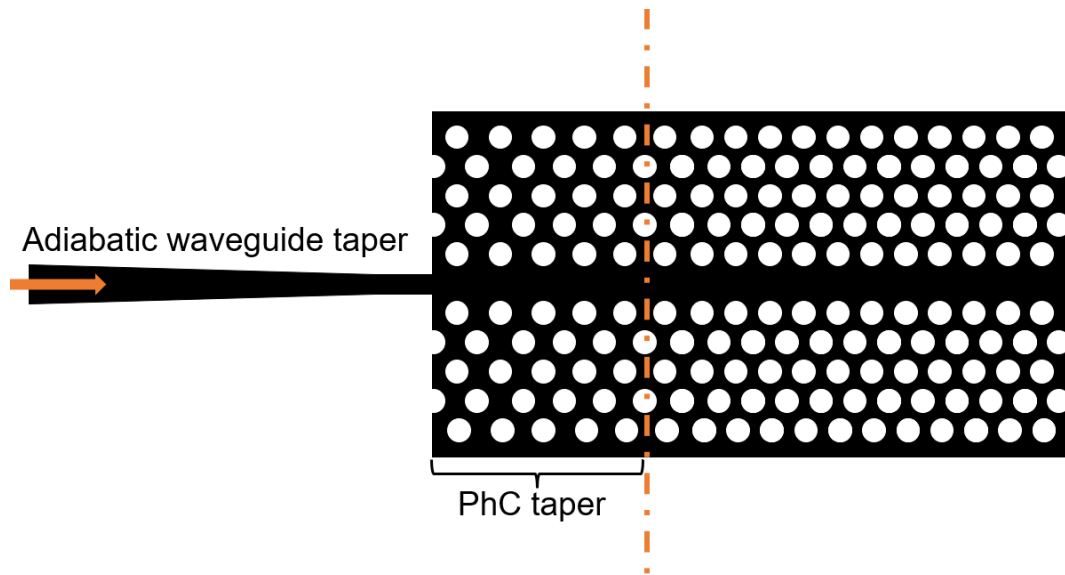


FIGURE 4.12: Proposed solution to optimize coupling into the photonic crystal waveguide region.

Chapter 5

InP/InGaAsP Heated Plasma Etching

InP is one of the most commercialized III-V semiconductor material [114]–[116]. It has been widely used to make active devices such as 1310 nm laser sources, detectors and modulators, and it finds wide applications in the telecommunication industry. $\text{In}_x\text{Ga}_{1-x}\text{As}_y\text{P}_{1-y}$ is a quaternary III-V semiconductor in which the bandgap can be tuned by varying the concentrations of either of the four elements such that x and $1 - x$, and y and $1 - y$ sum up to 1. Therefore, quaternary materials allow more flexibility in tuning the optical parameters as compared to ternary materials. The quaternary alloy, InGaAsP, is of great interest due to its attractive linear and nonlinear optical properties [117], [118]. It can be grown on InP substrate with negligible lattice mismatch [119].

In this project, I collaborated with Ehsan Mobini and Daniel Espinosa, members of the same group. Ehsan performed the design simulations and the characterization work was carried out by Daniel Espinosa and Ehsan Mobini. The aim of this project was to design, fabricate and demonstrate FWM in InGaAsP waveguides of two different geometries, *viz.* the half-core-etched and nanowire, operating in the telecommunication C-band. The major challenge in this project was coming up with an efficient plasma etching recipe to etch the material down to 2 μm etching depth with minimal surface roughness. InP is known to be an extremely challenging material to etch. There have been studies of etching InP in methane-hydrogen chemistries [120], methane-hydrogen-chlorine chemistries [59], and chlorine-based chemistries [121], all of which showing a necessity to maintain high substrate temperatures ranging from 50°C to 150°C [122], [123]. The primary reason of using elevated

temperatures is because the volatile etching byproduct, InCl_x , is only produced above 150°C . Nevertheless, we were able to overcome the challenges and develop an optimized etching recipe that we are going to describe below. The developed etching process leads to good-quality proof-of-principle devices which will be further described in the last section of this chapter which focuses on experimental characterization of the fabricated devices using the optimized etching process.

5.1 Epitaxy and Waveguide Design

As introduced in Chapter 3, the first step before designing any waveguide (or light-guiding structure) is to establish the epitaxial stack to ensure sufficient refractive index contrast and maximum guidance in the core region. Similar to the AlGaAs-based devices that were discussed in the previous chapters, we started by exploring an epitaxial stack which would work well for passive devices to operate at 1550 nm. All the previously discussed concepts for light guiding in a 3-layer heterostructure apply here as well.

There generally exist three waveguide geometries based on a 3-layer heterostructure [63]. The lowest-loss geometry that has been previously studied in a number of works [80], [109], [117] (the strip-loaded waveguide) has the mode buried inside the core and part of the top cladding etched to create a ridge-like structure (Fig. 5.1 (a)). The fundamental guided modes for such geometries typically have a large effective mode area ($A_{\text{eff}} \sim 4\text{--}6 \mu\text{m}^2$), but the propagation losses are lower due to the etch depths remaining restricted to the top cladding. The second geometry is one in which the waveguide width is very narrow (300–800 nm) and is etched down to the bottom of the core (or even deeper into the lower cladding). Such waveguide geometries are called wire/nano-wire waveguides as shown in Fig. 5.1 (c). The nanowire geometries have much tighter mode confinement ($A_{\text{eff}} < 0.5 \mu\text{m}^2$) and therefore exhibit large nonlinearities (as the nonlinear parameter γ is inversely proportional to the effective mode area, A_{eff}). The losses in these waveguides are usually on the higher end because the sidewalls of the guiding layer are exposed to the air and have a high refractive index contrast, while the mode “sees” a lot of sidewall roughness from the core etching. The third, more interesting, geometry is a compromise between the first two and is called a half-core-etched waveguide. These waveguides have a width in the range between those of the strip-loaded and the nanowire waveguides (usually

1 – 2 μm), and, as the name suggests, such waveguides are etched halfway through the core layer as shows in Fig. 5.1 (b). In this way, one can achieve a relatively tight light confinement and therefore higher nonlinearities at the expense of a lower propagation loss compared to that of the nanowires. The strip-loaded geometry in InGaAsP waveguides was explored in the past and exhibited the propagation losses of 2.4–2.7 dB/cm [117]. In the current thesis work, we designed, fabricated and tested the waveguides of other two geometries: half-core etched and nanowires.

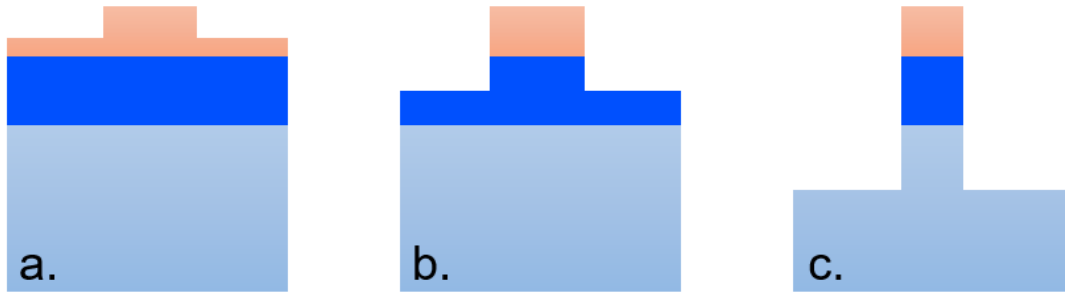


FIGURE 5.1: Schematic representation of three possible waveguide geometries as introduced in [63] : (a) Strip-loaded; (b) Half-core etched; (c) Nanowire

InGaAsP generally exhibits a larger refractive index compared to that of InP. As a result, we selected InGaAsP as a guiding layer and InP as the cladding material to maximize the refractive index contrast. In the choice of InGaAsP material composition for the guiding layer, we chose the material concentrations to obtain maximum refractive-index contrast between the core and claddings, and near-zero group velocity dispersion for the simulated waveguide modes, which allows for minimal temporal walk-off. Two epitaxial stacks were finalized for the two different waveguide geometries, namely: for the half-core waveguides and the nanowires. The former gets the advantage of relatively low optical losses while the latter is superior in terms of light confinement and therefore exhibits stronger nonlinearities. The finalized epitaxial stacks consisted of $\text{In}_{85.1\%}\text{Ga}_{14.1\%}\text{As}_{30\%}\text{P}_{70\%}$ as the core layer and InP as claddings. Fig. 5.2 shows the schematic cross-section for the two chosen epitaxial stacks.

The waveguide design was performed using Lumerical MODE solutions for operation in the telecom C-band frequency range. The designs were optimized for minimizing A_{eff} for higher nonlinearities and for operating at near-zero group-velocity dispersion (GVD). The optimized waveguide designs together with the simulated fundamental mode profiles are shown in

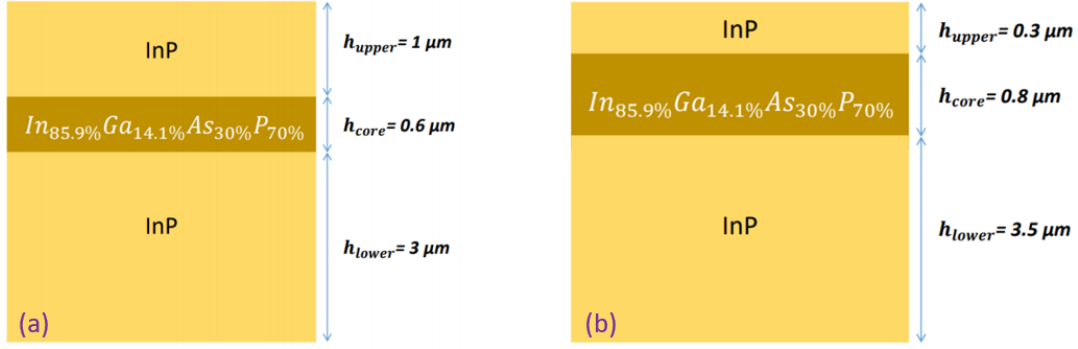


FIGURE 5.2: Epitaxial stack for InP waveguides: (a) for the half-core geometry; (b) for the nanowire waveguide geometry.

Fig. 5.3. The effective modal area for the optimized half-core waveguides was $1.75 \mu\text{m}^2$, and for the nanowire designs was $0.37 \mu\text{m}^2$. Initially, the simulations were performed under the assumption that the fabricated waveguides will have vertical sidewalls. The optimized nanowire geometry had an etch depth of $1.8 \mu\text{m}$. But in our attempts to optimize the etch recipe while minimizing the sidewall roughness, we were unable to obtain perfectly vertical sidewalls, which will be further discussed in the next section. Therefore, modifications were made to the design based on the aforementioned fabrication limitation on the verticality of the sidewall angle. Fig. 5.4 shows the updated design featuring waveguides with angled sidewalls. To understand the effect of tilted sidewalls in nanowire geometry, simulations were carried out by making modifications to the total etch depth of the lower cladding. The simulations concluded that, if the sidewalls are angled, a larger etch depth is preferred. Larger etch depths ensure that the mode does not leak into the substrate. This consideration required an increase in the overall etch depth for the nanowires from $1.8 \mu\text{m}$ to $2.1 \mu\text{m}$, by 300 nm . Similarly, for the half-core geometry, the etch depth requirements were $1.3 \mu\text{m}$. Although the above dimensions are fairly challenging, we decided to go ahead with these fabrication requirements.

Since the waveguide widths for the designed structures are smaller than $1 \mu\text{m}$, it becomes extremely difficult to couple light into these devices by the edge coupling. Ideally, the coupling objective should focus the radiation down to a spot of approximately $2 \mu\text{m}$ in diameter, but in reality, since the beam is not perfectly Gaussian, and due to the additional effects of diffraction, we get a spot size larger than $2 \mu\text{m}$ (refer to Fig. 3.3). Consequently, light coupling into a 600-nm -wide device would result in large coupling losses. Therefore, we added $2\text{-}\mu\text{m}$ -wide coupling waveguides at the entrance and

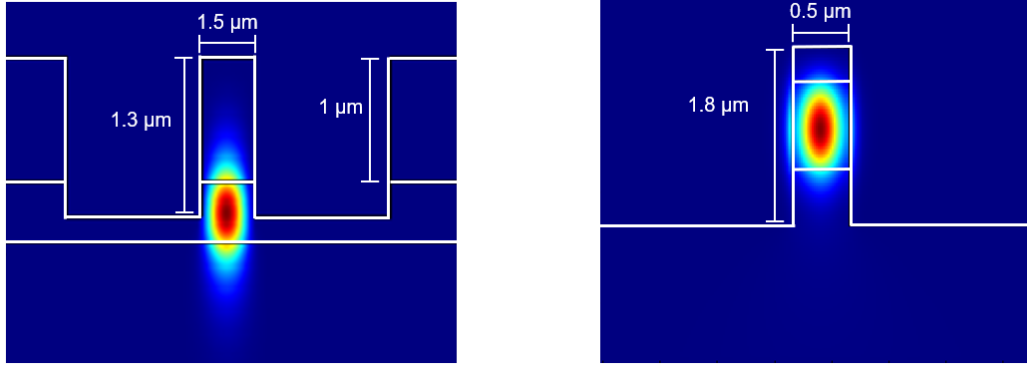


FIGURE 5.3: Guided-mode profiles for: (left) a half-core waveguide; (right) a nanowire waveguide.

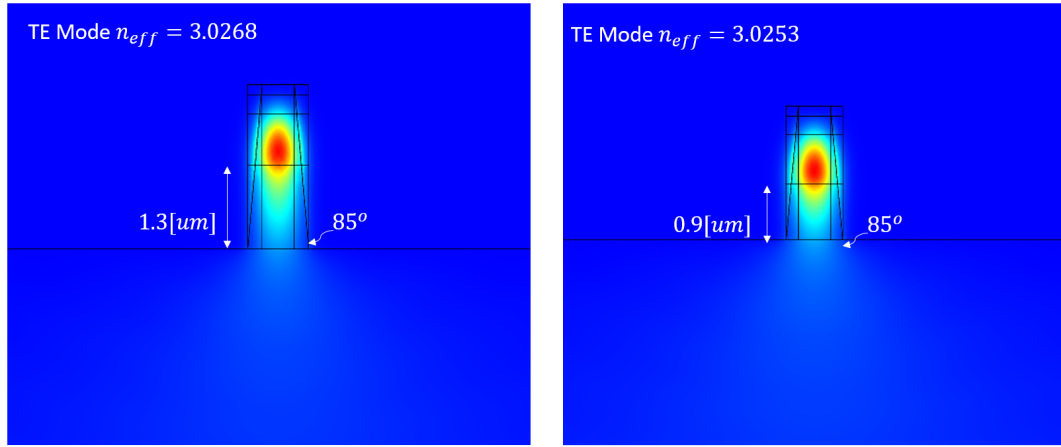


FIGURE 5.4: Guided-mode profiles for the nanowires with tilted sidewalls: (left) The etch depth is 1.3 μm ; (right) the etch depth is 0.9 μm .

the exit of the chip, and adiabatically tapered them down to the width of the waveguide. The schematic of the corresponding waveguide with coupling input and output is represented in Fig. 5.5. The lengths of the tapers were 200 μm . On the GDS file, we also added some 2- μm -wide (untapered, uniform-width) reference waveguides and some taper-to-taper structures to evaluate the contributions of different parts to the overall results. These additional structures also allowed us to quantify the loss contributions from different parts of the devices.

5.2 Waveguide Fabrication

The InP/InGaAsP wafers were grown using MOCVD process at SANDIA National Labs (USA). The grown wafer stacks were cleaved into 2 cm $\times$ 2 cm

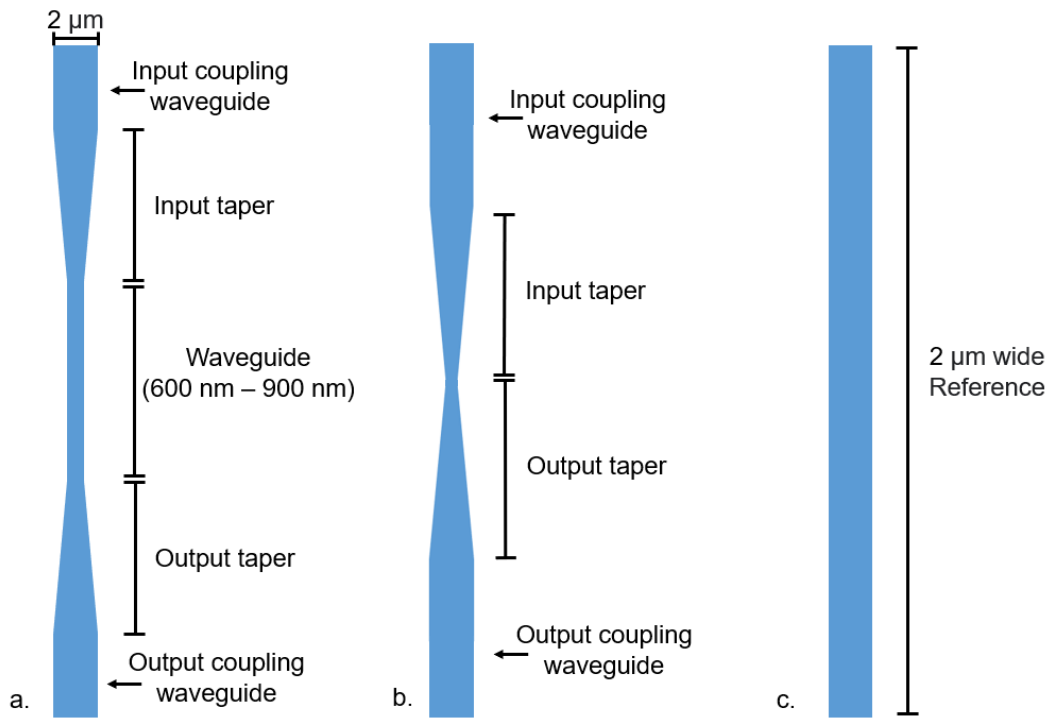


FIGURE 5.5: (a) A schematic of a waveguide with 2- μm coupling facets and adiabatic tapers; (b) taper-to-taper devices to evaluate the impact of the tapers; (c) 2- μm -wide reference waveguide.

pieces, cleaned in acetone and IPA, and blow-dried with nitrogen. As mentioned in the previous sections, the required etch depth was fairly large, and different fabrication processes were tested before we arrived at the finalized process. Three major etching tests were performed, which will be discussed in the upcoming sections. For all the tests, waveguides with varying thicknesses were patterned using electron-beam lithography at 30 kV and 10-micron aperture and developed in n-amyl acetate for 90 seconds, followed by a 30 second rinse in IPA to stop the development process.

5.2.1 Etching using ZEP mask

The first tests were performed using ZEP520a mask because using an E-beam resist as a mask offers an easier process flow requiring a single-step etching and because ZEP was readily available at our facility. Clean samples were spin-coated with 500 nm of ZEP. The resist was baked at 180 °C for 3 minutes after spinning. After that, a patterning using E-beam lithography was performed. We carried out 5 etch tests using chlorine-based gases. It is known

that the etching byproducts of InP are volatile at high temperatures, therefore, we tried etching at 60°C. We did not attempt etching InP at higher temperatures because ZEP is a polymer-based resist and it starts reflowing at temperatures higher than 60°C. The best results using ZEP mask are shown in Fig. 5.6. The SEM image on the figure reveals an etch depth of 248 nm before the resist completely eroded. These results were obtained using the following recipe for a 2-minute etch trial:

$\text{Cl}_2:\text{BCl}_3:\text{Ar} = 1 : 4 : 2$ sccm; Pressure= 0.15 Pa; ICP= 60 W; Bias= 20 W

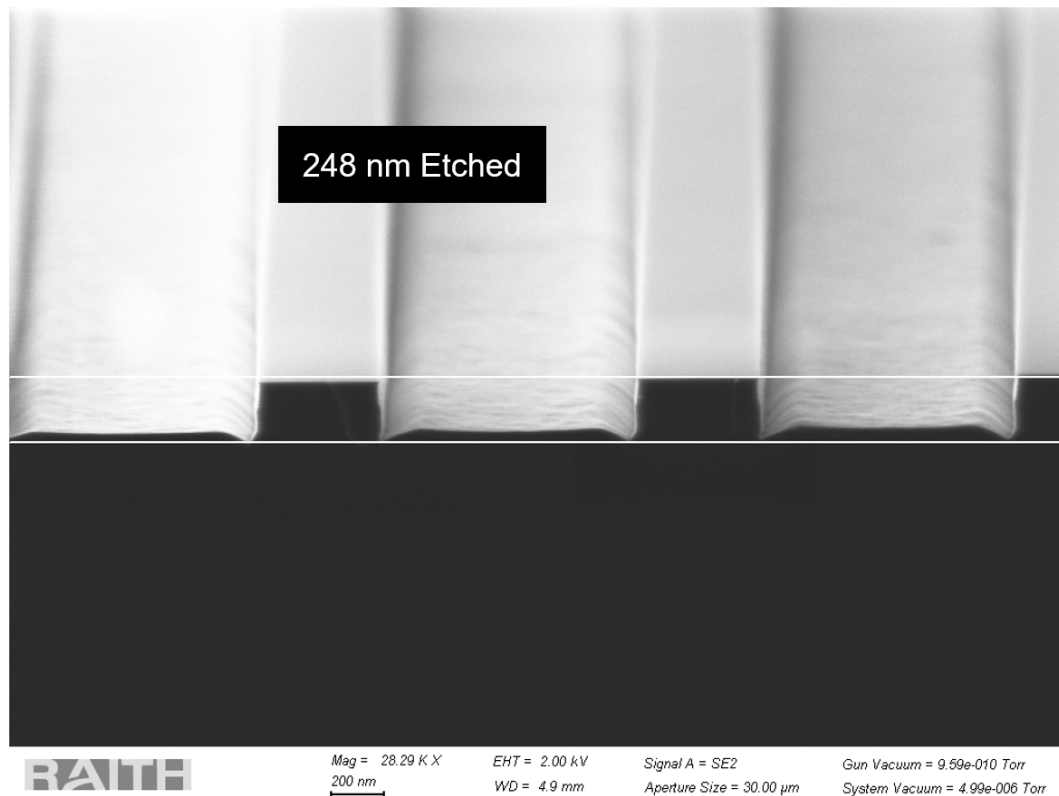


FIGURE 5.6: Cross-section SEM image of InP etched using ZEP mask.

The above etching recipe using ZEP yields a selectivity of roughly 1:0.5 (ZEP:InP) which is unacceptably low. Although the etch profile looks vertical and the roughness is also low, the etch depth of 248 nm was roughly one order of magnitude less than that required by the design. We concluded that a resist that would stay for a longer duration would be necessary. Therefore, we decided to move ahead with HSQ resist which can be used at higher temperatures (greater than 150 °C) and can have a high selectivity.

5.2.2 Etching Using HSQ Mask

HSQ is known to have large selectivity to etch III-Vs [64], and therefore we performed some etch trials using HSQ resist. As previously discussed in Chapter 1, HSQ is a negative-tone resist which takes the form of silica glass after a hard-bake process, and therefore can be used for deeply etched structures. HSQ was not available at our in-house facility, and we used the University of Waterloo's QNF facility where 6% HSQ was available. Clean samples were spin-coated with HSQ at 2000 rpm, which resulted in a 160-nm-thick resist layer. The sample was then baked at 250°C for 2 minutes. The etch-test patterns were written using JEOL 100 kV E-beam lithography system with a base dose of 1200 $\mu\text{C}/\text{cm}^2$. The samples were developed in 2.3% TMAH (MF-319) for 75 seconds and were rinsed in DI water for 30 seconds afterwards to stop the development process. These samples were then used for etch trials using the ICP-RIE etcher at CRPuO. The etching chamber was first cleaned using a standard Cl_2/Ar cleaning recipe. Then the chamber was conditioned for 15 minutes with the recipe which was planned to be used for etching. This step is performed to make the etching chamber to have a repeatable environment. The circulator was then turned ON, and the chamber's temperature was set to 190°C (this is the maximum temperature that is allowed on this tool). A second conditioning run was done with the increased chamber temperature and with the same plasma condition which was meant to be used for the etch trial. The etch-test samples were then carefully thermally bonded on the quartz tray with silicon grease on the back side to hold them down. The best resulting etch test had the following recipe:

$\text{Cl}_2:\text{BCl}_3:\text{Ar} = 1 : 2.5 : 2$ sccm; Pressure = 0.1 Pa; ICP = 25 W; Bias = 10 W

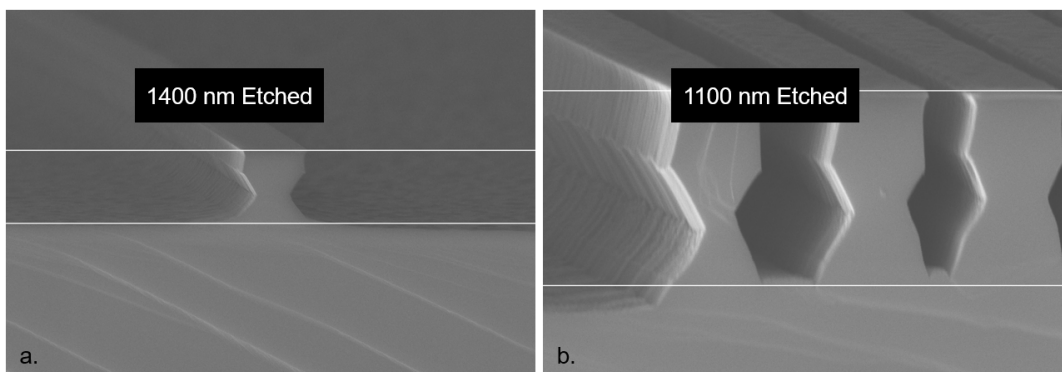


FIGURE 5.7: Cross-section SEM image of InP etched using HSQ mask.

As can be seen from the cross-section SEM images in Fig. 5.7, although the

selectivity using HSQ was good, we observed some unusual sidewall profile after the etching. The etching started with a vertical sidewall but had a very strong undercut halfway through the process. This result remained consistent after a slight change in parameters and repeated tests. Fig. 5.7 (left) shows roughly 1400 nm of material etched, whereas the image on the right shows 1100 nm of etching (lower etch depth because of the RIE lag). Although we were able to get to a selectivity close to 1:9, we did not move ahead with this process primarily because the sidewall verticality was extremely poor. Additionally, 6% HSQ is only suitable for creating a 160–180 nm resist thickness. If we consider selectivity of 1:9, we would have been able to achieve 1600 nm of etch depth (using 180 nm mask) which is significantly lower than that required by the designs. Therefore, we concluded that a thicker silica mask would be needed for these devices.

5.2.3 Etching using Silica Hard-Mask

Since the first two methods (using ZEP and HSQ) did not deliver the desired etch depth, we had to resort to the hard-mask method. The process flow used was the same as discussed in Chapter 2. The samples were cleaned in acetone and IPA, and 320 nm of silica was deposited using an optimized LPCVD process with a deposition rate of 25 Å/second. This step was performed at Carleton University. The wafers were then coated with ZEP520a at 2000 rpm to get a film thickness of 500 nm and were baked at 180°C for 3 minutes before the patterning. The etch-test waveguides with varying widths were patterned using the 30 kV E-beam system at uOttawa. The final devices for half-core-etched waveguides were patterned at uOttawa using the 30 kV E-beam system, and for nanowires were patterned by our collaborator, Kashif Awan, at Stewart Blusson Quantum Matter Institute using the 100 kV E-beam tool. The patterns were transferred into the underlying silica layer using the optimized etch recipe introduced in Chapter 2. Next, the samples were dipped in 5% HF for 5 seconds before transferring the pattern to the InP layers. This step was performed to make sure that no silica mask remained in the trenches around the waveguide.

The etch tests were conducted with a long 1 hour chlorine-argon-based cleaning recipe. This is an extremely important step when etching InP because the etching byproducts of InP contaminate the etching chamber the most of all compared to those of other III-V semiconductors. Therefore, it is important to

perform long cleaning cycles before starting the etch trials so that the chamber condition always remains the same, and the etch tests lead to repeatable results. The next step after the chamber cleaning is the conditioning of the chamber, which was performed twice for 15 minutes - the first time at room temperature and the second time at the desired elevated temperature. Next, the etch tests were performed in a chamber heated up to 190°C. The samples were attached to the quartz carrier wafer with uniform silicon grease at the back to hold them down.

The etch tests were performed starting with the following test parameters:

$\text{Cl}_2:\text{BCl}_3:\text{Ar} = 1 : 2.5 : 2$ sccm; Pressure= 0.25 Pa; ICP= 60 W; Bias= 30 W

This test was run for 10 minutes and resulted in 1 micron of etch depth while 166 nm of the mask was left, giving a selectivity of roughly 1:7. This meant that 300 nm of silica mask would have been just enough to obtain the required etch depth of up to 2 microns. But the roughness at the bottom of the surface was very evident. Some more tests were performed by varying the gas concentrations but keeping the relatively high background pressure (0.25 Pa) and all the tests resulted in extreme roughness caused by needle-like formation at the surface, as shown in Fig. 5.8. Fig. 5.9 shows the AFM measurements results taken before and after plasma etching recipe optimization. These needles chemically are Indium Chloride (InCl_x) and are a common occurrence in InP etching due to redeposition of etch byproducts; this is one of the reasons InP is considered to be a difficult material to etch.

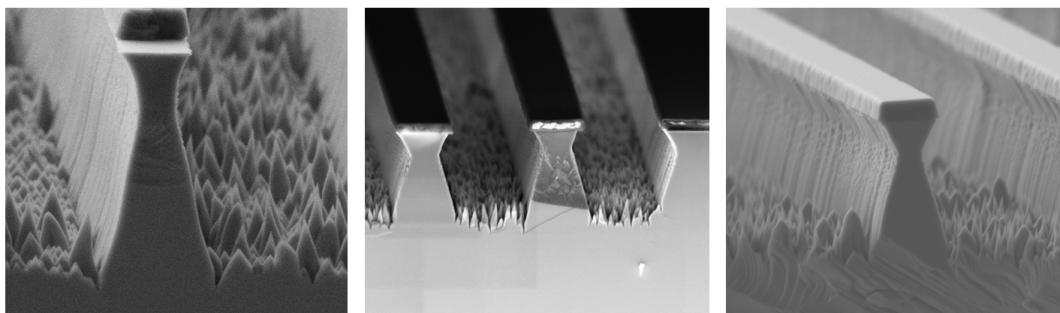


FIGURE 5.8: InCl_x formation while etching InP at high pressure.

The reason for these needles was found to be a high chamber pressure and the presence of slight moisture in the etching chamber. InP etching is highly sensitive to chamber pressure, and the etch results are drastically affected by even the slightest moisture in the chamber. Therefore, it was established that the ideal requirements for InP plasma etching are:

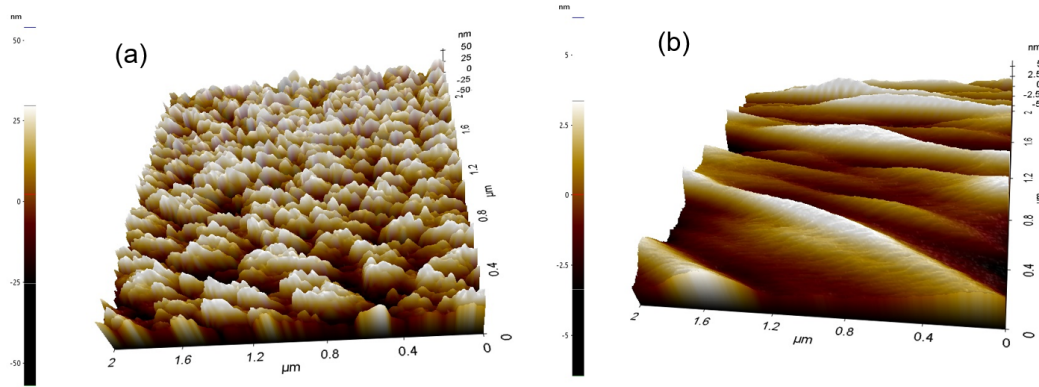


FIGURE 5.9: (a) AFM measurements taken before the recipe optimization that show a large surface roughness; (b) AFM measurements taken after the recipe optimisation revealing smooth surface.

1. High chamber temperature;
2. Low background pressure;
3. Large ICP power;
4. No moisture in the chamber.

To make sure that there is no moisture on the surface, we added an additional step of argon discharge for 10 seconds, which helped in increasing the wafer temperature thereby evaporating the surface moisture. Although this step depletes the mask slightly (20-40 nm), it was essential to perform this process to make sure that the needles are not formed at the surface. In the end, the actual etch process had a 280 nm of mask instead of 300 nm. Systematic etch tests were then performed by varying the ICP and Bias powers, and the final optimized etch process had the following parameters:

$\text{Cl}_2:\text{BCl}_3:\text{Ar} = 1 : 4 : 4$ sccm; Pressure= 0.15 Pa; ICP= 50 W; Bias= 20 W

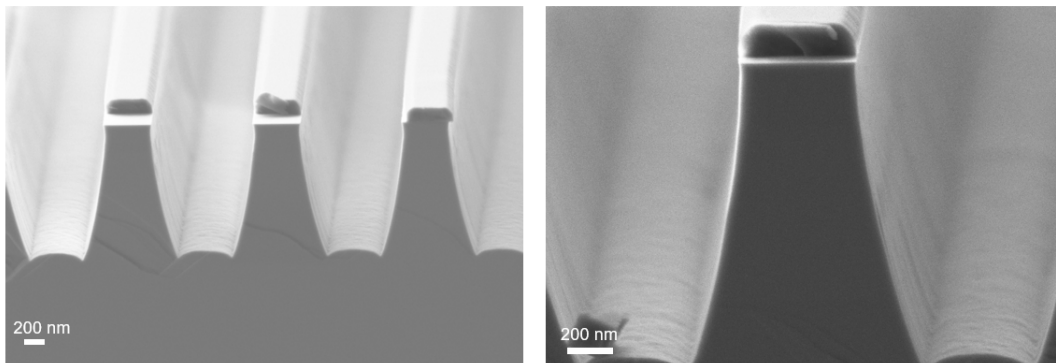


FIGURE 5.10: Etching results for half-core etched waveguide.

The results obtained using these parameters are shown in Fig. 5.10. As can be seen from this cross-section SEM, 1.32 μm of the waveguide was etched in 3 minutes. This was the required etch depth for the half-core-etched waveguides. We can also see that 150 nm of the mask was still left (only 130 nm of the mask eroded). This gives an etch rate for InP 440 nm/minute and the selectivity slightly higher than 1:10 (silica:InP). We also observed that the sidewalls are not perfectly vertical. This happens because there is always a trade-off between the roughness and verticality while working with chlorine-based gases to etch InP. Better verticality requires lower ICP and higher pressure, but having low ICP and higher pressure also leads to high surface roughness, as demonstrated in Fig. 5.8. Since our design modifications confirmed that we can afford to have angled sidewalls (refer to Fig. 5.4), we decided to prioritize sidewall smoothness over verticality.

As can be seen for the final optimized etch recipe parameters, we chose a gas concentration such that the ratio of Cl_2 to BCl_3 remains high. This was done to make sure that the etch selectivity for the core and cladding layers remains similar. We also had high argon concentration for more physical etching. As discussed earlier, InP byproducts are not easily volatile, so, a high chamber temperature along with argon ions helps in making sure that the etch byproducts are removed and ensures a high etching rate. Additionally, low pressure and high ICP power values were used in the process. Once the etching recipe was finalized, we tried some tests by varying the temperature of the chamber from room temperature to 190°C to compare the effect of material etching at different temperature values, and the resulting plot is shown in Fig. 5.11. It is evident from the plot that the actual etching process only commences after 150°C . For the temperature values less than 150°C , the etch rates are lower than 200 nm/min, which would result in a maximum of 1300 nm of etching before the 280 nm mask completely runs away. Therefore, it is essential to have high chamber temperatures.

Later, some more etch tests were performed, and we were able to achieve an etch depth of up to 3.2 microns before completely running out of the resist. This corresponds to the selectivity of 1:11, as shown in Fig. 5.12. With these results, we concluded a detailed study of heated plasma etching of InP/InGaAsP and demonstrated the selectivities of more than 1:11.

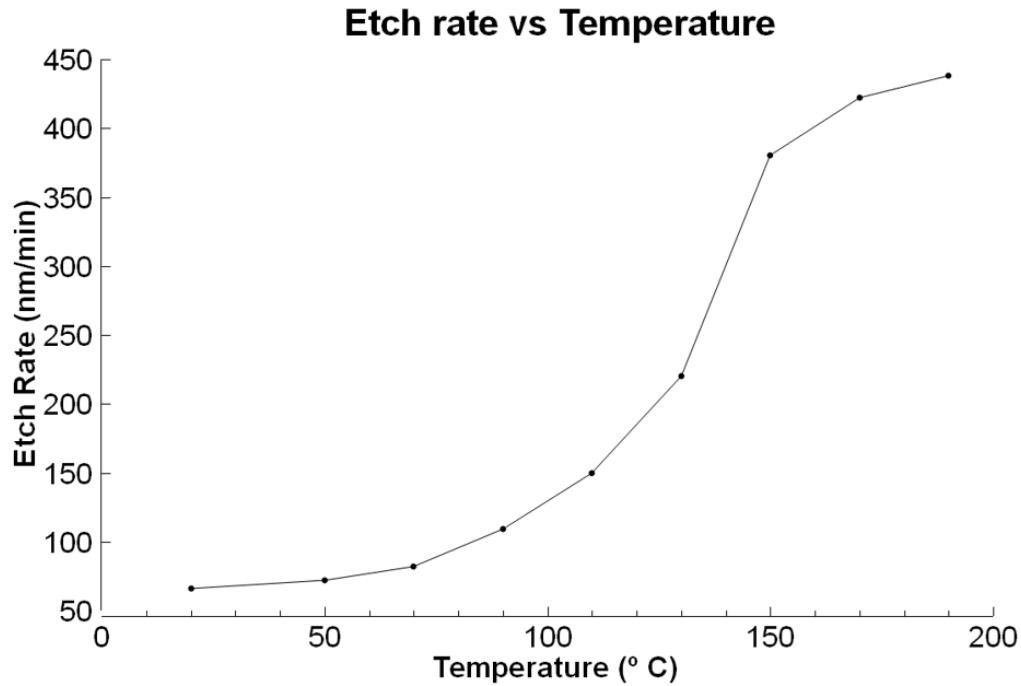


FIGURE 5.11: Plot showing the etch rate of InP as a function of the chamber temperature.

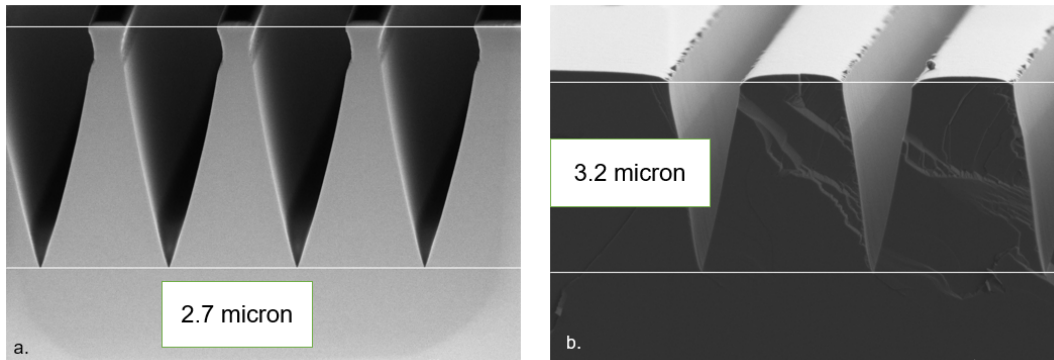


FIGURE 5.12: Further optimized etched process with the selectivity of 1:11 for deeper etch requirements: (a) 2.7 μm etched with 20 nm of mask remaining; (b) 3.2 μm etched while all the mask was depleted.

5.3 Optical Characterization

The fabricated half-core and nanowire InP/InGaAsP devices were optically characterized. The linear loss measurements and the FWM experiments were performed which are presented in the next sections.

5.3.1 Linear Characterization

The transmission measurements were performed using a free-space edge coupling setup, as described in Chapter 4. The linear loss measurements were performed using a tunable CW laser and Fabry-Perot (FP) method [124]. The light at 1550 nm passed through a polarizer and a quarter-wave plate to set the polarization state (TE or TM). Next, the beam passed through a non-polarizing beam splitter, and half of the optical power was sent to the reference arm, while the second half went to the coupling lens. The coupling lens focused the light on the edge facet of the waveguide. After passing through the waveguide, the light was collected by the out-coupling lens and then sent to the output detector. The coupling optimization was performed using a 3-axis motion stage by moving the sample in each direction and trying to optimize the output power measured using the output detector. The transmission measurements were performed for the wavelengths between 1549.7 and 1550.3 nm (in the range of 0.6 nm) with a step size of 0.06 nm to obtain the Fabry-Perot cavity fringes. Fig. 5.13 (a) shows the Fabry-Perot measurement results for the half-core-etched waveguide, which revealed the propagation loss of 13.8 dB/cm for the TM polarization. Fig. 5.13 (b) shows the Fabry-Perot measurements for the nanowire waveguide which results in the propagation loss of 23.2 dB/cm for TM-polarized mode.

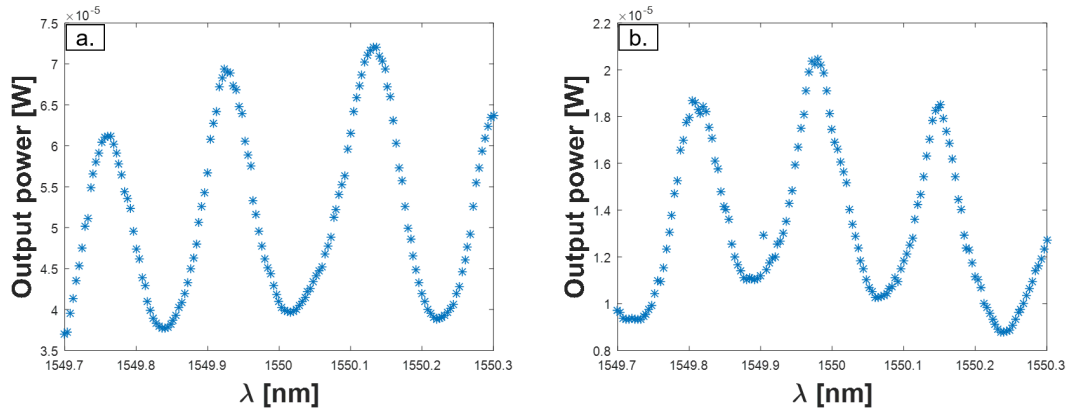


FIGURE 5.13: Linear loss measurements using Fabry-Perot method for (a) half-core waveguide; (b) nanowire waveguide.

5.3.2 Four-Wave Mixing

Following the linear measurements, the nonlinear FWM experiments were performed. Fig. 5.14 shows a schematic for the setup used for FWM experiments. The experiment uses an amplified CW laser, known as the signal, and

a picosecond pulsed laser source, known as the pump. The CW beam gets amplified by an Erbium-Doped Fiber Amplifier (EDFA). The resulting output is aligned (and overlapped) with the pump beam. The signal and pump powers are measured before coupling the light into the waveguide using a reference IR photodetector. The overlapped beams travel together and are coupled into the waveguide using free-space coupling. The output from the waveguide is collected and sent to the output spectrum analyzer (OSA). For the half-core waveguides, 100 mW of average pump power and 500 mW of signal power were coupled into the waveguides to achieve FWM. Similarly, for the nanowire devices, 10 mW of average pump power and 200 mW of signal power were used for the measurements. These results are demonstrated in Fig. 5.15. We can see from the figure that the idler frequency component is generated around 1480 nm for the half-core waveguide (Fig. 5.15 (a)) and around 1470 nm for the nanowire waveguide (Fig. 5.15 (b)). The experimental study of these devices was carried out by Ehsan Mobini, and the detailed results will be mentioned in his PhD thesis. The two photon absorption (TPA) coefficient value for InGaAsP waveguides was also calculated from the experimental data shown in Fig. 5.16, and the reported value at 1550 nm was 19 cm/GW. Further, the nonlinear refractive index n_2 was extracted from the FWM measurements, exhibiting the value of $1.9 \times 10^{-13} \text{ cm}^2/\text{W}$. This is the first accurate measurement of n_2 in InGaAsP/InP waveguides.

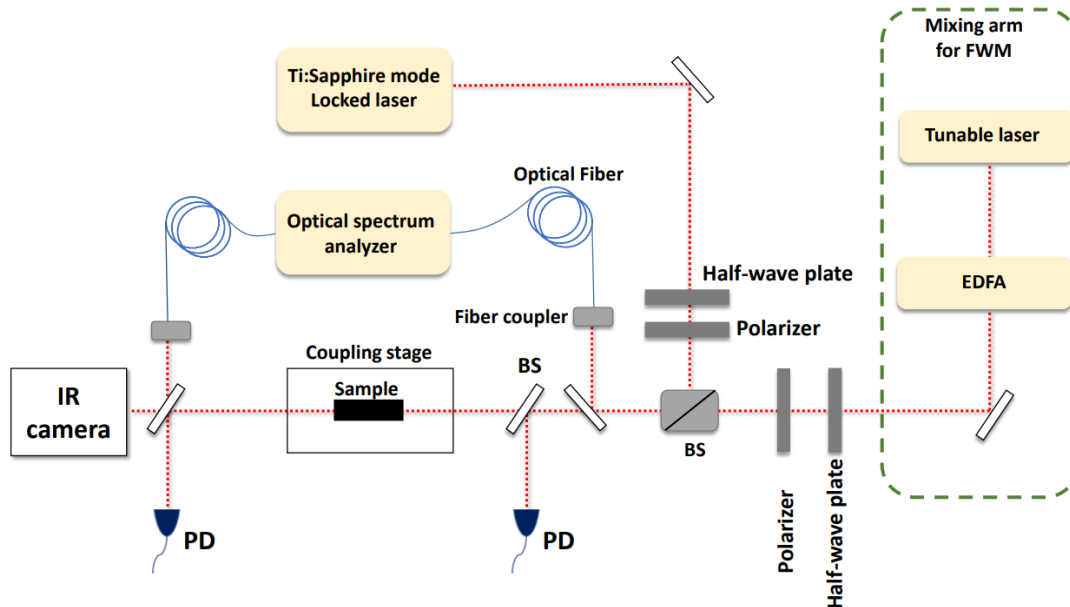


FIGURE 5.14: Schematic representation of the setup used for nonlinear FWM experiments. This figure was created by Ehsan Mobini.

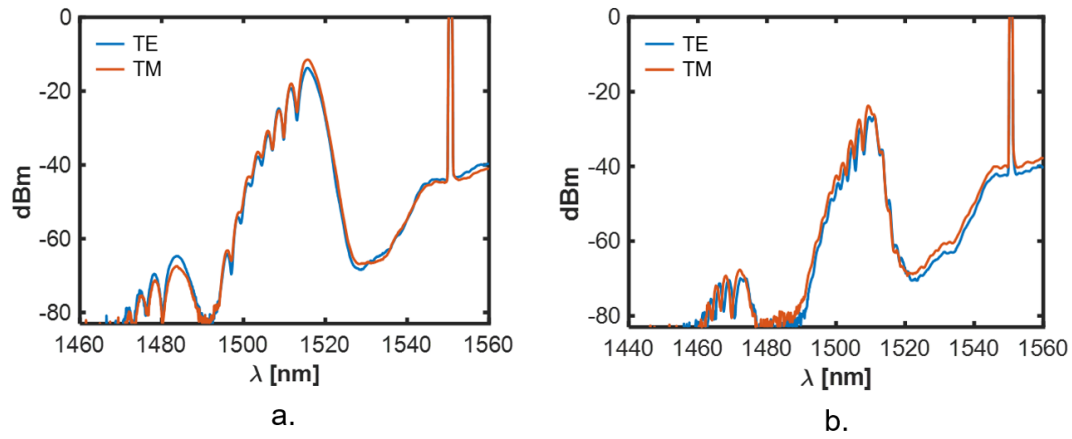


FIGURE 5.15: FWM spectra for the TE- and TM-polarized modes for (a) half-core-etched waveguide; (b) nanowire waveguide.

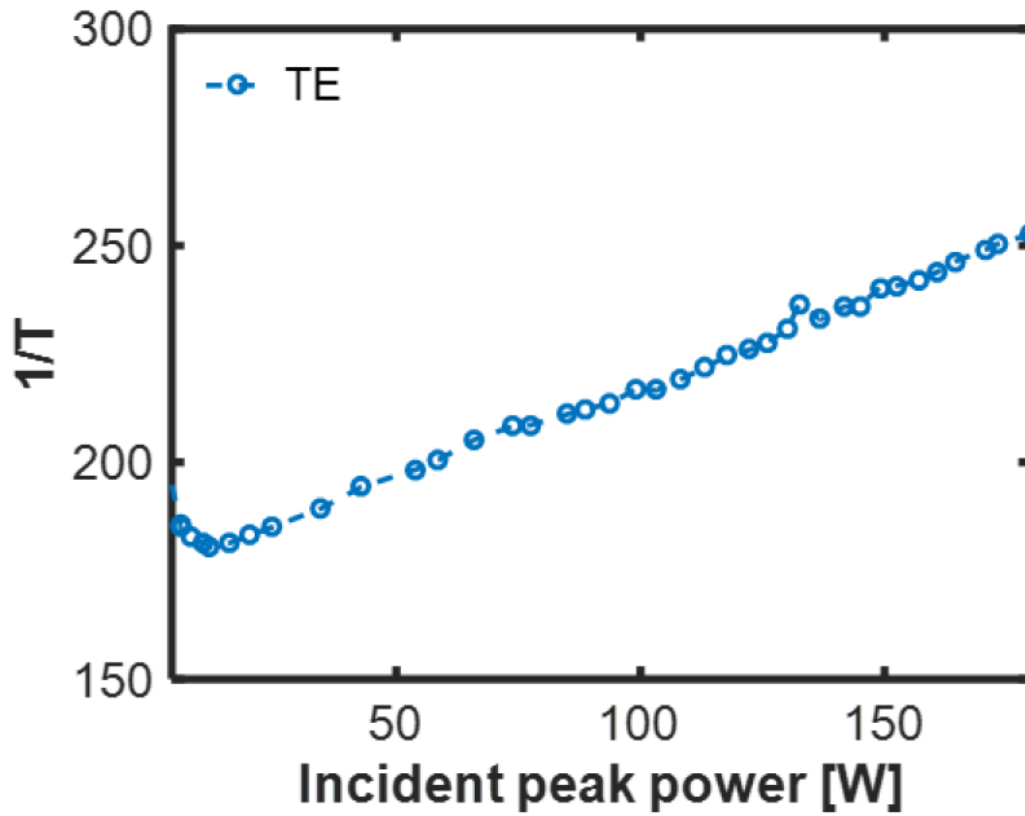


FIGURE 5.16: Inverse of transmission plotted against incident peak power. This figure was created by Ehsan Mobini

5.4 Conclusion

In conclusion, this was the first demonstration of InP/InGaAsP waveguides with half-core and nanowire geometries. We developed a fabrication procedure for InP structures with extremely low surface roughness. The resulting structures were used in nonlinear four-wave mixing experiments. InP/InGaAsP passive nonlinear optical waveguides combined with InP-based laser sources offer great potential for monolithic integrated photonic devices for on-chip wavelength conversion, spectroscopy and sensing. As the next step, the devices such as ring resonators and photonic-crystal waveguides based on InP will be designed. The fabrication of such structures will require further etching recipe optimization.

Chapter 6

Theoretical Demonstration of Third Harmonic Generation in Suspended AlGaAs Photonic Crystal Waveguide

In Chapter 3 and 4, we explored the fabrication of integrated photonic devices using the 3-layer AlGaAs heterostructure which was described in Chapter 3. We also observed that for almost all the designs, the etch depth requirements were rather large because the majority of the structures required etching to the bottom of the core. The 500-nm core was buried under a 300-nm AlGaAs top cladding and a 100-nm GaAs capping layer on top. In the z -direction, this translates to a layer spanning from $z = 400$ nm to $z = 900$ nm, therefore making the required etch depths 900 nm and larger. One way to relax the requirement to etch deeply while obtaining structures with higher index contrast is to create air channels on both sides of the core. This is accomplished by treating the epitaxial stack with some wet chemicals to etch the higher-aluminum-concentration claddings away. The resulting structures are known as suspended structures or air-bridge structures. In this chapter, we present our effort in fabricating suspended AlGaAs structures using the 3-layer AlGaAs epitaxial stack (Fig. 3.2). We theoretically demonstrate the possibility of phase-matched third-harmonic generation in a W1 suspended AlGaAs photonic crystal waveguide. To couple light into the PhC, we also designed suspended coupling waveguides. These structures were designed and fabricated in a 500-nm Al₁₈Ga₈₂As layer. We performed dispersion engineering on the photonic crystal waveguide to obtain a decent bandwidth of operation near the slow-light region. The THG process is designed such that

the mode near 1596 nm can be phase-matched to the 532-nm mode. In this chapter, we present the theoretical results of our designs and the detail of the fabrication process that we developed to create suspended structures.

6.1 Dispersion-Engineered Photonic Crystal Waveguides

As introduced in Chapter 4, a W1 waveguide is the one in which the defect is created by removing one row of holes of the photonic crystal structure to make a waveguide-like structure. W1 waveguides were chosen for this work because they can have guided modes below the light line and allow for a slow-light regime. The group index near the band edge sees a sharp increase which makes the effect non-usable for practical applications. To generate a usable slow light effect, we require a high group index operating over at least a few nanometers of bandwidth. This is accomplished by engineering the devices for low GVD [125], [126] and is known as dispersion engineering.

Since the photonic crystal waveguide has a periodicity in two directions, it can host both index- and bandgap-guided modes. While performing dispersion engineering, we modify the properties of these modes by tuning the defect waveguide width or by tuning the lattice parameters [127], [128]. More details about the physics of photonic crystals and slow-modes have been discussed in Chapter 4. Owing to the low losses and being transparent in the mid-IR wavelength regions, suspended PhC based on AlGaAs devices hold promise in mid-IR sensing applications beyond what silicon-on-insulator can offer [129].

6.2 Simulation

MIT Photonic Bands (MPB) [78] that utilizes the plane wave expansion method was used to obtain the dispersion relation $\omega(k)$. The effective index method was applied to obtain the effective refractive index at 1550 nm, resulting in n_{eff} value of 3.06 at 1550 nm for $\text{Al}_{0.18}\text{Ga}_{0.82}\text{As}$. 2D simulations were performed using a 500-nm core with the air claddings on both sides. The r/a ratio was swept (from 0.15 to 0.50 with a step of 0.01) to explore how the size of the bandgap region changes and how the variation influences the number of optical modes that the bandgap can host as its size increases or decreases. For $r/a > 0.33$, there were additional even TE modes appearing inside the

bandgap, and therefore the r/a ratio was finalized as 0.32. Fig. 6.1 shows

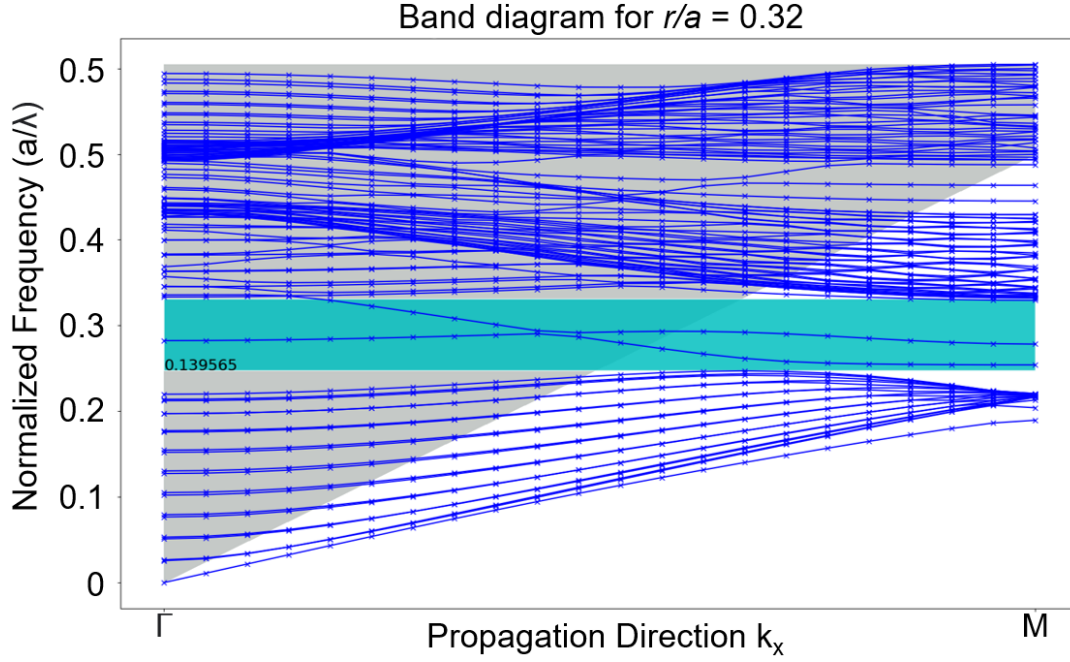


FIGURE 6.1: Optimized band diagram showing two guided modes inside a complete bandgap for air-bridge AlGaAs.

two gap-guided modes representing TE even and TE odd modes based on the lateral symmetry of magnetic fields. In PhC waveguides, the even mode is a preferred selection for operation because the field distribution of the even mode is the same as that in a single-mode waveguide, and it exhibits lower group velocities. We can also see from Fig. 6.1 that the even mode has a flatter band profile below the light line and therefore is expected to have lower group velocities and higher n_g values. The simulations were repeated using 3D Lumerical FDTD to determine if the results match with the MPB results. The results from both the softwares matched, confirming the design correctness. Once the band diagram was optimized, dispersion engineering was performed by moving the first two rows of holes ($s1$ and $s2$ shifts, respectively) [126]. An s -shift is a shift of the holes in the direction perpendicular to the light propagation direction, whereas a p -shift is a shift of the holes parallel to the light propagation. The 1 and 2 correspond to the position of the row of holes from the line defect, *i.e.* if the first row of holes is shifted, the shift is called $s1$ or $p1$. These shifts (in nanometers) can be calculated by multiplying the shift order numbers by the lattice constant values. The dispersion engineering curves were optimized for maximizing the group index values for a sizable bandwidth and are shown in Fig. 6.2. The first solid curve shows the results for 0.03 $s1$ and 0.02 $s2$ shifts, as a result the group index curve does

not get as flat as expected. The second curve shows the results for 0.04 s_1 shift and 0.01 s_2 shift which resulted in a group index of around 100 and a bandwidth of operation around 2 nm. The last curve shows the results for 0.05 s_1 shifts only. This resulted in a group index of around 60 and a bandwidth of operation around 10 nm. Therefore, 0.05 s_1 was selected as the final dispersion engineering shift.

The dispersion engineering curves were designed to have a flat band profile near 1596 nm. The next step was to phase-match this slow-light mode to the refractive index mode at 532 nm. Since we have a periodic structure in the propagation direction, the index-guided mode starts folding back at the edge of the Brillouin zone. It is very difficult to trace back the band-folding of the refractive index mode, and therefore, finding the phase matching frequency accurately is not possible. This was also mentioned by Corcoran *et al.* [130] in the first THG in silicon photonic crystal waveguides demonstration. In the course of solving this problem, we were able to come up with a method which can simulate the folded-back refractive index mode with 100% accuracy and therefore helped us to perfectly design the phase matching condition. We named this a RAPID method and will be using this terminology for the remainder of the chapter. More details about the RAPID method will be further discussed in the last section 7.3 of this thesis. Using the RAPID method, we were able to design the 1596 nm mode to phase-match perfectly well with the 532-nm mode. Fig. 6.3 (a) shows the 3D-FDTD simulation results for the photonic crystal band diagram overlapped with the simulations performed using the RAPID method to simulate the index-guided mode. Fig. 6.3 (b) shows the dispersion-engineered slow light mode. Fig. 6.3 (c) shows the simulation results for the phase-matched point when the slow-light mode crosses the index-guided mode. We were able to design the structure to perfectly match the slow-light mode occurring at 1596 nm with the folded-back refractive-index mode occurring at 532 nm. This is one of the first numerical demonstrations of THG in AlGaAs PhC waveguides.

In Chapter 4, we observed that the transmission in photonic crystal waveguides drops dramatically near the slow-light regime. To compensate for this effect, different kinds of couplers have been researched with an aim to increase the coupling efficiency into the photonic crystal waveguide [107]. Recently, it was demonstrated that the coupling efficiency can be increased up to 90% using the inverse-design method [131]. Amongst the different kinds of couplers, step couplers, in which the pitch of the PhC holes is slightly

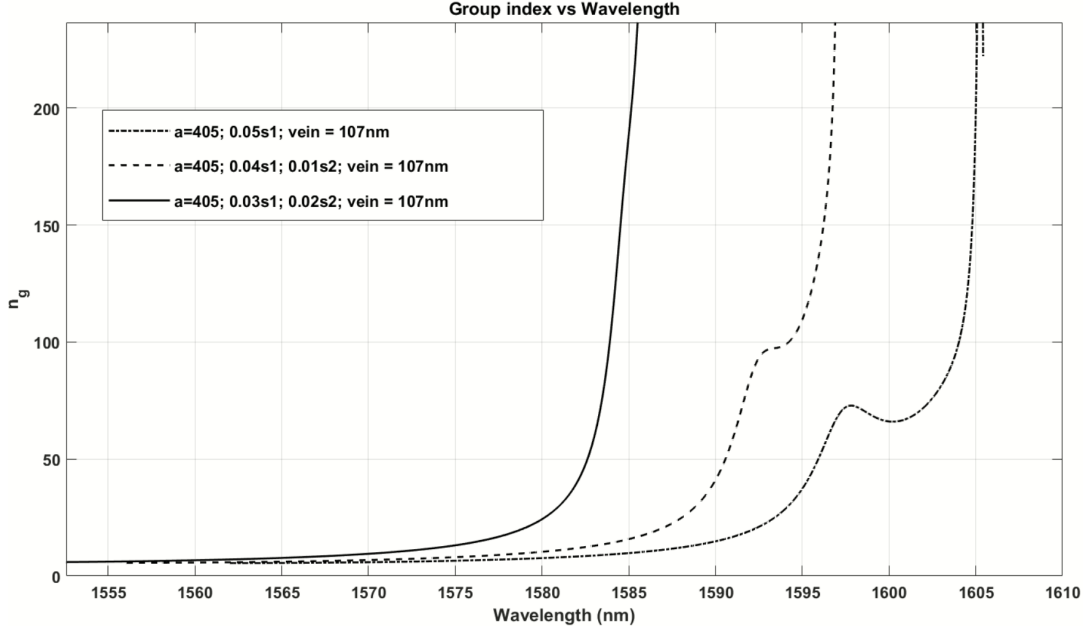


FIGURE 6.2: Dispersion engineering in slow-light PhC waveguide.

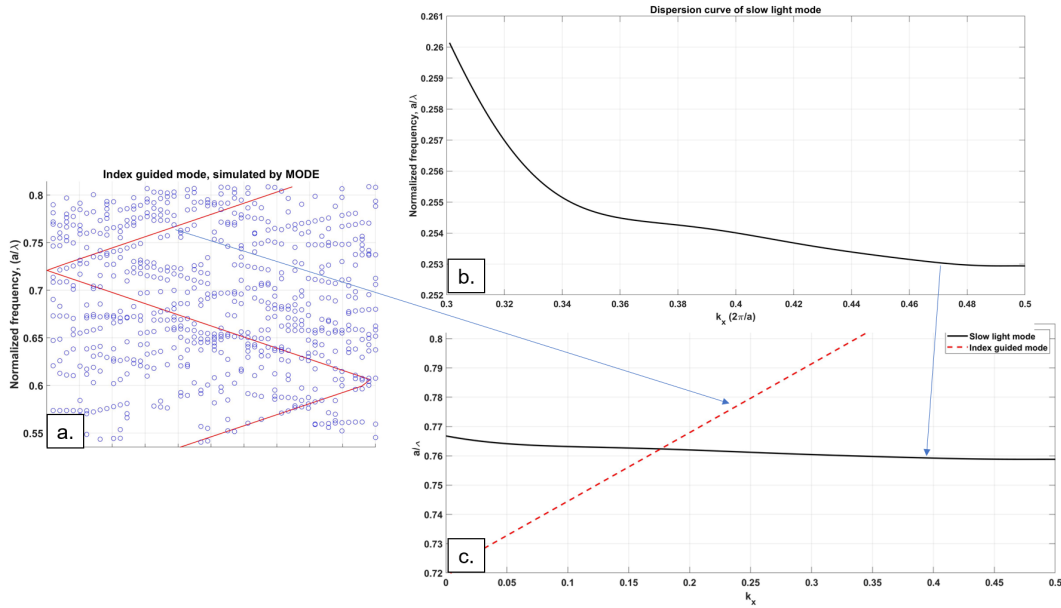


FIGURE 6.3: Simulation results showing the phase-matching point for the slow-light mode and the index-guided mode.

increased for 10-12 periods at the in- and out-coupling facets, was used for this work. Such couplers are the most widely accepted and used in the PhC community for transmission improvements into the photonic crystal waveguides. This is because they are easier to design and fabricate and result in increasing the coupling efficiency to almost 40%. To optimize our designs, we performed some simulations to increase the coupling efficiency using step

couplers. An exaggerated schematic of the step couplers is shown in Fig. 6.4. Ten periods of holes were added on both sides of the photonic crystal waveguide, and the simulations were repeated by increasing the pitch width of the added holes to enhance the coupling efficiency into the PhC region. The optimized coupler design had a pitch of 420 nm, and it led to an increase in the transmission up to 65%. These results are shown in Fig. 6.5.

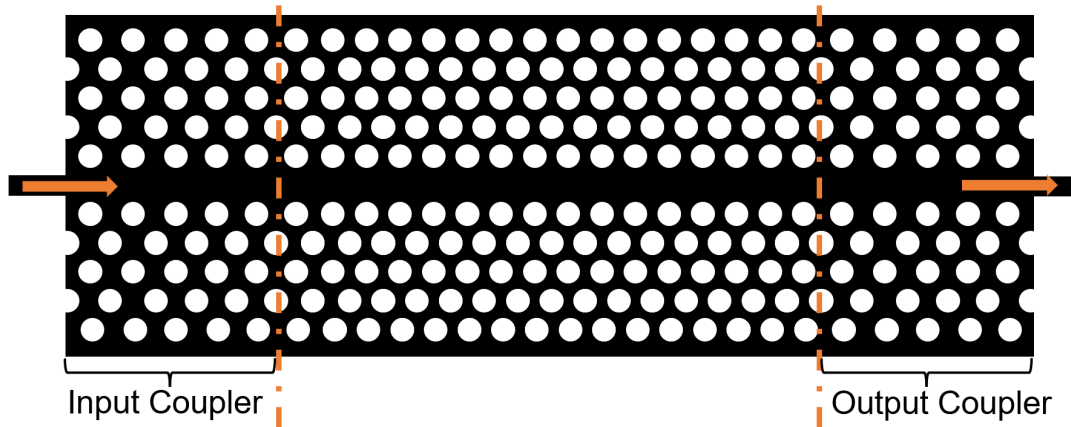


FIGURE 6.4: Schematic representation of a step coupler used to increase the transmission in photonic crystal waveguide.

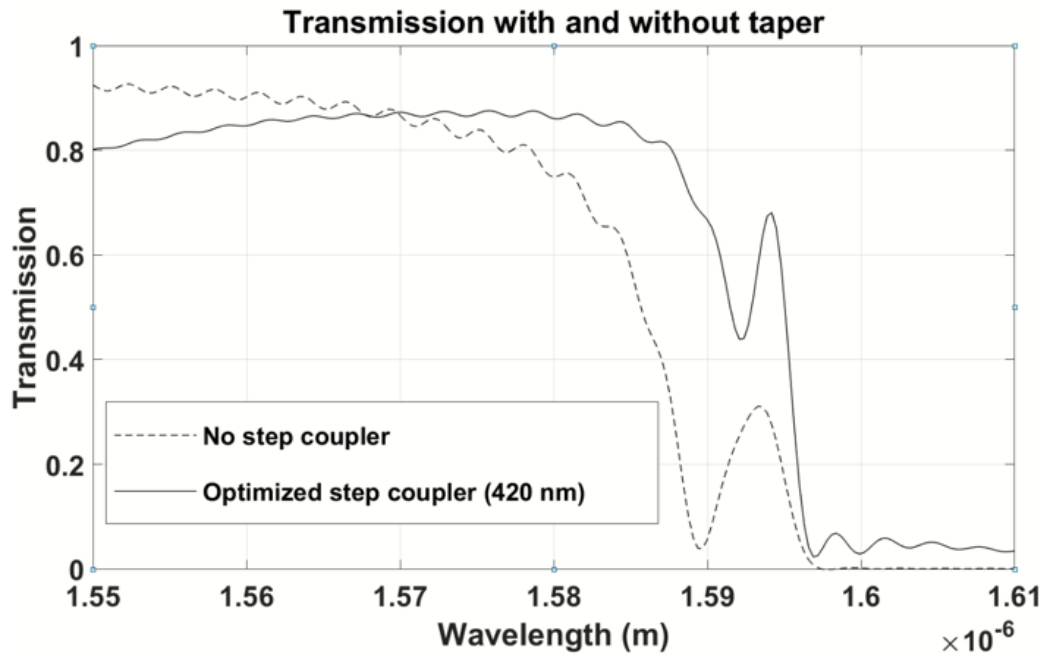


FIGURE 6.5: Simulation results demonstrating a 50% increase in transmission by using step couplers.

To have completely suspended structures, the coupling waveguides also need to be suspended. However, it is mechanically impossible to suspend

1 cm of bulk waveguides with support points only at the input and output ends. There has been only one work so far on AlGaAs suspended waveguides [75] where the authors demonstrated SHG in 123 nm thin $\text{Al}_{19}\text{Ga}_{71}\text{As}$ film, and the waveguides reported in that work were suspended using tethers placed 50 microns apart with respect to each other. To couple light into the photonic crystal structures, we designed subwavelength grating support tethers [132], [133]. The $500 \text{ nm} \times 1000 \text{ nm}$ waveguides were designed with a fundamental modal area of $0.33 \mu\text{m}^2$ with 100-nm-wide supporting tethers and a pitch of 250 nm; the results are shown in Fig. 6.6. The transmission results near 1550 nm are close to 97%. Some minimal leakage exists at the places where the tethers attach to the waveguides.

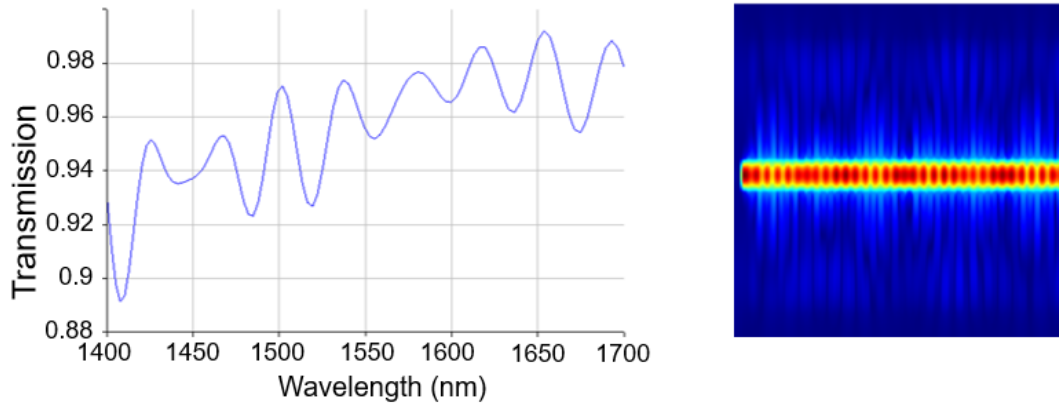


FIGURE 6.6: (a) Transmission spectrum of sub-wavelength couplers; (b) Field profile.

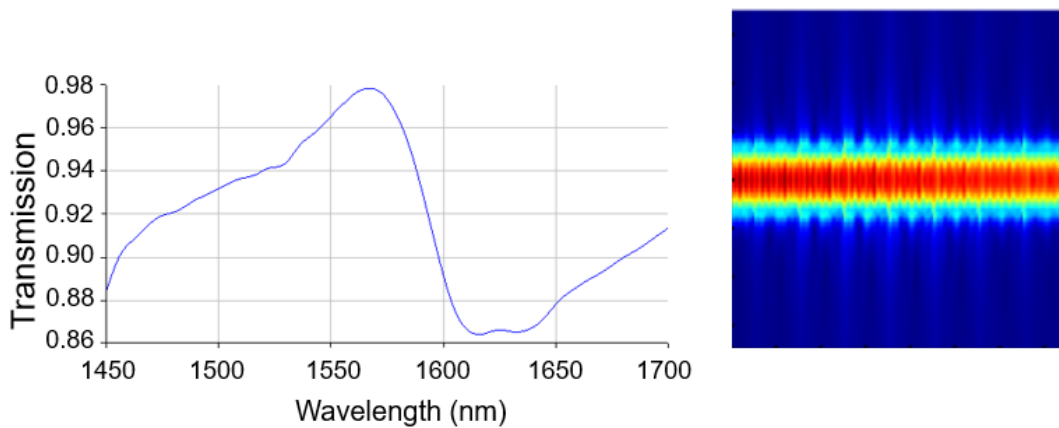


FIGURE 6.7: Simulation results for 150 nm supporting tethers spaced $2 \mu\text{m}$ apart.

Since etching the subwavelength structures down to 500 nm is relatively hard without a hard mask, we also designed a second supporting structure with

tethers spaced far apart similar to what was demonstrated in [75]. The simulations were optimized for a near unity transmission at 1550 nm; the results are shown in Fig. 6.7. Such supporting structures are relatively easy to fabricate compared to subwavelength structures because of low structure density and slower erosion rate of the mask. As a next step, the fabrication of these structures was carried out, which is discussed in the next section.

6.3 Fabrication and testing

The fabrication process started with the process of cleaning the wafers with acetone and IPA. Next, we worked on developing a wet etching recipe which can etch away the higher aluminum concentration $\text{Al}_{0.70}\text{Ga}_{0.30}\text{As}$ layers.

Twenty-five wet etching trials were performed by varying HF concentration and etch time. The optimized recipe that removed all of the cladding layer was as follows: 5% diluted hydrofluoric acid (HF) for 5 minutes. Fig. 6.8 shows the results obtained for suspended AlGaAs core.

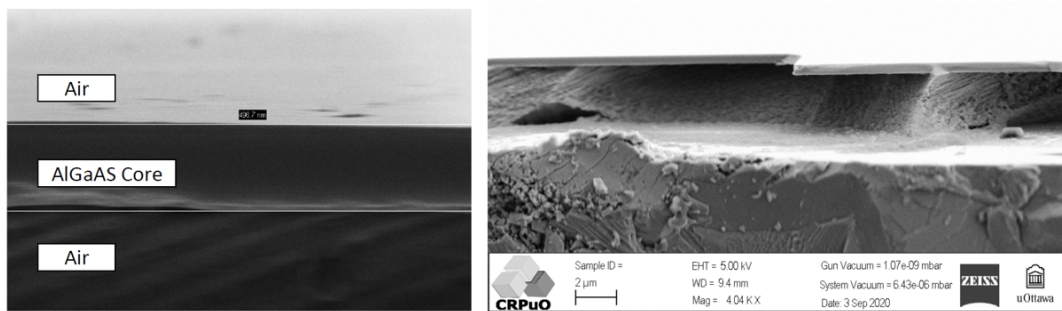


FIGURE 6.8: Cross-section SEM image of etched suspended Al-GaAs core after HF wet etching.

The clean wafers were first treated with 5% HF for removing the top cladding. Then the standard process followed, *i.e.* spin-coating 500 nm of ZEP resist, followed by writing the structures using the 30 kV Raith E-beam system. The patterns were treated with PEC before patterning. As mentioned in chapter 1, PEC plays a major role when the structures are densely packed. This was evident while writing the subwavelength structures. As shown in Fig. 6.9 (b), without PEC, the dimensions of the structures do not come out correct. Additionally, LER is clearly visible in these writes. Fig. 6.9 (a), on the other hand, shows the PEC-corrected structure. We were able to obtain tethers with 100 nm width and 250 nm pitch. Also, LER is significantly low in the PEC-corrected structures.

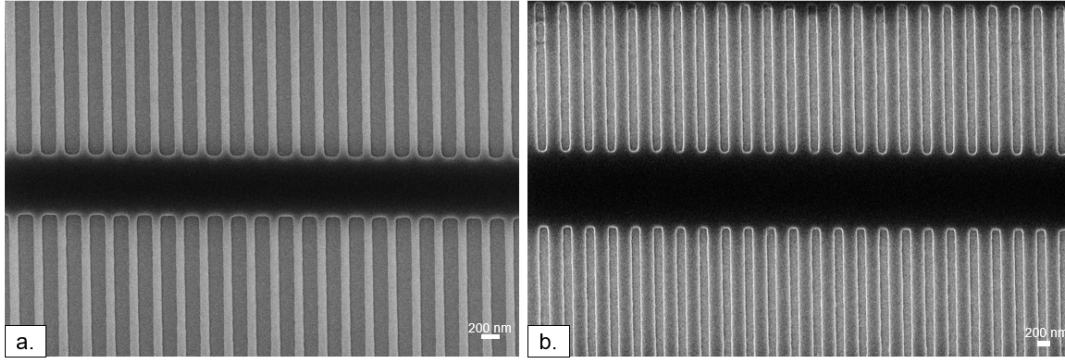


FIGURE 6.9: Patterning subwavelength structures with PEC (left) and without PEC (right).

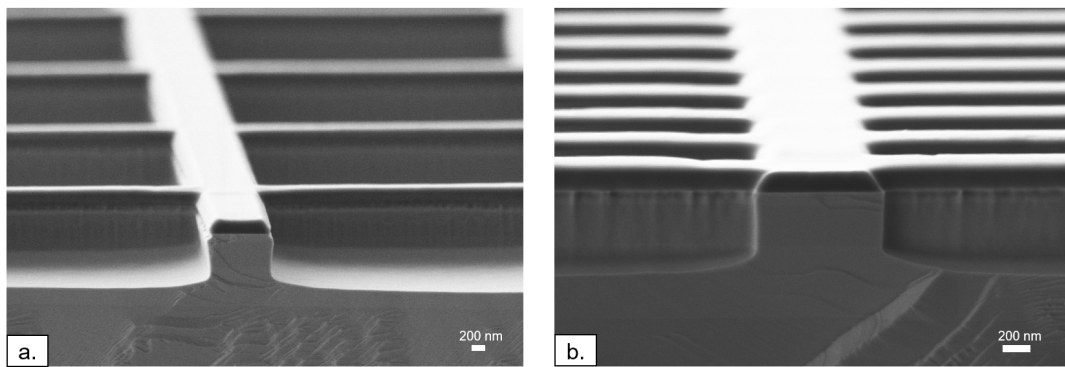


FIGURE 6.10: SEM cross-section imaging after etching: (a) 150-nm tethers spaced 2 micron apart; (b) subwavelength waveguide.

The written structures were then etched using an ICP-RIE plasma etcher with the slow etch process described in Chapter 3. Fig. 6.10 shows a comparison of etched facets of the two different supporting waveguides. Once the waveguides were etched, they were treated with the 5% HF process as introduced above. The second HF process was carried out so that the acid flows between the tethers and etches the lower cladding away completely leaving only the hanging waveguide with supporting tethers. Figure 6.11 shows the waveguide after the second treatment with HF. We can see that the lower cladding is completely removed, and the waveguide is suspended in the air using the supporting tethers.

The fabricated waveguides were used for linear characterization using a tunable CW laser on the setup shown in Fig. 4.11. Linear transmission measurements were performed using Fabry-Perot method and resulted in a total transmission of 22 dB/cm. The transmission curve overlapped with the simulated transmission is shown in Fig. 6.12. Although there are plenty of advantages associated with suspended integrated photonic devices, such

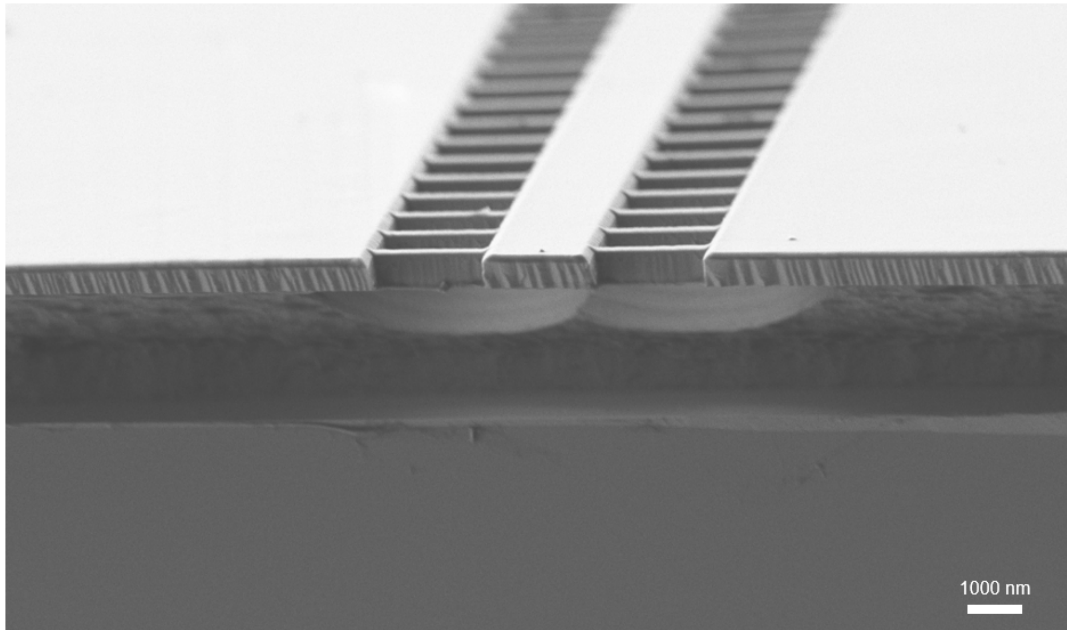


FIGURE 6.11: Cross-section SEM image of suspended AlGaAs waveguide.

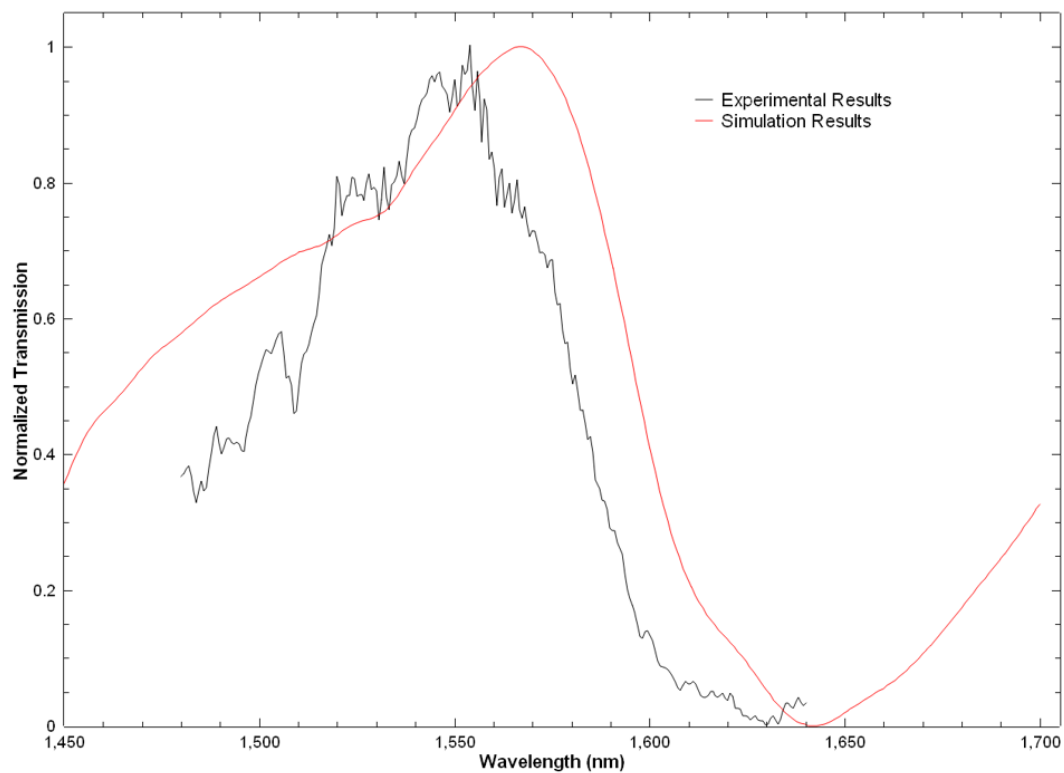


FIGURE 6.12: Simulated (red) and experimental (black) linear transmission spectrum using the AlGaAs suspended nanother waveguide.

structures are relatively hard to fabricate and handle. Since these structures are on the order of a few 100 nanometers in size and are not resting on

any slab/substrate, they tend to be extremely fragile and prone to damage. Fig. 6.13 shows the image of the sample with broken tethers when the sample was accidentally dropped from the stage during the characterization. In conclusion, we numerically demonstrated a possibility of phase-matched THG in AlGaAs photonic crystal waveguides. We also introduced a process flow for fabricating suspended structures using a 500-nm AlGaAs core.

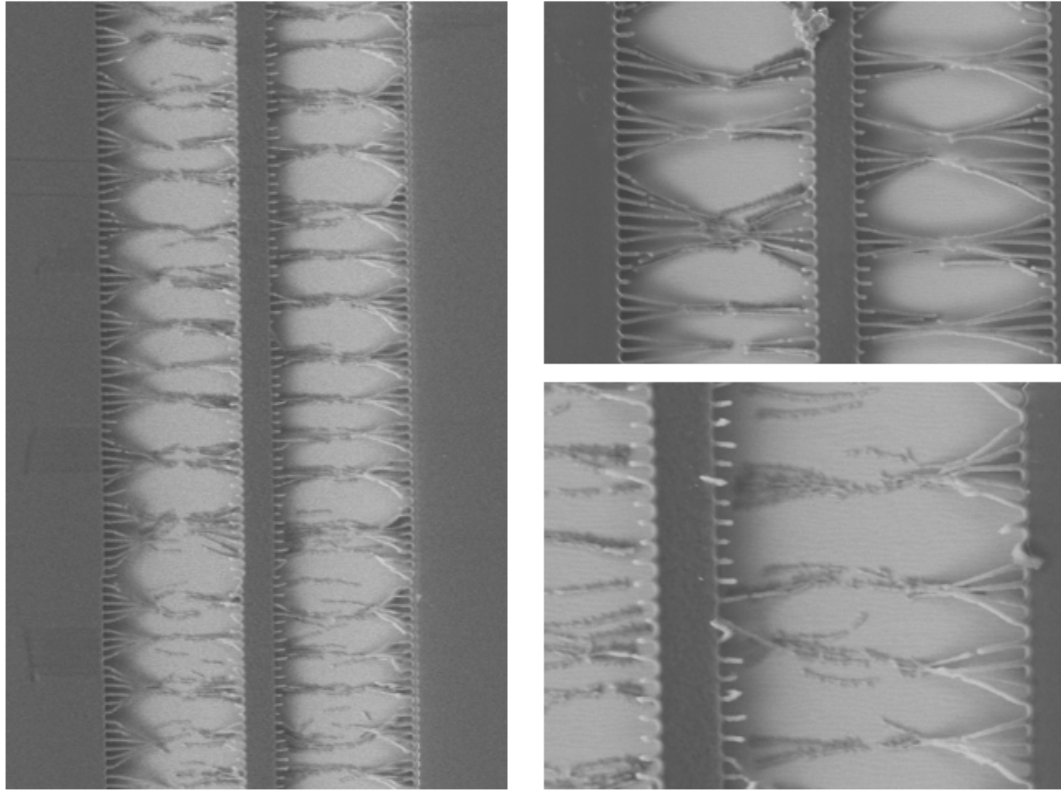


FIGURE 6.13: Broken Tethers.

Chapter 7

Additional Projects

In this chapter, we consolidate some additional projects which were undertaken as part of the thesis work. These are the projects based on platforms other than III-V semiconductors. The first of these works entailed fabrication of Kagome Lattice photonic crystal waveguides on silicon. This is an ongoing project in collaboration with Dr. Sebastian Schulz from St. Andrews University, UK. In the second project, we experimentally demonstrate third harmonic generation in silicon nitride waveguides. This project was performed in collaboration with Surendar Vijaykumar from the University of Rochester, USA, Dr. Orad Reshef and Dr. Daniel Espinosa from the University of Ottawa. In the last project, we propose a novel method to accurately simulate folded-back index-guided modes in photonic-crystal line-defect waveguides. This work was carried out in collaboration with Surendar Vijaykumar, Dr. Sebastian Schulz and Dr. Jer Upham.

7.1 Fabrication of Slow Light Silicon Kagome Lattice Photonic Crystal Waveguides

As discussed in the previous few chapters, photonic crystals are interesting optical structures hosting the property of bandgap. In all the previous works mentioned in this thesis, we only discussed the triangular lattice PhCs, but there has been one work done in the past by Schulz *et. al* [58] on a novel photonic crystal lattice called the Kagome lattice, which was inspired by the electron-hole models from solid state physics [134]. Geometrically, Kagome lattice can be considered as a depleted triangular lattice in which every other hole is removed from every other row of holes as shown in Fig. 7.1.

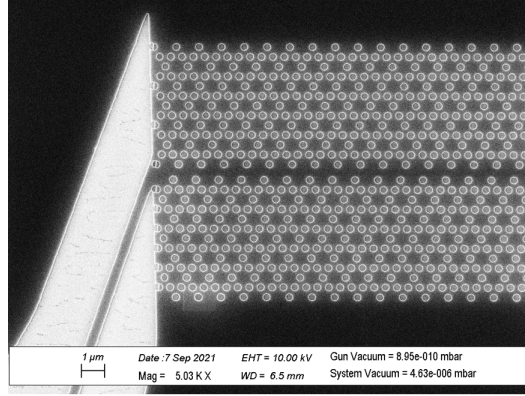


FIGURE 7.1: Fabricated image of Kagome Lattice waveguide showing the lattice structure with missing alternate holes.

In the previous Kagome lattice PhC work [58], it was theoretically demonstrated that Kagome lattice based PhC waveguides intrinsically have group index close to 100. With some dispersion engineering, the group index can reach up to 10^5 demonstrating almost stopped-light-like behavior [85]. Since the modes in a Kagome lattice waveguide are higher-order modes lying in the higher bandgap regions, such modes are very difficult to couple to, and therefore, in the previous work, the authors were only able to experimentally couple to the second guided mode which had relatively low group index.

In this work, we are trying to resolve the problems of the previous generation of devices and come up with an efficient coupler to couple to the correct slow-light mode which has the large group index. The design and simulations for the improved couplers were carried out by Dr. Schulz's group at the University of St. Andrews. The idea behind designing angled couplers is based on the field profile of the optical-mode which also possesses a similar angled shape [58]. We performed the fabrication of the device in-house at uOttawa's fabrication facility. As mentioned previously, it is extremely important to do PEC for photonic-crystal structures, so, the designs were corrected for the proximity effects and written on a 220 nm Silicon on Insulator sample. Small pieces of $1\text{ cm} \times 1\text{ cm}$ were cleaved, and cleaned in acetone and IPA. ZEP was spin-coated at 3000 rpm resulting in a thickness of 400 nm. PEC-corrected structures were then written using E-beam at 30 kV acceleration voltage with a base dose of $55\text{ }\mu\text{C}/\text{cm}^2$. The first batch of structures were etched at the University of St. Andrews because the etcher at uOttawa was still in the chlorine based chemistry which is not suitable to etch Silicon. The etched samples were then treated with 5% HF acid for 20 minutes to remove the lower cladding thereby creating an air-bridge for the photonic

crystal region. Fig. 7.2 (left) shows the top-view SEM image for the Kagome Lattice PhC with optimized angled couplers and Fig. 7.2 (right) shows the PEC-corrected GDS file used for patterning. Fig. 7.3 depicts the top-view SEM image for Kagome Lattice PhC with optimized straight couplers, the image on the right is the corresponding PEC-corrected GDS file.

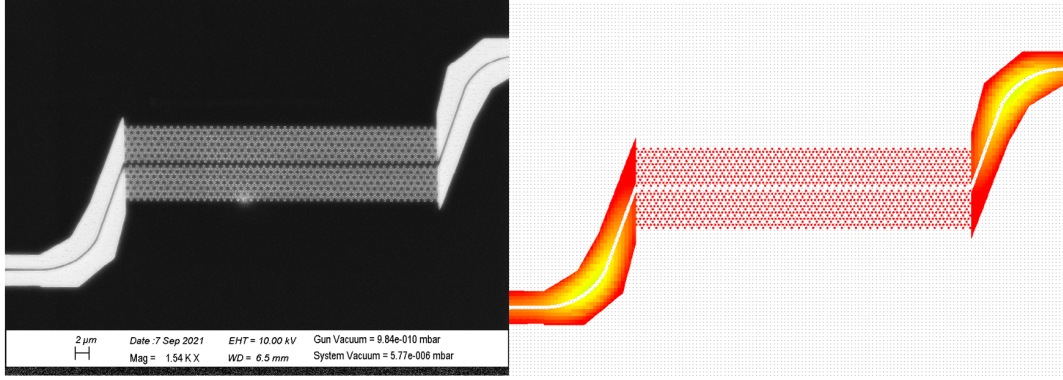


FIGURE 7.2: Top-view SEM image of fabricated Kagome lattice waveguide with optimized angled couplers (left); Proximity effect corrected GDS file (right).

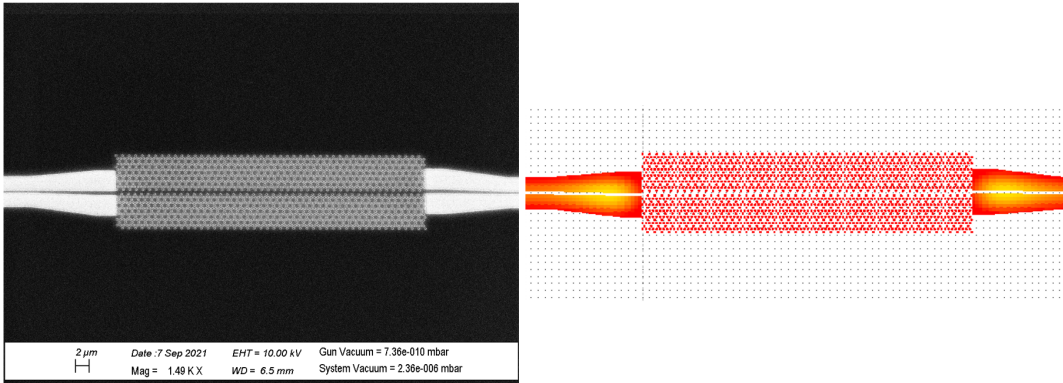


FIGURE 7.3: Top-view SEM image of fabricated Kagome lattice waveguide with optimized straight couplers (left); Proximity effect corrected GDS file (right).

Linear loss measurements of the fabricated device were performed using the Fabry-Perot method which was introduced in Chapter 5, and the results are shown in Fig. 7.4. From this, we concluded that the total loss is roughly 20 dB/cm. The transmission in our fabricated devices is relatively high compared to the previous work, and therefore, we anticipate coupling to the correct mode using the optimized couplers. We are now developing an in-house setup to measure group index of these devices, which can further confirm these claims.

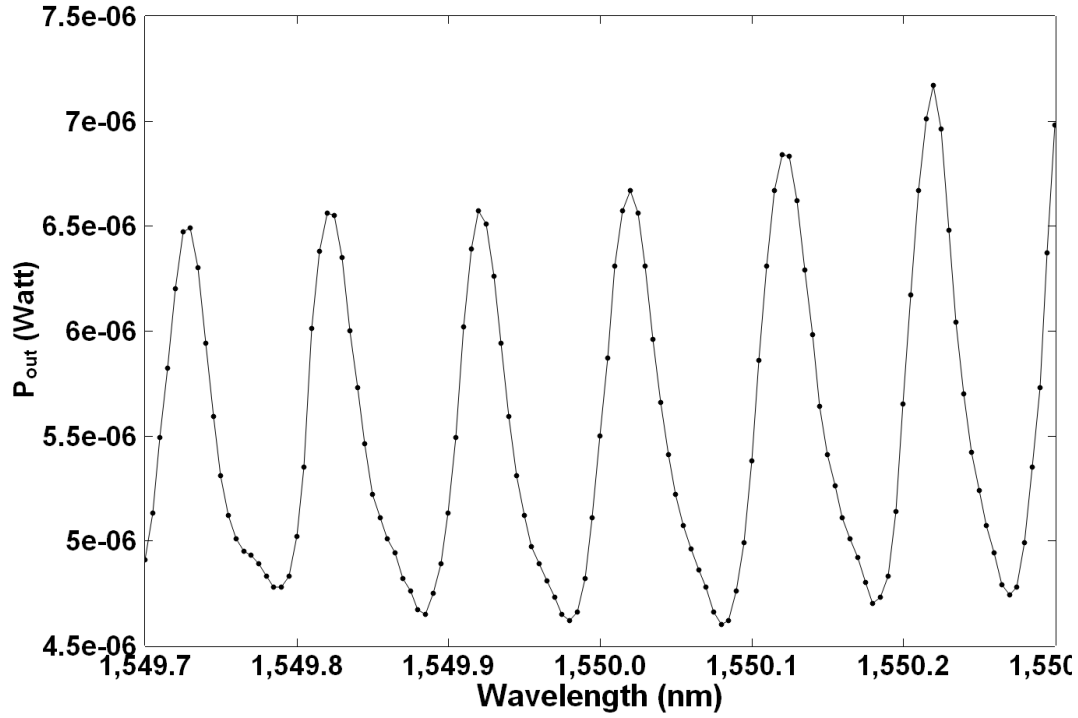


FIGURE 7.4: Fabry-Perot measurement for the loss characterization of Kagome Lattice PhC waveguide.

7.2 Phase Matched THG in Silicon Nitride Waveguides

In this project, I primarily collaborated with Dr. Daniel Espinosa from our group and Surendar Vijaykumar from the University of Rochester to demonstrate THG effect in silicon nitride waveguides. As introduced in Chapter 1, THG is a third-order nonlinear process in which the input wavelength (fundamental) is converted into a third-harmonic signal with the wavelength equal to $1/3$ of the fundamental wavelength [15]. This process is enabled by a $\chi^{(3)}$ medium, where the wavenumber of the third harmonic must be three times the wavenumber of the fundamental to fulfil the phase-matching requirement.

Due to dispersion, the refractive index of optical materials typically decreases with an increase in the wavelength, leading to a phase mismatch. To overcome the material dispersion, we phase-match the fundamental TM mode of the waveguide at $\lambda_F = 1596$ nm with a TM_{02} mode of the waveguide at $\lambda_F = 532$ nm. The reason for choosing a design to have a THG output 532 nm is because green light sources at 532 nm are commercially available.

Since the eventual aim of this project is to perform parametric down conversion which essentially is the quantum reversal process of THG process leading to entangled photon states, it is important to use the same wavelength for THG generation which can later be used for the reverse triplet generation process. The advantage of working with a TM mode is that the mode is confined vertically, and the field does not scatter off the sidewalls as much (compared to a higher-order TE mode) and therefore the scattering losses won't affect the higher-order modes as badly. The phase matching is possible because the higher order mode of a waveguide at a given wavelength has a lower refractive index than the fundamental mode at the same wavelength. By employing a higher-order mode at 532 nm, we can lower the refractive index of the mode to match the refractive index of a fundamental mode at 1596 nm, as shown in Fig. 7.5.

The efficiency of the THG process (η) depends on the phase-mismatch(Δk) as:

$$\eta = \eta_0 \text{sinc}^2\left(\frac{\Delta k L}{2}\right) = \eta_0 \text{sinc}^2\left(\frac{L}{L_{\text{coh}}}\right), \quad (7.1)$$

where η_0 is the efficiency of a phase-matched ($\Delta k = 0$) process, L is the waveguide length and the coherence length is defined as $L_{\text{coh}} = 2/\Delta k$. Ideally, the waveguide length should be less than L_{coh} to avoid degrading the efficiency by the phase mismatch. Indeed, based on Equation (7.1), the THG efficiency drops to 71% of its maximum value when $L = L_{\text{coh}}$. By definition, coherence length can be calculated from the refractive index mismatch between the fundamental and the higher-order mode (Δn_{eff}) as follows:

$$L_{\text{coh}} = \frac{\lambda_{\text{pump}}}{3\pi\Delta n_{\text{eff}}} \quad (7.2)$$

The simulations were carried out by tuning the height and the width of the waveguide with an aim to minimize the the refractive-index mismatch between the fundamental mode and the higher-order mode. The two modes are phase-matched at a refractive index of approximately 1.62 with a refractive index mismatch of $\Delta n_{\text{eff}} = 6.94 \times 10^{-5}$.

The structures were designed using Lumerical's mode solver. The fabrication of the structures required epitaxial growth of stoichiometric silicon nitride (Si_3N_4). This was performed by Kashif Awan at Cornell University's CNF cleanroom using the LPCVD system. Stoichiometric silicon nitride has

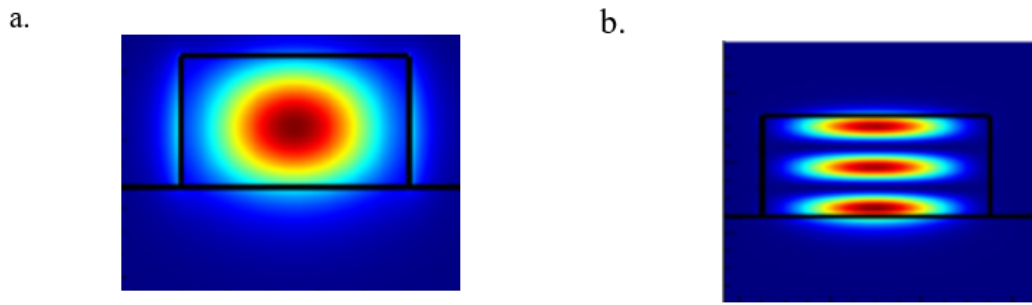


FIGURE 7.5: Field profile for (a) Fundamental TM mode at 1596 nm; (b) third harmonic TM_{02} mode at 532 nm.

the best optical quality because it leads to the lowest surface roughness after etching [135]. However, it suffers from a high stress for thicker films, leading to cracking of films for the film thicknesses greater than 300 nm. Several groups are trying to improve this with an aim to achieve thicker films by using in-situ processes such as using additional gases and annealing. We used bare silicon wafer which had 5 μm of thermal oxide on top. Silicon nitride films were grown on top of these layers, and we were able to achieve the films with a mean thickness of 580 nm by in-chamber annealing. As can be seen from the reflectance measurement in Fig. 7.6, the thicknesses are uneven, which is very common for CVD-grown wafers. This can be attributed to the gas flows in different parts of the furnace, and to the surface morphology of the carrier wafers which are never perfectly flat. The design and fabrication tasks were performed at the University of Rochester and Cornell University, respectively.

The fabricated waveguides had optimised inverse tapers for efficient light coupling to the waveguide, and directional couplers on top of the waveguide for efficient coupling to the higher-order modes. Fig. 7.7 shows a top-view schematic of the waveguide with inverse tapers and directional couplers. Unfortunately, the aspect ratio of height to width for the directional couplers was too large. Consequently, most of the directional couplers collapsed onto the waveguide and therefore were not working. But we still were able to observe the generated THG using the output facet of the main waveguide.

In our THG characterization, we use a 3 ps laser, with a repetition rate of 76 MHz and an average power of 30 mW. Since the losses in silicon nitride are expected to be 1 dB/cm, it is negligible on the scale of the interaction length of our waveguides (1 mm). IR light at 1596 nm was coupled into

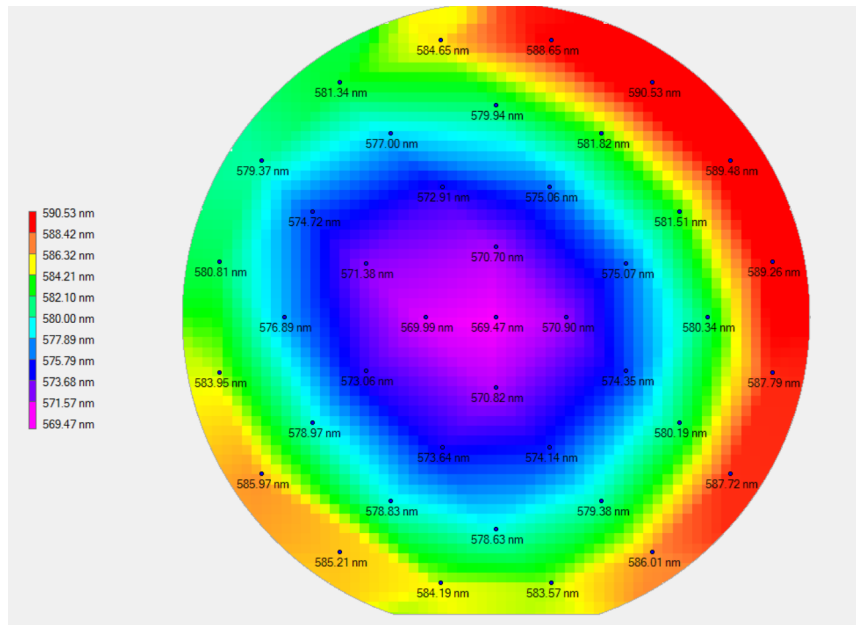


FIGURE 7.6: Reflectance measurement showing the mean thickness of 580 nm for the deposited silicon nitride film. The thickness measurement was carried out using Filmetrics F50 tool.

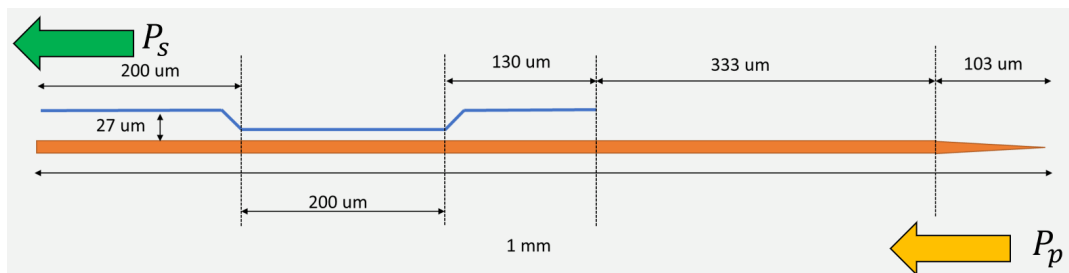


FIGURE 7.7: Top-view schematic representation of the waveguide with inverse coupler at input, and direction coupler on top.

the input facet of the waveguide, and the output light was coupled into a USB spectrometer to observe the output spectrum of the visible light. We also had a split mirror at the output which was arranged such that the light can either be coupled into the USB spectrometer, or to the IR and visible detector for the power measurements. We were able to confirm the generation of the higher-order third harmonic by visually inspecting the output facet of the waveguide where a bright green spot was observed, as shown in Fig. 7.8 (a). The results were also confirmed from a top-view camera (see Fig. 7.8 (b) which shows the light scattering off the output facet). To further confirm if the generated output was a higher-order mode and had the desired polarization (*i.e.* TM_{02}), the far-field profile of the mode was projected on a piece of paper as shown in Fig. 7.9 (a). We can clearly see from the far-field

profile that the observed higher-order mode is the correct TM_{02} mode. The far-field profile can also be confirmed from the simulated FF profile which is shown in Fig. 7.9 (b).

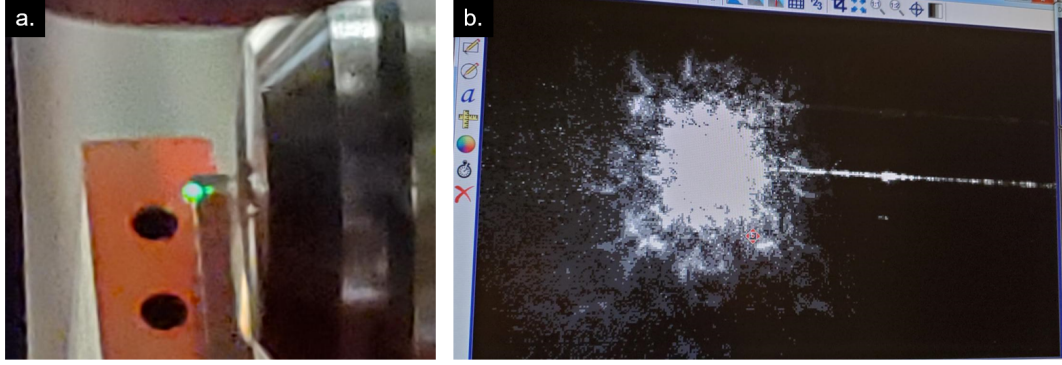


FIGURE 7.8: (a) Green light observed at the output facet of the waveguide; (b) The confirmation of the observed light from the output facet, as seen from the top-view camera.

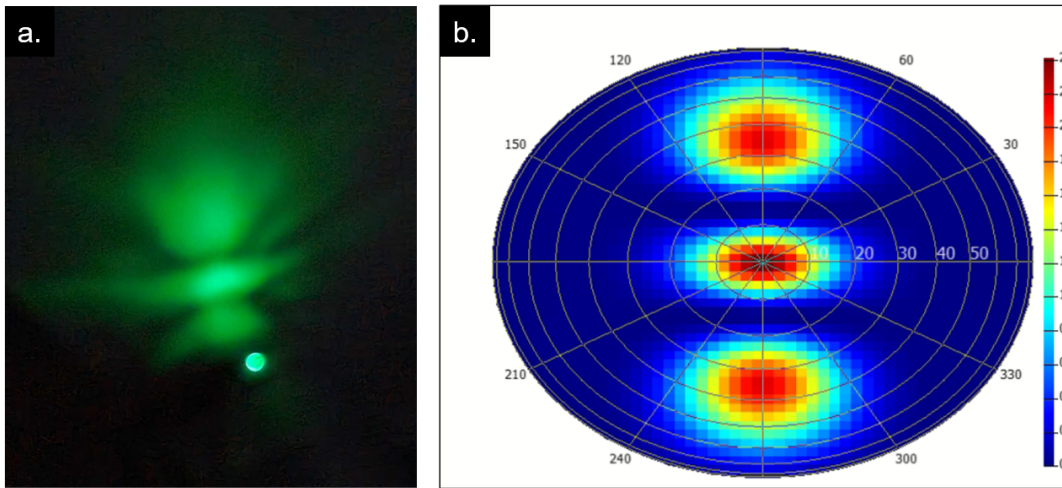


FIGURE 7.9: (a) Far field profile of the green light projected on a screen; (b) Simulated far-field profile using Lumerical MODE solver.

The measurements were performed using a 3 ps ultrafast laser system at an average power of 90 mW. The wavelength of the optical parametric oscillator was swept in the range between 1550 and 1600 nm with the step of 1 nm, and was coupled to the waveguide. To make sure that the waveguide width used in the experiment matched the simulated width, several waveguides were fabricated on the chip with a 2 nm variation in width. Ideally, the waveguide width of 680 nm was supposed to have the simulated THG at 532 nm, but in our experiments, we observed that the waveguide with a 678 nm width was giving the most accurate results, which meant that the fabrication results were off by only 2 nm. The THG spectrum is shown in Figure 7.10 (a)

where we can see the peak of the curve at 531.63 nm which is fairly close to the designed results aimed at 532 nm. To calculate the efficiency, we vary the pump power and measure the output green light as a function of the measured pump power; this is shown in Fig. 7.10 (b). We achieved a THG efficiency of $6.8 \times 10^{-7}\%/W^2$. For the process to be a THG process, the output power must scale as the incident power cubed. This was confirmed by doing the curve fitting, which proves that this is, indeed, a third-order nonlinear process as shown in Fig. 7.10 (b). In conclusion, we demonstrated the first phase-matched highly efficient THG in silicon nitride waveguides.

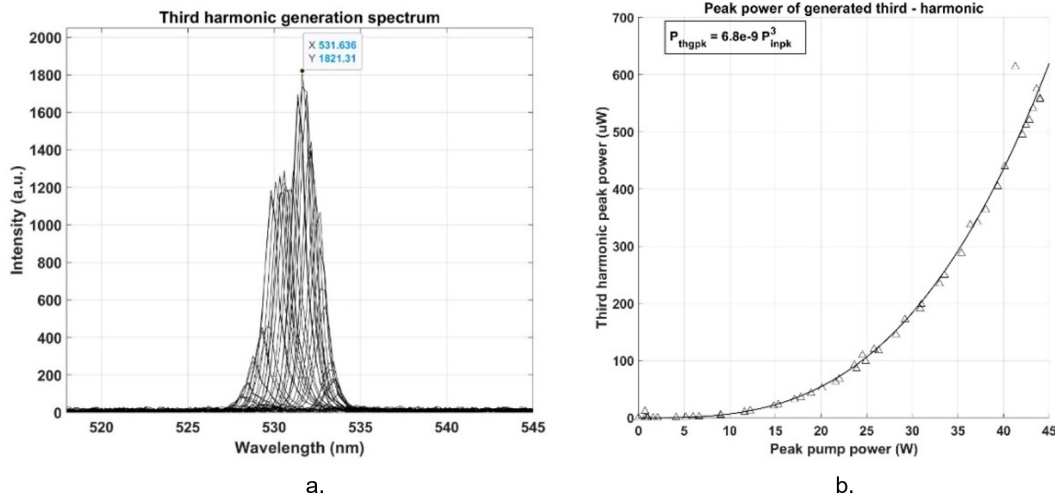


FIGURE 7.10: (a) Experimental results demonstrating THG spectrum with a peak at 531.63 nm; (b) Peak THG power vs peak pump power showing a third-power relation confirming the THG process.

7.3 RAPID Method for Simulation of Higher-Order Modes in Photonic Crystal Waveguides

In Chapter 6, the concepts of index-guided and slow-light modes were introduced. The band folds back into the first Brillouin zone at each edge as we go to higher frequencies on the dispersion curve. Above the light line, it becomes difficult to distinguish between the continuum modes and the refractive-index mode of the system. It is important to predict the band folding with a high degree of accuracy as it can help one to better understand the optics of photonic-crystal structures, especially the region above the light line, where interesting phenomena such as BIC (which was introduced in Chapter 4) can occur. However, simulation of the band diagram with a full

3D-FDTD and high meshing does not clarify the folded mode for the regions lying above the light line.

Jamois, *et. al.* [113] compared the modes in a ridge waveguide with the index-guided modes in photonic-crystal waveguides and stated that the two modes are very similar in terms of field profiles. This served as a motivation for this work. In this project, we recreated the simulations performed in the pioneer paper on THG in silicon photonic crystal waveguide [130], in which the authors were trying to phase-match the slow-light mode with the folded-back index-guided mode. Although they were able to demonstrate the generated THG, they mentioned that it was impossible to trace back the index-guided mode correctly. As introduced in Chapter 6, in our photonic crystal designs, we also faced a similar issue while tracing back the index-guided mode. In this work, we demonstrate a method which can simulate the higher-order modes of photonic crystals with a very high degree of accuracy and in an order of magnitude less time.

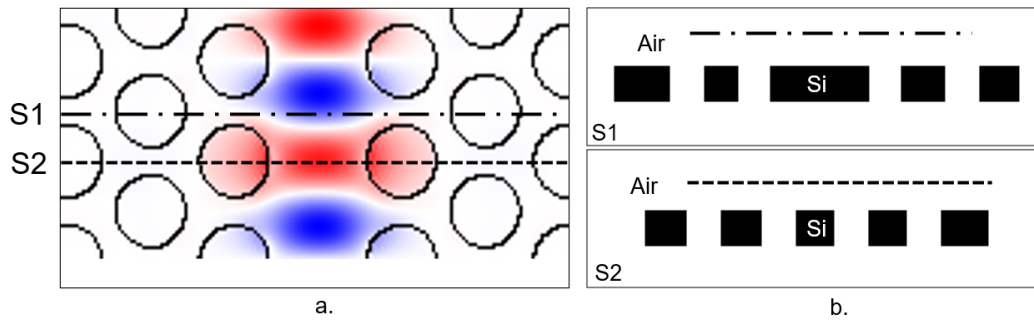


FIGURE 7.11: a. Refractive index mode in a photonic crystal waveguide simulated using MPB, S1 and S2 are the considered cross-section points; b. Schematic of how cross-section will look like at S1 and S2.

As the mode travels along the propagation direction, the photonic crystal structure changes periodically. Consequently, the optical mode travels across different cross-sections along the period. Therefore, we need an effective medium approximation. In this work, we are trying to take the average of the periodic structure along the propagation direction, and then project it on a single plane, therefore we have to resort to effective media. Consider a photonic crystal waveguide as shown in Fig. 7.11 (a). The cross-section of this waveguide will see different physical structures at different places and therefore the effective index at every single cross-section plane will be different. If cross-sections are taken at S1 and S2, the respective cross-sections will look like what is shown in Fig. 7.11 (b). If we simulate the index-guided mode

using a 2D transverse eigensolver at S1 and S2 (using Lumerical MODE in our case), and overlap the frequency vs wavevector graph for S1 and S2 with the full 3D-FDTD band diagram of the same photonic crystal waveguide, we obtain the result shown in Fig. 7.12. It is evident from the graph that the index-guided mode, as seen on the FDTD plot, can be traced almost in the middle of the lines S1 and S2. This means that we need to come up with an effective medium approximation which can average not only the region between S1 and S2, but rather can precisely average the complete photonic crystal structure and yield a transverse effective-index profile.

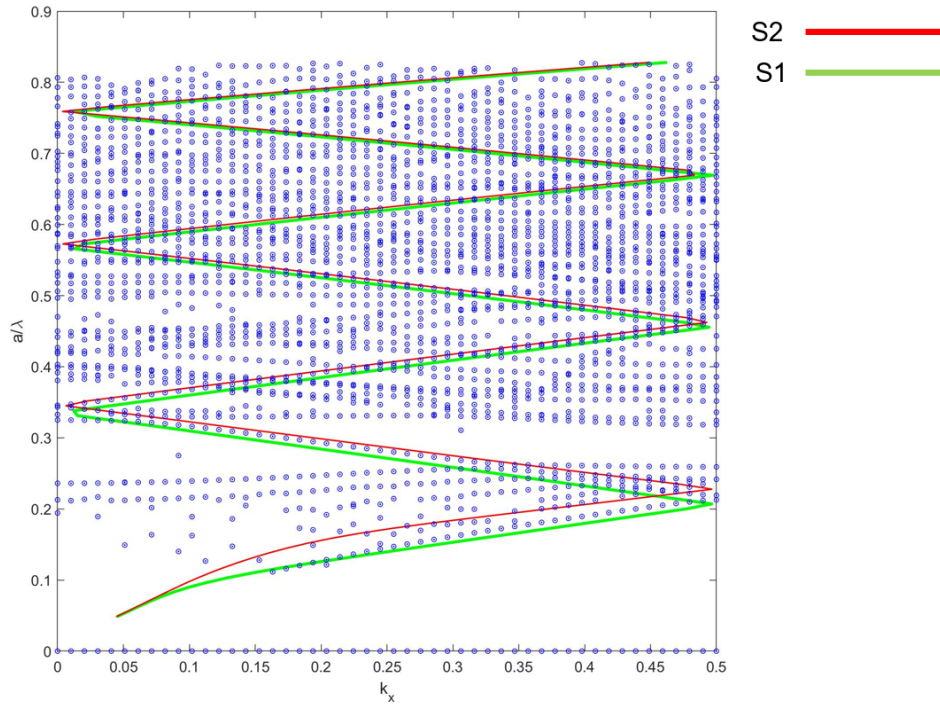


FIGURE 7.12: Band diagram of photonic crystal waveguide obtained using fully vectorial 3D FDTD solver, overlapped with the frequency vs wave vector simulations performed at S1 and S2 using Lumerical MODE solutions.

To perform this averaging using our effective-index method, let us consider the dotted line in Fig. 7.13. The refractive index varies such that the light sees a high refractive index region and then low and then high again as we move across the holes cross-section. For the plot shown on the right in Fig. 7.13, the x -axis represents the dotted line, and the y -axis represents the refractive index. $2d$ is the duty cycle, which represents the fill fraction of silicon. Therefore, from the plot we can see that the effective index goes to n_{eff} when we are not in the hole region, and becomes 1 when we are within the hole. This n_{eff} is the variable that we need to find. The formula introduced here is based

on Rytov approximation [136]. Using this approximation, we obtain the average refractive index inside the hole which can be seen from Fig. 7.14. At the center, we have the largest fill factor of air, but still have a lot of Si, therefore, the n_{eff} does not go to unity and still sees some effective index greater than 1.

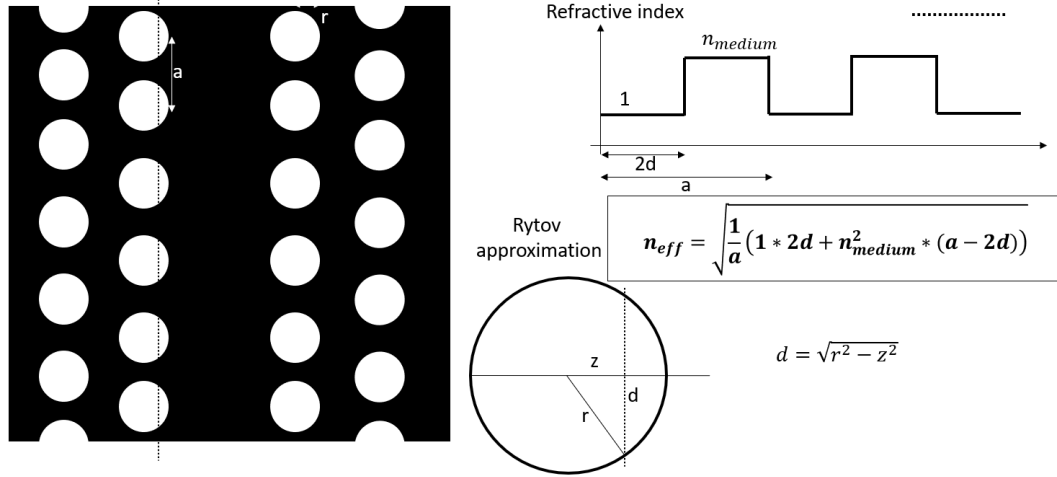


FIGURE 7.13: The method of performing effective index approximation using Rytov approximation.

We finally use this approximation of refractive index to generate the frequency vs wave-vector plot using Lumerical MODE solver and overlap it with the 3D-FDTD results. As shown in Fig. 7.15, the results perfectly overlap with the index-guided mode of the FDTD results. This way, we can trace back this mode, and work out phase-matching process with a lot more accuracy. Also, our “RAPID method” is more than one order of magnitude faster compared to the 3D-FDTD method.

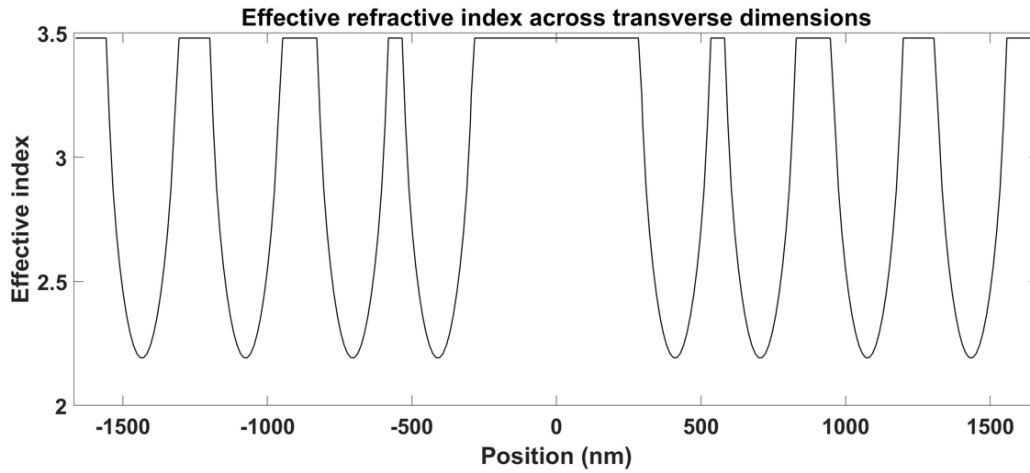


FIGURE 7.14: Effective refractive index of holes calculated by substituting the results of Rytov approximation.

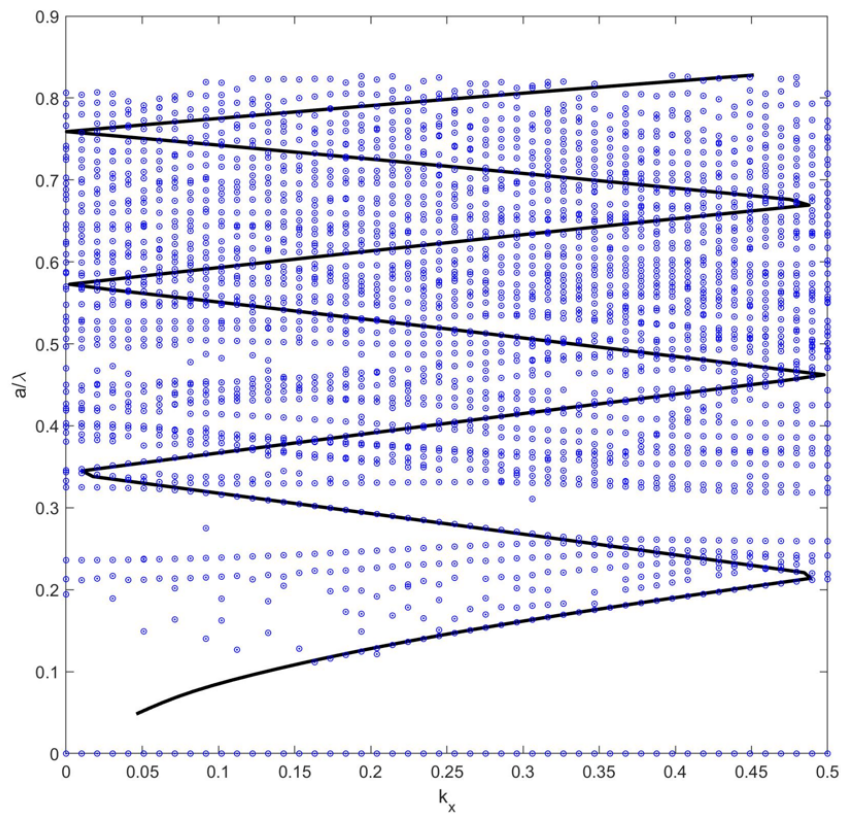


FIGURE 7.15: 3D-FDTD results overlapped with Rapid results obtained using MODE solver.

Chapter 8

Conclusion and Future Outlook

In this thesis, we outlined the fabrication processes and methodologies to fabricate integrated photonic devices based on III-V semiconductors. We described the basics of fabrication tools and the good practices to follow while performing nanofabrication. We then proposed a new process flow and demonstrated the results for creating a silica hard mask with nearly vertical sidewalls and negating the effect of RIE lag. Our process was repeatable and worked well for both, photoresists and E-beam resists.

We then demonstrated the challenges associated with the fabrication of structures with different physical dimensions and aspect ratios using the III-V semiconductor material AlGaAs. We presented the recipes for E-beam lithography and etching using different chemistries and discussed the advantages and disadvantages of each process. These recipes were used to fabricate structures like photonic-crystal waveguides, ring resonators, and suspended subwavelength waveguides based on the AlGaAs platform.

The design, fabrication and characterization results for AlGaAs photonic-crystal line-defect waveguides operating in the second bandgap region were demonstrated. We reported the first measurements of guided modes above the light line in the AlGaAs platform. The next step in this project is to fabricate structures with improved coupling efficiency and observe nonlinear optical interactions in such devices.

We carried out a detailed study of plasma etching recipe discovery for InP/InGaAsP material platform. We outlined the challenges associated with etching InP and the ways to overcome them. We introduced a recipe to etch InP using silica hard mask with a selectivity of 1:11 (silica:InP). We presented the first demonstration of the fabrication of half-core-etched and nanowire

waveguides based on InP/InGaAsP and demonstrated linear loss measurements and nonlinear four-wave mixing effect in these structures. Different designs of InP-based passive waveguides are being carried out by other members of the group, and the fabrication recipe developed in this thesis can be used to fabricate the next batch of nonlinear integrated photonic devices based on InP/InGaAsP.

Suspended structures allow for the highest possible index contrast which is crucial for light guidance in integrated photonic devices. We demonstrated the procedure to create suspended devices using AlGaAs material and fabricated suspended AlGaAs waveguides with supporting tethers. Further, we introduced the procedure for reducing line-edge roughness in subwavelength AlGaAs waveguides using PEC. We also numerically demonstrated an ability to phase-match the slow-light mode (fundamental) to the higher-order index-guided third-harmonic mode in suspended AlGaAs photonic-crystal waveguides.

To overcome the complications of deeply etched structures using the 3-layer geometry, novel platforms like AlGaAs-on-insulator have been introduced recently [68], [137]–[141]. Such structures offer higher refractive-index contrast between the AlGaAs core and silica cladding and a simplified AlGaAs etching due to the thinner AlGaAs membrane. By making use of the processes described in this thesis for plasma etching of AlGaAs and wet etching of the higher-aluminum-concentration layers, the next steps in the projects related to AlGaAs platforms are to work on the AlGaAs on insulator platform which offers much promise for integrated nonlinear photonics [68], [142]. Additionally, using the similar work-flow of wafer-bonding and selective wet etching which is used to produce AlGaAs-on-insulator wafers, we envision producing thin film InP-on-insulator as a novel material platform which will have immense potential for integrated nonlinear optics, particularly at larger wavelengths.

We fabricated Kagome lattice photonic-crystal waveguides using a suspended silicon membrane with optimized couplers. The linear characterization on these devices was finished, and the next step is to measure the group index, which is expected to be very large in these structures. The following step would be using the benefit of the large group index to observe enhanced nonlinear optical interactions in these structures.

We also demonstrated third-harmonic generation in silicon nitride waveguides with simulation results perfectly matching the experimental data. Such

devices can be used as an on-chip frequency conversion source. As a next step, using SiN as a material platform and an efficient THG process, we aim to reverse THG process to obtain on-chip sources of photon triplets via spontaneous parametric down conversion. We are also developing designs for performing THG in other platforms like GaN and AlGaAs which will follow the footprints of this experiment.

Finally, we introduced a RAPID method that can accurately simulate and trace the folded-back index-guided mode with high accuracy and less computational resources.

All the etch recipes used to fabricate various devices in this thesis have been documented in the table below:

Etch Recipe	Gases and flow (sccm)	ICP (W)	BIAS (W)	Pressure (Pa)	Temperature (°C)	Selectivity (mask:material)	Etch Rate (nm/sec)
Silica using ZEP	Ar:CF ₄ = 2:15	150	75	0.2	20	1:0.68	39
AlGaAs using ZEP (fast process)	Cl ₂ :BCl ₃ :Ar= 12:4:2	100	75	0.6	20	1:2.9	48
AlGaAs using ZEP (slow process)	Cl ₂ :BCl ₃ = 0.5:1.3	20	12	0.1	20	1:2	0.26
AlGaAs using SiO ₂ (ring resonator)	Cl ₂ :BCl ₃ :Ar= 5:5:2	250	30	0.65	20	1:10	11
InP/InGaAsP	Cl ₂ :BCl ₃ :Ar= 1:4:4	50	20	0.15	190	1:10	7

FIGURE 8.1: Table representing all the developed etch processes in this thesis.

In summary, this doctoral thesis outlines the nuances and subtleties of fabricating structures using III-V semiconductor material platforms, and details the process which can be used to repeatably create similar integrated photonic devices using III-V semiconductor material platforms. Looking forward, III-V semiconductors will be of tremendous interest in telecommunications, quantum, and sensing based applications [143], [144] due to their bandgap advantages and high nonlinearities. The holy grail in integrated optics still remains to be the monolithic integration of all functioning devices such as sources, detectors, interferometers, resonators, *etc*, on a single chip. This dream is only possible using either hybrid integration or monolithic integration, both of which are not possible without III-V semiconductors.

Bibliography

- [1] G. Roelkens, A. Abassi, P. Cardile, *et al.*, “III-V-on-silicon photonic devices for optical communication and sensing,” in *Photonics*, MDPI, vol. 2, 2015, pp. 969–1004.
- [2] E. Agrell, M. Karlsson, A. Chraplyvy, *et al.*, “Roadmap of optical communications,” *Journal of Optics*, vol. 18, no. 6, p. 063 002, 2016.
- [3] T. Vo-Dinh, *Biomedical photonics handbook: biomedical diagnostics*. CRC press, 2014.
- [4] K. Amsalu and S. Palani, “A review on photonics and its applications,” *Materials Today: Proceedings*, vol. 33, pp. 3372–3377, 2020.
- [5] M. E. Manka, “Microwave photonics for electronic warfare applications,” in *2008 International Topical Meeting on Microwave Photonics jointly held with the 2008 Asia-Pacific Microwave Photonics Conference*, IEEE, 2008, pp. 275–278.
- [6] M. Martínez-Corral and B. Javidi, “Fundamentals of 3D imaging and displays: A tutorial on integral imaging, light-field, and plenoptic systems,” *Advances in Optics and Photonics*, vol. 10, no. 3, pp. 512–566, 2018.
- [7] S. E. Miller, “Integrated optics: An introduction,” *The Bell System Technical Journal*, vol. 48, no. 7, pp. 2059–2069, 1969.
- [8] J Schmidtchen, A Splett, B Schuppert, K Petermann, and G Burbach, “Low loss singlemode optical waveguides with large cross-section in silicon-on-insulator,” *Electronics letters*, vol. 16, no. 27, pp. 1486–1488, 1991.
- [9] T. Horikawa, D. Shimura, and T. Mogami, “Low-loss silicon wire waveguides for optical integrated circuits,” *MRS Communications*, vol. 6, no. 1, pp. 9–15, 2016.
- [10] P. Dumon, W. Bogaerts, V. Wiaux, *et al.*, “Low-loss SOI photonic wires and ring resonators fabricated with deep uv lithography,” *IEEE Photonics Technology Letters*, vol. 16, no. 5, pp. 1328–1330, 2004.
- [11] W. W. Chow and S. W. Koch, *Semiconductor-laser fundamentals: physics of the gain materials*. Springer Science & Business Media, 1999.

- [12] B. E. Saleh and M. C. Teich, *Fundamentals of photonics*. John Wiley & sons, 2019.
- [13] R. Haldar, "Integrated photonic devices and components for linear, nonlinear and quantum optical applications," in *Conference on Lasers and Electro-Optics*, 2021.
- [14] *Symmetric slab waveguides*, <https://www.fiberoptics4sale.com/blogs/wave-optics/symmetric-slab-waveguides>, Accessed: 2022-09-12.
- [15] R. W. Boyd, *Nonlinear optics*. Academic press, 2020.
- [16] A. E. Willner, S. Khaleghi, M. R. Chitgarha, and O. F. Yilmaz, "All-optical signal processing," *Journal of Lightwave Technology*, vol. 32, no. 4, pp. 660–680, 2013.
- [17] P. Absil, J. Hryniewicz, B. Little, *et al.*, "Wavelength conversion in gaas micro-ring resonators," *Optics Letters*, vol. 25, no. 8, pp. 554–556, 2000.
- [18] L. Caspani, C. Xiong, B. J. Eggleton, *et al.*, "Integrated sources of photon quantum states based on nonlinear optics," *Light: Science & Applications*, vol. 6, no. 11, e17100–e17100, 2017.
- [19] G. Van Soest, E. Regar, and A. F. Van Der Steen, "Photonics in cardiovascular medicine," *Nature Photonics*, vol. 9, no. 10, pp. 626–629, 2015, ISSN: 17494893. DOI: [10.1038/nphoton.2015.177](https://doi.org/10.1038/nphoton.2015.177). [Online]. Available: <http://www.nature.com/articles/nphoton.2015.177>.
- [20] B. Norris and J. Bland-Hawthorn, "Astrophotonics: The rise of integrated photonics in astronomy," *Optics and Photonics News*, vol. 30, no. 5, pp. 26–33, 2019.
- [21] J. M. Arrazola, V. Bergholm, K. Brádler, *et al.*, "Quantum circuits with many photons on a programmable nanophotonic chip," *Nature*, vol. 591, no. 7848, pp. 54–60, 2021, ISSN: 0028-0836. DOI: [10.1038/s41586-021-03202-1](https://doi.org/10.1038/s41586-021-03202-1). [Online]. Available: <http://www.nature.com/articles/s41586-021-03202-1>.
- [22] M. L. M. Lalieu, R. Lavrijsen, and B. Koopmans, "Integrating all-optical switching with spintronics," *Nature Communications*, vol. 10, no. 1, p. 110, 2019, ISSN: 2041-1723. DOI: [10.1038/s41467-018-08062-4](https://doi.org/10.1038/s41467-018-08062-4). [Online]. Available: <http://www.nature.com/articles/s41467-018-08062-4>.
- [23] W. J. Kozlovsky, C. Nabors, and R. L. Byer, "Efficient second harmonic generation of a diode-laser-pumped CW Nd: Yag laser using monolithic mgo: LiNbO/sub 3/external resonant cavities," *IEEE journal of quantum electronics*, vol. 24, no. 6, pp. 913–919, 1988.

- [24] H. Fukuda, K. Yamada, T. Shoji, *et al.*, "Four-wave mixing in silicon wire waveguides," *Optics express*, vol. 13, no. 12, pp. 4629–4637, 2005.
- [25] S Sederberg, C. Firby, and A. Elezzabi, "Efficient, broadband third-harmonic generation in silicon nanophotonic waveguides spectrally shaped by nonlinear propagation," *Optics express*, vol. 27, no. 4, pp. 4990–5004, 2019.
- [26] M. R. Shcherbakov, D. N. Neshev, B. Hopkins, *et al.*, "Enhanced third-harmonic generation in silicon nanoparticles driven by magnetic response," *Nano Letters*, vol. 14, no. 11, pp. 6488–6492, 2014.
- [27] T. Li, M. Mastro, and A. Dadgar, *III–V compound semiconductors: integration with silicon-based microelectronics*. CRC press, 2010.
- [28] K. Matsumoto, J. Kishikawa, T. Nishiyama, Y. Onuki, and K. Shimomura, "Novel integration method for III–V semiconductor devices on silicon platform," *Japanese Journal of Applied Physics*, vol. 55, no. 11, p. 112 201, 2016.
- [29] A. R. Denton and N. W. Ashcroft, "Vegard's law," *Physical Review A*, vol. 43, p. 3161, 1991.
- [30] R. P. Feynman, "There's plenty of room at the bottom [data storage]," *Journal of Microelectromechanical Systems*, vol. 1, no. 1, pp. 60–66, 1992, ISSN: 1057-7157. DOI: [10.1109/84.128057](https://doi.org/10.1109/84.128057). [Online]. Available: <http://ieeexplore.ieee.org/document/128057/>.
- [31] G. E. Moore *et al.*, *Cramming more components onto integrated circuits*, 1965.
- [32] MS Windows NT kernel description, <https://www.basicknowledge101.com/categories/nano.html>, Accessed: 2022-04-20.
- [33] W. Lu and C. M. Lieber, "Nanoelectronics from the bottom up," *Nanoscience And Technology: A Collection of Reviews from Nature Journals*, pp. 137–146, 2010.
- [34] R. G. Hobbs, N. Petkov, and J. D. Holmes, "Semiconductor nanowire fabrication by bottom-up and top-down paradigms," *Chemistry of Materials*, vol. 24, no. 11, pp. 1975–1991, 2012.
- [35] X. Fu, J. Cai, X. Zhang, W.-D. Li, H. Ge, and Y. Hu, "Top-down fabrication of shape-controlled, monodisperse nanoparticles for biomedical applications," *Advanced Drug Delivery Reviews*, vol. 132, pp. 169–187, 2018.
- [36] A. E.-J. Lim, J. Song, Q. Fang, *et al.*, "Review of silicon photonics foundry efforts," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 20, no. 4, pp. 405–416, 2013.

- [37] Y. Chen and J. Washburn, "Structural transition in large-lattice-mismatch heteroepitaxy," *Physical review letters*, vol. 77, no. 19, p. 4046, 1996.
- [38] R. People and J. Bean, "Calculation of critical layer thickness versus lattice mismatch for $\text{Ge}_x\text{Si}_{1-x}/\text{Si}$ strained-layer heterostructures," *Applied Physics Letters*, vol. 47, no. 3, pp. 322–324, 1985.
- [39] Y. Hu, D. Liang, K. Mukherjee, *et al.*, "III/V-on-Si MQW lasers by using a novel photonic integration method of regrowth on a bonding template," *Light: Science and Applications*, vol. 8, p. 93, 2019.
- [40] D. Hansen and T. Kuech, "Epitaxial technology for integrated circuit manufacturing," *Encyclopedia of Physical Science and Technology*, pp. 641–652, 2003.
- [41] A. Y. Cho and J. Arthur, "Molecular beam epitaxy," *Progress in solid state chemistry*, vol. 10, pp. 157–191, 1975.
- [42] M. Ludowise, "Metalorganic chemical vapor deposition of III-V semiconductors," *Journal of Applied Physics*, vol. 58, no. 8, R31–R55, 1985.
- [43] E. Kuphal, "Liquid phase epitaxy," *Applied Physics A*, vol. 52, no. 6, pp. 380–409, 1991.
- [44] L. Ocola and A. Stein, "Effect of cold development on improvement in electron-beam nanopatterning resolution and line roughness," *Journal of Vacuum Science & Technology B: Microelectronics and Nanometer Structures Processing, Measurement, and Phenomena*, vol. 24, no. 6, pp. 3061–3065, 2006.
- [45] N. Sahu, B. Parija, and S. Panigrahi, "Fundamental understanding and modeling of spin coating process: A review," *Indian Journal of Physics*, vol. 83, no. 4, pp. 493–502, 2009.
- [46] C. Wagner and N. Harned, "Lithography gets extreme," *Nature Photonics*, vol. 4, no. 1, pp. 24–26, 2010.
- [47] M. Van de Kerkhof, J. Benschop, and V. Banine, "Lithography for now and the future," *Solid-State Electron*, vol. 155, pp. 20–26, 2019.
- [48] S. Reyntjens and R. Puers, "A review of focused ion beam applications in microsystem technology," *Journal of micromechanics and microengineering*, vol. 11, no. 4, p. 287, 2001.
- [49] V. R. Manfrinato, L. Zhang, D. Su, *et al.*, "Resolution limits of electron-beam lithography toward the atomic scale," *Nano Letters*, vol. 13, no. 4, pp. 1555–1558, 2013.
- [50] L. De Broglie, *The wave nature of the electron*, 1929.

- [51] C. Davisson and L. H. Germer, "Diffraction of electrons by a crystal of nickel," *Physical review*, vol. 30, no. 6, p. 705, 1927.
- [52] E. Harvey and M. Ghantasala, "12 - nanofabrication," in *Nanostructure Control of Materials*, R. Hannink and A. Hill, Eds., Woodhead Publishing, 2006, pp. 303–330, ISBN: 978-1-85573-933-8. DOI: <https://doi.org/10.1533/9781845691189.303>. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/B9781855739338500129>.
- [53] T. Chang, "Proximity effect in electron-beam lithography," *Journal of Vacuum Science and Technology*, vol. 12, no. 6, pp. 1271–1275, 1975.
- [54] D. Kyser and N. Viswanathan, "Monte carlo simulation of spatially distributed beams in electron-beam lithography," *Journal of Vacuum Science and Technology*, vol. 12, no. 6, pp. 1305–1308, 1975.
- [55] G. GmbH. "Webinar series: Proximity effect in E-Beam Lithography." (2020), [Online]. Available: <https://www.genisys-gmbh.com/part-1-electron-scattering-and-proximity-effect.html>.
- [56] J. W. Coburn and H. F. Winters, "Plasma etching—a discussion of mechanisms," *Journal of vacuum Science and Technology*, vol. 16, no. 2, pp. 391–403, 1979.
- [57] D. Rugar and P. Hansma, "Atomic force microscopy," *Physics today*, vol. 43, no. 10, pp. 23–30, 1990.
- [58] S. A. Schulz, J. Upham, L. O'Faolain, and R. W. Boyd, "Photonic crystal slow light waveguides in a kagome lattice," *Optics letters*, vol. 42, no. 16, pp. 3243–3246, 2017.
- [59] J. S. Parker, E. J. Norberg, R. S. Guzzon, S. C. Nicholes, and L. A. Coldren, "High verticality InP/InGaAsP etching in Cl₂/H₂/Ar inductively coupled plasma for photonic integrated circuits," *Journal of Vacuum Science & Technology B, Nanotechnology and Microelectronics: Materials, Processing, Measurement, and Phenomena*, vol. 29, no. 1, p. 011 016, 2011.
- [60] M. Volatier, D. Duchesne, R. Morandotti, R. Arès, and V. Aimez, "Extremely high aspect ratio GaAs and GaAs/AlGaAs nanowaveguides fabricated using chlorine ICP etching with N₂-promoted passivation," *Nanotechnology*, vol. 21, no. 13, p. 134 014, 2010, ISSN: 0957-4484. DOI: [10.1088/0957-4484/21/13/134014](https://doi.org/10.1088/0957-4484/21/13/134014). [Online]. Available: <https://iopscience.iop.org/article/10.1088/0957-4484/21/13/134014>.

- [61] K. Dolgaleva, P. Sarrafi, P. Kultavewuti, *et al.*, "Tuneable four-wave mixing in AlGaAs nanowires," *Optics Express*, vol. 23, no. 17, pp. 22 477–22 493, 2015.
- [62] K. M. Awan, M. M. Muhammad, M. Sivan, S. Bonca, I. S. Roqan, and K. Dolgaleva, "Fabrication and optical characterization of GaN waveguides on (201)-oriented β -Ga₂O₃," *Optical Materials Express*, vol. 8, no. 1, p. 88, 2018, ISSN: 2159-3930. DOI: [10.1364/OME.8.000088](https://doi.org/10.1364/OME.8.000088). [Online]. Available: <https://www.osapublishing.org/abstract.cfm?URI=ome-8-1-88>.
- [63] D. H. Espinosa, K. M. Awan, M. Odungide, S. R. Harrigan, D. R. Sanchez, and K. Dolgaleva, "Tunable four-wave mixing in AlGaAs waveguides of three different geometries," *Optics Communications*, vol. 479, p. 126 450, 2021.
- [64] "Resists for sub-20-nm electron beam lithography with a focus on HSQ: state of the art," vol. 20, no. 29, p. 292 001, 2009. [Online]. Available: <https://iopscience.iop.org/article/10.1088/0957-4484/20/29/292001>.
- [65] T. Akimoto, H. Nanbu, and E. Ikawa, "Reactive ion etching lag on high rate oxide etching using high density plasma," *Journal of Vacuum Science & Technology B: Microelectronics and Nanometer Structures Processing, Measurement, and Phenomena*, vol. 13, no. 6, pp. 2390–2393, 1995.
- [66] E. Mobini, D. H. Espinosa, K. Vyas, and K. Dolgaleva, "AlGaAs non-linear integrated photonics," *Micromachines*, vol. 13, no. 7, p. 991, 2022.
- [67] D. H. Espinosa, S. R. Harrigan, K. M. Awan, P. Rasekh, and K. Dolgaleva, "Geometry-dependent two-photon absorption followed by free-carrier absorption in AlGaAs waveguides," *JOSA B*, vol. 38, no. 12, pp. 3765–3774, 2021.
- [68] M. Pu, L. Ottaviano, E. Semenova, and K. Yvind, "Efficient frequency comb generation in AlGaAs-on-Insulator," *Optica*, vol. 3, no. 8, pp. 823–826, 2016.
- [69] B. Kuyken, M. Billet, F. Leo, K. Yvind, and M. Pu, "Octave-spanning coherent supercontinuum generation in an AlGaAs-on-Insulator waveguide," *Optics Letters*, vol. 45, no. 3, pp. 603–606, 2020.
- [70] M. Holm, D Burns, A. Ferguson, and M. Dawson, "Actively stabilized single-frequency vertical-external-cavity AlGaAs laser," *IEEE Photonics Technology Letters*, vol. 11, no. 12, pp. 1551–1553, 1999.

- [71] A. Köck, E. Gornik, G. Abstreiter, G. Böhm, M. Walther, and G. Weimann, "Double wavelength selective GaAs/AlGaAs infrared detector device," *Applied physics letters*, vol. 60, no. 16, pp. 2011–2013, 1992.
- [72] S. Gehrsitz, F. K. Reinhart, C. Gourgon, N. Herres, A. Vonlanthen, and H. Sigg, "The refractive index of $\text{Al}_x\text{Ga}_{1-x}\text{As}$ below the band gap: Accurate determination and empirical modeling," *Journal of Applied Physics*, vol. 87, no. 11, pp. 7825–7837, 2000, ISSN: 0021-8979. DOI: 10.1063/1.373462. [Online]. Available: <http://aip.scitation.org/doi/10.1063/1.373462>.
- [73] J. Aitchison, D. Hutchings, J. Kang, G. Stegeman, and A. Villeneuve, "The nonlinear optical properties of AlGaAs at the half band gap," *IEEE Journal of Quantum Electronics*, vol. 33, no. 3, pp. 341–348, 1997, ISSN: 00189197. DOI: 10.1109/3.556002. [Online]. Available: <http://ieeexplore.ieee.org/document/556002/>.
- [74] Z. Yang, P. Chak, A. D. Bristow, *et al.*, "Enhanced second-harmonic generation in AlGaAs microring resonators," *Optics letters*, vol. 32, no. 7, pp. 826–828, 2007.
- [75] I. Roland, M. Ravaro, S. Suffit, *et al.*, "Second-Harmonic Generation in Suspended AlGaAs Waveguides: A Comparative Study," *Micromachines*, vol. 11, no. 2, p. 229, 2020, ISSN: 2072-666X. DOI: 10.3390/mi11020229. [Online]. Available: <https://www.mdpi.com/2072-666X/11/2/229>.
- [76] K. Vyas, S. Vijayakumar, F. St-Amand, *et al.*, "Third-harmonic generation in AlGaAs photonic crystal waveguides," in *Photonic and Phononic Properties of Engineered Nanostructures XII*, SPIE, 2022, PC120101E.
- [77] R. Benevides, M. Ménard, G. S. Wiederhecker, and T. P. M. Alegre, "Ar/cl 2 etching of gaas optomechanical microdisks fabricated with positive electroresist," *Optical Materials Express*, vol. 10, no. 1, pp. 57–67, 2020.
- [78] S. Johnson and J. Joannopoulos, "Block-iterative frequency-domain methods for Maxwell's equations in a planewave basis," *Optics Express*, vol. 8, no. 3, p. 173, 2001, ISSN: 1094-4087. DOI: 10.1364/OE.8.000173. [Online]. Available: <https://www.osapublishing.org/oe/abstract.cfm?uri=oe-8-3-173>.

- [79] G. STEGEMAN, A. VILLENEUVE, J. KANG, *et al.*, "AlGaAs BELOW HALF BANDGAP: THE SILICON OF NONLINEAR OPTICAL MATERIALS," *Journal of Nonlinear Optical Physics Materials*, vol. 03, no. 03, pp. 347–371, 1994, ISSN: 0218-8635. DOI: [10.1142 / S0218199194000213](https://doi.org/10.1142/S0218199194000213). [Online]. Available: [https : / / www . worldscientific.com/doi/abs/10.1142/S0218199194000213](https://www.worldscientific.com/doi/abs/10.1142/S0218199194000213).
- [80] K. Dolgaleva, W. C. Ng, L. Qian, and J. S. Aitchison, "Compact highly-nonlinear AlGaAs waveguides for efficient wavelength conversion," *Optics Express*, vol. 19, no. 13, p. 12440, 2011, ISSN: 1094-4087. DOI: [10.1364/OE.19.012440](https://doi.org/10.1364/OE.19.012440). [Online]. Available: <https://www.osapublishing.org/oe/abstract.cfm?uri=oe-19-13-12440>.
- [81] Z. Liao and J. S. Aitchison, "Precision etching for multi-level AlGaAs waveguides," *Optical Materials Express*, vol. 7, no. 3, pp. 895–903, 2017.
- [82] E. Yablonovitch, "Inhibited spontaneous emission in solid-state physics and electronics," *Physical review letters*, vol. 58, no. 20, p. 2059, 1987.
- [83] S. John, "Strong localization of photons in certain disordered dielectric superlattices," *Physical review letters*, vol. 58, no. 23, p. 2486, 1987.
- [84] E. Yablonovitch, "Photonic band-gap structures," *JOSA B*, vol. 10, no. 2, pp. 283–295, 1993.
- [85] J. E. Heebner and R. W. Boyd, "Slow and stopped light'slow'and'fast'light in resonator-coupled waveguides," *journal of modern optics*, vol. 49, no. 14-15, pp. 2629–2636, 2002.
- [86] T. F. Krauss, "Slow light in photonic crystal waveguides," *Journal of Physics D: Applied Physics*, vol. 40, no. 9, p. 2666, 2007.
- [87] H. Kosaka, T. Kawashima, A. Tomita, *et al.*, "Superprism phenomena in photonic crystals," *Physical review B*, vol. 58, no. 16, R10096, 1998.
- [88] A. Berrier, M. Mulot, M. Swillo, *et al.*, "Negative refraction at infrared wavelengths in a two-dimensional photonic crystal," *Physical review letters*, vol. 93, no. 7, p. 073 902, 2004.
- [89] Y. Zheng, M. Pu, H. K. Sahoo, E. Semenova, and K. Yvind, "High-quality-factor AlGaAs-on-sapphire microring resonators," *Journal of Lightwave Technology*, vol. 37, no. 3, pp. 868–874, 2019.
- [90] A. Gondarenko, J. S. Levy, and M. Lipson, "High confinement micron-scale silicon nitride high q ring resonator," *Optics express*, vol. 17, no. 14, pp. 11 366–11 370, 2009.

- [91] Y. Okawachi, K. Saha, J. S. Levy, Y. H. Wen, M. Lipson, and A. L. Gaeta, "Octave-spanning frequency comb generation in a silicon nitride chip," *Optics letters*, vol. 36, no. 17, pp. 3398–3400, 2011.
- [92] R. Cheriton, S. Sivanandam, A. Densmore, *et al.*, "Spectrum-free integrated photonic remote molecular identification and sensing," *Optics Express*, vol. 28, no. 19, pp. 27 951–27 965, 2020.
- [93] T. H. Stievater, M. W. Pruessner, D. Park, *et al.*, "Trace gas absorption spectroscopy using functionalized microring resonators," *Optics letters*, vol. 39, no. 4, pp. 969–972, 2014.
- [94] D. Marinica, A. Borisov, and S. Shabanov, "Bound states in the continuum in photonics," *Physical review letters*, vol. 100, no. 18, p. 183 902, 2008.
- [95] K. Koshelev, A. Bogdanov, and Y. Kivshar, "Meta-optics and bound states in the continuum," *Science Bulletin*, vol. 64, no. 12, pp. 836–842, 2019.
- [96] E. Mobini, R. Alaee, R. W. Boyd, and K. Dolgaleva, "Giant asymmetric second-harmonic generation in bianisotropic metasurfaces based on bound states in the continuum," *ACS Photonics*, vol. 8, no. 11, pp. 3234–3240, 2021.
- [97] L. C. Andreani and D. Gerace, "Light-matter interaction in photonic crystal slabs," *Physica status solidi (b)*, vol. 244, no. 10, pp. 3528–3539, 2007.
- [98] Y. Akahane, T. Asano, B.-S. Song, and S. Noda, "High-q photonic nanocavity in a two-dimensional photonic crystal," *nature*, vol. 425, no. 6961, pp. 944–947, 2003.
- [99] M. Deubel, M. Wegener, S. Linden, G. Von Freymann, and S. John, "3d-2d-3d photonic crystal heterostructures fabricated by direct laser writing," *Optics letters*, vol. 31, no. 6, pp. 805–807, 2006.
- [100] S. Takahashi, K. Suzuki, M. Okano, *et al.*, "Direct creation of three-dimensional photonic crystals by a top-down approach," *Nature materials*, vol. 8, no. 9, pp. 721–725, 2009.
- [101] Y. Hu, B. T. Miles, Y.-L. D. Ho, *et al.*, "Toward direct laser writing of actively tuneable 3d photonic crystals," *Advanced Optical Materials*, vol. 5, no. 3, p. 1 600 458, 2017.
- [102] J. D. Joannopoulos, S. G. Johnson, J. N. Winn, and R. D. Meade, "Molding the flow of light," *Princeton Univ. Press, Princeton, NJ [ua]*, 2008.
- [103] M. Notomi, K. Yamada, A. Shinya, J. Takahashi, C. Takahashi, and I. Yokohama, "Extremely large group-velocity dispersion of line-defect

- waveguides in photonic crystal slabs," *Physical review letters*, vol. 87, no. 25, p. 253 902, 2001.
- [104] T. F. Krauss, "Why do we need slow light?" *Nature photonics*, vol. 2, no. 8, pp. 448–450, 2008.
- [105] T. Baba, "Slow light in photonic crystals," *Nature photonics*, vol. 2, no. 8, pp. 465–473, 2008.
- [106] R. Engelen, Y. Sugimoto, Y. Watanabe, *et al.*, "The effect of higher-order dispersion on slow light propagation in photonic crystal waveguides," *Optics Express*, vol. 14, no. 4, p. 1658, 2006, ISSN: 1094-4087. DOI: 10.1364/OE.14.001658. [Online]. Available: <https://www.osapublishing.org/oe/abstract.cfm?uri=oe-14-4-1658>.
- [107] H. S. Dutta, A. K. Goyal, V. Srivastava, and S. Pal, "Coupling light in photonic crystal waveguides: A review," *Photonics and Nanostructures-Fundamentals and Applications*, vol. 20, pp. 41–58, 2016.
- [108] "Polyatomic photonic crystal waveguides with semi-slow light and tailored dispersion properties," in *Optoelectronic Materials and Devices*, vol. 14, OSA, 2011, p. 83081X, ISBN: 978-0-8194-8956-2. DOI: 10.1364/ACP.2011.83081X. [Online]. Available: <https://www.osapublishing.org/abstract.cfm?URI=ACP-2011-83081X>.
- [109] K. Dolgaleva, W. C. Ng, L. Qian, J. S. Aitchison, M. C. Camasta, and M. Sorel, "Broadband self-phase modulation, cross-phase modulation, and four-wave mixing in 9-mm-long AlGaAs waveguides," *Optics Letters*, vol. 35, no. 24, p. 4093, 2010, ISSN: 0146-9592. DOI: 10.1364/OL.35.004093. [Online]. Available: <https://www.osapublishing.org/abstract.cfm?URI=ol-35-24-4093>.
- [110] M. Qiu, "Effective index method for heterostructure-slab-waveguide-based two-dimensional photonic crystals," *Applied physics letters*, vol. 81, no. 7, pp. 1163–1165, 2002.
- [111] S. A. Schulz, A. H. Park, I. De Leon, J. Upham, and R. W. Boyd, "Beyond the effective index method: Improved accuracy for 2d simulations of photonic crystal waveguides," *Journal of Optics*, vol. 17, no. 7, p. 075 006, 2015.
- [112] L. H. Frandsen, A. V. Lavrinenko, J. Fage-Pedersen, and P. I. Borel, "Photonic crystal waveguides with semi-slow light and tailored dispersion properties," *Optics Express*, vol. 14, no. 20, pp. 9444–9450, 2006.

- [113] C. Jamois, R. Wehrspohn, L. Andreani, C. Hermann, O. Hess, and U. Gösele, "Silicon-based two-dimensional photonic crystal waveguides," *Photonics and Nanostructures - Fundamentals and Applications*, vol. 1, no. 1, pp. 1–13, 2003, ISSN: 15694410. DOI: [10 . 1016 / j . photonics . 2003 . 10 . 001](https://doi.org/10.1016/j.photonics.2003.10.001). [Online]. Available: <https://linkinghub.elsevier.com/retrieve/pii/S1569441003000099>.
- [114] M. Razeghi, "High-power laser diodes based on ingaasp alloys," *Nature*, vol. 369, no. 6482, pp. 631–633, 1994.
- [115] G. Roelkens, D. Van Thourhout, R. Baets, R Nötzel, and M. Smit, "Laser emission and photodetection in an inp/ingaasp layer integrated on and coupled to a silicon-on-insulator waveguide circuit," *Optics express*, vol. 14, no. 18, pp. 8154–8159, 2006.
- [116] J. Zhang, M. A. Itzler, H. Zbinden, and J.-W. Pan, "Advances in ingaas/inp single-photon detector systems for quantum communication," *Light: Science & Applications*, vol. 4, no. 5, e286–e286, 2015.
- [117] S. Saeidi, P. Rasekh, K. M. Awan, A. Tügen, M. J. Huttunen, and K. Dolgaleva, "Demonstration of optical nonlinearity in ingaasp/inp passive waveguides," *Optical Materials*, vol. 84, pp. 524–530, 2018.
- [118] H. Tsang, R. Penty, I. White, *et al.*, "Two-photon absorption and self-phase modulation in ingaasp/inp multi-quantum-well waveguides," *Journal of applied physics*, vol. 70, no. 7, pp. 3992–3994, 1991.
- [119] E Kuphal, "Phase diagrams of ingaasp, ingaas and inp lattice-matched to (100) inp," *Journal of crystal growth*, vol. 67, no. 3, pp. 441–457, 1984.
- [120] J. McNabb, H. Craighead, H Temkin, and R. Logan, "Anisotropic reactive ion etching of inp in methane/hydrogen based plasmas," *Journal of Vacuum Science & Technology B: Microelectronics and Nanometer Structures Processing, Measurement, and Phenomena*, vol. 9, no. 6, pp. 3535–3537, 1991.
- [121] J Etrillard, P Ossart, G Patriarche, M Juhel, J. Bresse, and C Daguet, "Anisotropic etching of inp with low sidewall and surface induced damage in inductively coupled plasma etching using sicl₄," *Journal of Vacuum Science & Technology A: Vacuum, Surfaces, and Films*, vol. 15, no. 3, pp. 626–632, 1997.
- [122] L. Chee-Wei and C. Mee-Koy, "Room-Temperature Inductively Coupled Plasma Etching of InP Using Cl₂ /N₂ and Cl₂ /CH₄ /H₂,"

- Chinese Physics Letters*, vol. 23, no. 4, pp. 903–906, 2006, ISSN: 0256-307X. DOI: 10.1088/0256-307X/23/4/039. [Online]. Available: <https://iopscience.iop.org/article/10.1088/0256-307X/23/4/039>.
- [123] V. M. Donnelly, D. L. Flamm, C. W. Tu, and D. E. Ibbotson, “Temperature Dependence of InP and GaAs Etching in a Chlorine Plasma,” *Journal of The Electrochemical Society*, vol. 129, no. 11, pp. 2533–2537, 1982, ISSN: 0013-4651. DOI: 10.1149/1.2123600. [Online]. Available: <https://iopscience.iop.org/article/10.1149/1.2123600>.
- [124] T. Feuchter and C. Thirstrup, “High precision planar waveguide propagation loss measurement technique using a fabry-perot cavity,” *IEEE photonics technology letters*, vol. 6, no. 10, pp. 1244–1247, 1994.
- [125] S. Schulz, C. Hu, J. Upham, R. W. Boyd, and L. O’Faolain, “Controllable low-loss slow light in photonic crystals,” in *Steep Dispersion Engineering and Opto-Atomic Precision Metrology XI*, S. M. Shahriar and J. Scheuer, Eds., SPIE, 2018, p. 5, ISBN: 9781510615816. DOI: 10.1117/12.2290240. [Online]. Available: <https://www.spiedigitallibrary.org/conference-proceedings-of-spie/10548/2290240/Controllable-low-loss-slow-light-in-photonic-crystals/10.1117/12.2290240.full>.
- [126] S. A. Schulz, L. O’Faolain, D. M. Beggs, T. P. White, A. Melloni, and T. F. Krauss, “Dispersion engineered slow light in photonic crystals: a comparison,” *Journal of Optics*, vol. 12, no. 10, p. 104 004, 2010, ISSN: 2040-8978. DOI: 10.1088/2040-8978/12/10/104004. [Online]. Available: <https://iopscience.iop.org/article/10.1088/2040-8978/12/10/104004>.
- [127] T. F. Krauss, L. O’Faolain, S. Schulz, *et al.*, “Understanding the rich physics of light propagation in slow photonic crystal waveguides,” in *Advances in Slow and Fast Light III*, S. M. Shahriar and P. R. Hemmer, Eds., vol. 7612, 2010, p. 76120L, ISBN: 9780819480088. DOI: 10.1117/12.848655. [Online]. Available: <http://proceedings.spiedigitallibrary.org/proceeding.aspx?doi=10.1117/12.848655>.
- [128] J. Li, T. P. White, L. O’Faolain, A. Gomez-Iglesias, and T. F. Krauss, “Systematic design of flat band slow light in photonic crystal waveguides,” *Optics Express*, vol. 16, no. 9, p. 6227, 2008, ISSN: 1094-4087. DOI: 10.1364/oe.16.006227.
- [129] H. Lin, Z. Luo, T. Gu, *et al.*, “Mid-infrared integrated photonics on silicon: a perspective,” *Nanophotonics*, vol. 7, no. 2, pp. 393–420, 2017,

- ISSN: 2192-8614. DOI: [10.1515/nanoph-2017-0085](https://doi.org/10.1515/nanoph-2017-0085). [Online]. Available: <https://www.degruyter.com/document/doi/10.1515/nanoph-2017-0085/html>.
- [130] B. Corcoran, C. Monat, C. Grillet, *et al.*, “Green light emission in silicon through slow-light enhanced third-harmonic generation in photonic-crystal waveguides,” *Nature photonics*, vol. 3, no. 4, pp. 206–210, 2009.
- [131] D. Vercruyssen, N. V. Saprà, K. Y. Yang, and J. Vuckovic, “Inverse-designed photonic crystal circuits for optical beam steering,” *ACS Photonics*, vol. 8, no. 10, pp. 3085–3093, 2021.
- [132] G. Z. Mashanovich, S. Stankovic, R. Topley, *et al.*, “Silicon Photonic Waveguides and Devices for Near- and Mid-IR Applications,” *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 21, no. 4, pp. 407–418, 2015, ISSN: 1077-260X. DOI: [10.1109/JSTQE.2014.2381469](https://doi.org/10.1109/JSTQE.2014.2381469). [Online]. Available: <https://ieeexplore.ieee.org/document/6985544/>.
- [133] J. S. Penadés, A. Sánchez-Postigo, M. Nedeljkovic, *et al.*, “Suspended silicon waveguides for long-wave infrared wavelengths,” *Optics Letters*, vol. 43, no. 4, p. 795, 2018, ISSN: 0146-9592. DOI: [10.1364/OL.43.000795](https://doi.org/10.1364/OL.43.000795). [Online]. Available: <https://www.osapublishing.org/abstract.cfm?URI=ol-43-4-795>.
- [134] K. Matan, T. Ono, Y. Fukumoto, *et al.*, “Pinwheel valence-bond solid and triplet excitations in the two-dimensional deformed kagome lattice,” *Nature Physics*, vol. 6, no. 11, pp. 865–869, 2010.
- [135] M. H. Pfeiffer, J. Liu, A. S. Raja, T. Morais, B. Ghadiani, and T. J. Kippenberg, “Ultra-smooth silicon nitride waveguides based on the damascene reflow process: Fabrication and loss origins,” *Optica*, vol. 5, no. 7, pp. 884–892, 2018.
- [136] S. Rytov, “Electromagnetic properties of a finely stratified medium,” *Soviet Physics JEPT*, vol. 2, pp. 466–475, 1956.
- [137] L. Ottaviano, M. Pu, E. Semenova, and K. Yvind, “Low-loss high-confinement waveguides and microring resonators in AlGaAs-on-insulator,” *Optics Letters*, vol. 41, no. 17, pp. 3996–3999, 2016.
- [138] M. Pu, H. Hu, L. Ottaviano, *et al.*, “Ultra-efficient and broadband non-linear AlGaAs-on-insulator chip for low-power optical signal processing,” *Laser & Photonics Reviews*, vol. 12, no. 12, p. 1800111, 2018.
- [139] S. May, M. Kues, M. Clerici, and M. Sorel, “Second-harmonic generation in AlGaAs-on-insulator waveguides,” *Optics Letters*, vol. 44, no. 6, pp. 1339–1342, 2019.

- [140] L. Chang, W. Xie, H. Shu, *et al.*, “Ultra-efficient frequency comb generation in AlGaAs-on-insulator microresonators,” *Nature communications*, vol. 11, no. 1, pp. 1–8, 2020.
- [141] S. May, M. Clerici, and M. Sorel, “Supercontinuum generation in dispersion engineered AlGaAs-on-insulator waveguides,” *Scientific Reports*, vol. 11, no. 1, pp. 1–7, 2021.
- [142] M. Placke and S. Ramelow, “Engineering AlGaAs-on-insulator toward quantum optical applications,” *Optics Letters*, vol. 45, no. 24, pp. 6763–6766, 2020.
- [143] L. Chang, G. D. Cole, G. Moody, and J. E. Bowers, “CSOI: Beyond silicon-on-insulator photonics,” *Optics and Photonics News*, vol. 33, no. 1, pp. 24–31, 2022.
- [144] K. Vyas, D. H. G. Espinosa, D. Hutama, *et al.*, “Group III-V semiconductors as promising nonlinear integrated photonic platforms,” *Advances in Physics: X*, vol. 7, no. 1, p. 2097020, 2022. DOI: [10 . 1080 / 23746149 . 2022 . 2097020](https://doi.org/10.1080/23746149.2022.2097020). eprint: <https://www.tandfonline.com/doi/pdf/10.1080/23746149.2022.2097020>. [Online]. Available: <https://www.tandfonline.com/doi/abs/10.1080/23746149.2022.2097020>.