IMPROVING THE FABRICATION OF SEMICONDUCTOR BRAGG LASERS

by

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A thesis submitted in conformity with the requirements for the degree of Master of Applied Science
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Abstract

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Fabrication process developments for Bragg reflection lasers have been optimized in this thesis using resources available to the group. New e-beam lithography and oxide etch recipes have been developed to minimize sidewall roughness and residues. E-beam evaporated metal contacts for semiconductor diode laser utilizing oblique angle deposition have also been developed in-house for the first time. Furthermore, improvement in micro-loading effect of DFB laser etching has been demonstrated where the ratio of tapered portion of the sidewall to total etch depth is reduced by half, from 33% to 15%. Electrical, optical and thermal performance of the fabricated lasers are characterized. Comparing the results to previous generation lasers, average dynamic resistance is decreased drastically from 14Ω to 7Ω and threshold current density also reduced from 1705A/cm² to 1383A/cm². Improvement in laser performance is result of reduced loss from optimized fabrication processes. BRL bow-tie tapered lasers is then fabricated for the first time and output power of 18mW at 200mA input is measured. Benefiting from the increased effective area and better carrier utilization, reduction in threshold current density from 1383A/cm² to 712A/cm² is observed.
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Chapter 1

Introduction

Lasers and its wide range of applications have significantly revolutionized modern technologies. The concept of laser dates back almost 60 years to the prominent theory proposed by Schawlow and Townes in 1958 [8]. Developments in various kinds of lasers quickly followed; for example, solid-state ruby laser [9], He-Ne gas laser [10], semiconductor laser [11][12][13][14] and chemical laser [15], to just name a few. Since then, more powerful and compact lasers have been developed and implemented with practical applications that spread across industrial, medical, military and scientific fields.

Semiconductor lasers, in particular, are widely recognized as one of the most important type of lasers thanks in part to its small footprint, low power consumption and compatibility in photonic integrated circuits [1][16]. Its usefulness spans across numerous applications such as medical sensing, CD/DVD, laser machining, targeting, and especially in the area of optical telecommunication.

1.1 Semiconductor Lasers

Semiconductor laser is also commonly referred to as a diode laser, as it consists of p-n junctions formed by semiconductor materials similar to that found in a light-emitted diode (LED). Structurally, an active medium of a narrower band-gap is sandwiched be-
tween a pair of semiconductor claddings with wider band-gap material. Coherent light is generated through radiative recombination of electron-hole pair. During a radiative recombination, photon is released with an energy equal to the bandgap energy of the active medium. Its wavelength, $\lambda$, satisfies the law of energy conservation given by $E_g = h\nu = hc/\lambda$. There are two kinds of radiative recombination, spontaneous and stimulated emission. For spontaneous emission, photons are emitted in random direction. Conversely, for stimulated emission, the emitted photons are initiated by an incoming photon and the emitted photon will match the original photon in both wavelength and phase. Therefore, it is this unique property of stimulated emission which renders the generated light to be coherent and desired for laser operations. Aside from the gain medium, optical feedback is also required (regardless of the laser type) in order to achieve lasing. For diode lasers, optical feedback can be conveniently accomplished by leveraging the cleaved facets to form Fabry-Pérot cavity mirrors.

Since the lasing wavelength is determined by the bandgap energy of the laser, different wavelength spectrum can be achieved by using various direct band-gap material such as AlGaAs, InP, InAs, GaAsP, GaInAs and InPAs. Whereas GaAs lasers typically operate in the vicinity of 0.8-0.9 $\mu$m, quaternary alloy of InGaAsP-InP can be utilized to lase in the range of 1.1-1.6 $\mu$m [17][18][19][20][21]. This particular range of wavelength is of great interest due to their applications in optical fiber communications where fibers exhibit low loss and low dispersion at 1.3 $\mu$m [22] and 1.5 $\mu$m [23].

### 1.1.1 Advantages of Semiconductor Lasers

There are several unique advantages to semiconductor lasers that make them favorable for widespread implementations [1][24][16]. First, it has low fabrication cost as it leverages mature integrated circuits (IC) semiconductor manufacturing to achieve high-yield and high-throughput production. Second, by leveraging the natural Fabry-Pérot cavity formed from the cleaved facets as the optical feedback mechanism, it eliminates time
Figure 1.1: Wavelength operation range for various material composition of semiconductor lasers, with permission to reproduce from [1].

Consuming and fragile mirror alignments and also reduces footprint to achieve super compact design. Third, it can attain different laser wavelengths operation simply by varying the semiconductor compound compositions or changing the semiconductor material of the active layer. Wavelengths ranging from visible to near-infrared (near-IR) could be achieved at room temperature while mid-IR is possible at lower temperatures, as illustrated in Figure 1.1. Finally, and perhaps one of the most important advantage, is the proven potential for monolithic integration either as a stand alone photonic integrated circuit (PIC) or hybrid with IC chip has made it very favorable over other types of lasers.

1.1.2 Applications of Semiconductor Lasers

Diode lasers have diverse applications ranging from consumer products to scientific researches and have profound impacts on our daily life. As mentioned in previous section, semiconductor lasers are capable of operating at room temperature across a broad range of wavelengths. This versatility has allowed it to find its way into mainstream consumer lives in a wide variety of practical applications. For example, laser barcode scanners [25] utilize red diode lasers in the visible spectrum around 650nm. Laser pointers are also
very common laser products with choices of green or red wavelengths. Optical storage also utilizes semiconductor lasers exclusively as light source to read/write inside an optical disk drive, with wavelengths ranging from 785 nm (near-IR) for CD-ROM, to 660 nm (red) for DVD drive, then now 405 nm (violet) in Blu-ray technology [26][27]. The applications of interest for this thesis however, would be more in the near-to mid-IR spectrum.

**Wavelength Converter in Optical Network**

A particular application of interest in the near-IR spectrum lies in the field of optical communication. Compared to its electrical counterpart, optical fiber networks exhibits lower loss, no cross-talk, and improved bandwidth [28]. Early development efforts focused on developing diode lasers operating around 1.55 \( \mu \text{m} \) [23] where it exhibits minimum total optical fiber loss, as evident in Figure 1.2. Subsequent developments in single frequency semiconductor lasers such as distributed feedback laser (DFB) [29], combined with optical amplifier such as Erbium-doped fiber amplifier (EDFA) [30], and dense wavelength division multiplexing (DWDM) [31] led to breakthroughs in optical-fiber telecommunication and enabled modern age high speed and high bandwidth internet.

DWDM is particularly important as it can increase the bandwidths using existing optical-fiber networks by combining multiple channels (signals of different wavelengths) simultaneously into a single optical fiber. An essential component of DWDM is the wavelength-routed network [32], which utilizes wavelength conversion to facilitate transmission of different wavelength signals. Optical frequency conversion is conventionally achieved through the use of electro-optic converters at the end of optical networks. However, switching back and forth between optical and electrical domain is not only costly, but also slower than all-optical network. Alternatively, wavelength conversion can also be accomplished through optical nonlinear frequency mixing such as the four-wave mixing \( \chi^3 \) [33] and three-wave mixing in \( \chi^2 \) [34]. \( \chi^2 \) process has the slight advantage such that
there is no potential crosstalk in the generated output idlers. Therefore, $\chi^2$ is an effective technique towards meeting the requirement of an all-optical network DWDM.

**Trace Gas Sensor**

On the other hand, lasers operating in mid-IR spectrum are extremely useful for gas sensing applications such as pollution monitoring and industrial process control, since the majority of gas molecules of interest occupy in well characterized absorption bands of this region, particularly in the 3 $\mu$m-5 $\mu$m and 8 $\mu$m-12 $\mu$m windows [35][36][37]. Therefore, mid-IR lasers could be effectively utilized to detect and identify gas composition and concentration. A simulation of the vibrationalrotational (V-T) molecular absorption spectra of various gas molecules from 3 $\mu$m to 12 $\mu$m is shown in Figure 1.3. Both quantum cascade lasers (QCLs) and interband cascade lasers (ICLs) have recently been utilized for this purpose [37] and even achieved a detection limit of parts-per-trillion (ppt) [38]. However, such system is only suitable for stationary application due to the tabletop setup requirement. As such, portability is still a challenge that has yet been addressed for this application. A monolithically integrated laser system would then benefit greatly.
Figure 1.3: Simulated mid-IR absorption spectra from 3 to 12 µm [2].

to capture such potential for highly efficient, sensitive and portable gas tracing.

1.2 Brief History of Semiconductor Lasers

The very first demonstrations of semiconductor laser were published by several groups working independently in 1962 [11][13][14]. The papers described a simple homostructure laser comprised of same GaAs material and forward biased p-n junction. The very next year, heterostructure laser was proposed [39], where a semiconductor material of a higher refractive index (and lower band gap) was confined between a different semiconductor material cladding with a lower refractive index (and higher band gap). The active layer (central semiconductor material) provided the optical gain. The difference in bandgap level helped to confine electrons and holes to the active layer, which helped to facilitate recombination. In addition, the refractive index difference helped to confine optical mode close to active layer and significantly reduced internal loss. However, precise lattice matching was required to realize such design. As a result, room temperature operation
was not successfully demonstrated until 1969 [40] with the breakthrough of liquid phase epitaxy (LPE) deposition [41].

Due to excessive overheat, diode lasers operated in pulse mode prior to 1970. Then finally, Alferov et al. [42] and Hayashi et al. [43] demonstrated the first room temperature (300 K), continuous-wave (CW) operation. Since then, interests and developments in semiconductor lasers exploded at an incredible pace. The threshold current density was reduced dramatically by two orders of magnitude in merely a few years, from $J_{th} \approx 4kA/cm^2$ in 1969 [42] to $J_{th} \approx 1.6kA/cm^2$ in 1970 [43] and $J_{th} \approx 0.5kA/cm^2$ in 1975 [44]. The vast improvements were attributed to the breakthrough in thin-film deposition technologies such as molecular beam epitaxy (MBE) and metal-organic chemical vapor deposition (MOCVD), which had enabled uniform, high quality and precise lattice matching of ultra thin films deposition less than 100 nm. More recently, with the introduction of quantum well and quantum dot lasers, threshold current density of $160A/cm^2$ [45] and $19A/cm^2$ [46] have been achieved, respectively. A trend outlining the evolution of threshold current density is shown in Figure 1.4.

In terms of the output power of diode lasers, typical GaAs laser generated less than
50 mW around the 1980s [48][49]. But Scifres et al. [50] was able to significantly improve the CW output power to 585 mW and over 20% power conversion efficiency by using array of phase-locked lasers. The CW output power was then further increased to 1 W by using single quantum well (∼60 Å) with coatings applied on the cleaved mirror facets [51]. In the early 1990s, Sakamoto et al. proposed the monolithic AlGaAs laser diode arrays and demonstrated drastic improvements in output power starting from 3 W [52], to 20 W [53] and even up to 120 W [54] over the course of next few years.

A comprehensive review of the subsequent vast developments in semiconductor lasers would not be practical and is beyond the scope of this thesis. Rather, a brief discussion of a few types of semiconductor lasers that are most relevant to this thesis will be covered in next section instead.

1.3 Types of Semiconductor Lasers

Since the intention of this thesis is to fabrication high power Bragg reflection laser (BRL), the types of semiconductor lasers that will be discussed in this section will be closely related to the intent and/or similarity to our design. Structurally, vertical-cavity surface-emitting laser (VCSEL) bares close resemblance to our design and also utilizes Bragg reflection for mode confinement. Next, distributed feedback (DFB) lasers are commonly utilized to achieve single frequency and single mode output. Finally, ring lasers are of interest due to the potential of high intra-cavity power.

1.3.1 Vertical-cavity Surface-emitting Lasers

Vertical-cavity surface-emitting laser (VCSEL) differs from conventional diode lasers in a sense that light is emitted perpendicular, rather than parallel, to the substrate surface. Hence the name surface-emitting. VCSEL bares close resemblance to our design where the claddings consist of alternating refractive index materials to form Bragg mirrors
and resonates through Bragg reflections. VCSEL was first demonstrated in 1979, which operated at 1.18 \( \mu m \) and had a threshold current density, \( J_{th} \), of \( 11kA/cm^2 \) \cite{55}. Then in 1989, room temperature, continuous-wave (CW) and single mode VCSEL with single mode suppression ratio (SMSR) of 35 dB was demonstrated \cite{56}. More recently, 850 nm VCSEL achieved a \( J_{th} \) of \( 0.5kA/cm^2 \) \cite{57}. In terms of output power, typical VCSEL emits in the low mW range. However, extremely powerful VCSEL can be accomplished in the formation of arrays, where more than 230W was demonstrated \cite{58}. Tuning range in excess of 100nm at 1.55 \( \mu m \) was also shown by Gierl et al. \cite{59}. VCSEL design also has tremendous fabrication process advantages over conventional edge-emitting lasers. Firstly, simplified fabrication process including the removal of cleaving requirements. Secondly, owing to the bottom up nature of thin film deposition process, it would be much easier to fabricate laser arrays using VCSEL design \cite{60}. Lastly, VCSEL improves manufacturability and testability \cite{61}. Whereas conventional FP lasers cannot be tested until lasers are fully fabricated, VCSELs enable inline testing prior to the full completion of laser. Thereby salvaging materials, labor and tool time to reduce manufacturing cost should any defects be detected. Therefore, despite the fact VCSEL being more labor intensive and expensive in materials, but the increase in yield has made it more favorable for the manufacturers.

1.3.2 Distributed Feedback Lasers

Conventional diode laser exhibits multi-mode output because the feedbacks from facet reflections have the same magnitude for all longitudinal modes. Thus, despite the longitudinal mode closest to gain peak have higher intensity, discrimination against a particular mode is poor due to other side modes being present near the gain peak. As a result, the emitted light becomes broadband. One of the solution to improve mode selectivity is through frequency dependent feedback such as distributed feedback (DFB) laser \cite{62}. The feedback mechanism of DFB laser, as the name might imply, is not depen-
dent on the cleaved facets anymore but rather based on periodic diffraction gratings etched into the upper cladding [63]. Bragg scattering induced by the alternating refractive indices provides feedback by coupling the forward and backward propagating waves. Only wavelengths that satisfy the Bragg condition, given by $\Lambda = m \lambda_m / 2$ where $\lambda_m$ is the wavelength inside the medium and $m$ is the mode order, will achieve coherent coupling between counter-propagating waves. Thereby reflecting only narrow bands of wavelengths to achieve single frequency lasing. As such, by choosing the appropriate Bragg diffraction gratings period, specific feedback wavelength can be selected and unwanted side modes are filtered out. For comparison, the spectral width of conventional diode laser at full width at half maximum (FWHM) is typically $\geq 20 \text{ Å}$, whereas DFB lasers can achieve around 1 Å at FWHM with around 1W CW power [64][65]. DFB lasers have also demonstrated wavelength tuning capabilities. Since the temperature has an effect on the refractive index, then one can manipulate the periodicity by varying the temperature and in turn change the lasing wavelength to achieve a tunable diode laser (TDL). Wavelength tunability in DFB laser is extremely useful in applications such as wavelength division multiplexing (WDM) [66], laser spectroscopy [67], and gas sensing [68]. 4 nm tuning range with output power of 20 mW has been demonstrated [69]. Furthermore, tunable DFB laser array (TLA) can be utilized to achieve 40nm tuning range with output power over 20mW [70][71]. Widely tunable DFB laser in the mid-IR range ($\sim 3.1 \mu\text{m}$) with over 80nm tuning range is also possible [72]. DFB lasers can also achieve high conversion efficiency, where 53% wall plug efficiency has been demonstrated [73].

### 1.3.3 Ring Laser

Semiconductor ring lasers (SRLs) have garnered increasing interest since its inception [74] as a contender for single mode laser. The basic structure of a SRL consists of a circular resonator coupled to a output waveguide. Aside from circular ring, other geometries such as racetrack [75], triangular [76] and square [77] have since been proposed. In addition
to geometries, various coupling methods like Y-junctions [78], multi-mode interference (MMI) coupler [79] and evanescent coupler [80] have also been demonstrated. The major benefit of such setup is the elimination of cleaved facets for optical feedback and gratings for single mode operation, thus making them ideal candidate for monolithic integration with other passive photonic devices. Due to its uni-directional bistability [80], SRL can produce bi-directional outputs with a straight output coupler. However, asymmetric feedback from external facets can suppress the unwanted mode to achieve stable uni-directional lasing [81]. Some critical parameters for SRL include ring radius and etch depth, both of which can significantly impact laser performance. In terms of ring radius, a larger radius will have lower bend loss, but the longer cavity length can result in higher total loss. On the other hand, shallower etch depth can increase bending loss but a deeper etch depth may increase scattering loss due to sidewall roughness [80].

1.4 Motivation

Semiconductor lasers have shown tremendous promises as a coherent light source in photonic integrated circuits thanks to its unique advantages. But one of the drawback as shown in previous section lies in its narrow wavelength tuning range. Alternatively, a widely tunable, monolithically integrated laser source could be accomplished through the utilization of nonlinear effects. Recently, our group had catered the Bragg reflection waveguide (BRW) platform to serve such needs. Intra-cavity frequency conversion is now possible by leveraging the $\chi^2$ nonlinear property of AlGaAs. Both the nonlinear processes [82][83][84] and laser characteristics [85] have been demonstrated separately; however, phase-matching between the Bragg and TIR mode proved more challenging than expected and remains to be demonstrated even after multiple iterations of design optimization. Furthermore, there remained fabrication challenges such as precise AlGaAs etch depth control and rough sidewalls that needed to be tackled to enhance device
performances. The main focus of this thesis will tackle the latter challenge from the fabrication perspective.

Thanks to the hard work of previous group members, an existing process flow is available within our group. However, fabrication complications such as evolving capabilities of Toronto Nanofabrication Center (TNFC), ongoing effort to improve laser fabrication quality, and the challenges in fabrication of DFB lasers motivated the work behind this thesis.

TNFC was originally established around 20 years ago as Nortel Institute for Telecommunications. It had come a long way since then and significantly expanded in terms of both capabilities and cleanroom spaces. An example of the most recent addition to the facility includes an Angstrom NEXDEP evaporator, which is capable of both e-beam and thermal evaporated deposition. This allowed us to develop an inhouse metal contact deposition recipe rather than outsourcing it to Sherbrook University as we had done before, which was both time consuming and costly. In addition, a new Oxford Cobra RIE tool was installed since February of this year. However, at the same time with new tool installations, some older tools inevitably suffer from machine failures, resulting in down times and even decommissions. Due to these complications, several fabrication process recipes had to be re-developed based on current TNFC offerings.

In addition, there was also an ongoing effort to continuously improve the laser fabrication quality. Opportunities for improvement are evident from Figure 1.5, which is an SEM cross-section of previously fabricated laser sample where the sidewall profile was quite rough. Thus, inducing nonideal scattering loss and reducing output power.

Lastly, DFB and ring lasers had been attempted in order to increase the laser power output. But unfortunately, previous attempts were not very successful due to fabrication complications. For DFB laser, the design of laterally corrugated surface gratings rendered AlGaAs etching very difficult due to the small surface area opening between the corrugated surface. Therefore, the original AlGaAs etching recipe that was developed
for straight FP laser was inadequate and resulted in differential etching. This problem is illustrated in Figure 1.6 (a), where the bottom 30% of the laser is tapered. Such nonideality resulted in the multi-moded output as shown in Figure 1.7. On the other hand, ring laser suffered from severe device damages as shown in Figure 1.6 (b).

In summary, complications in the currently established fabrication process lends itself to the goal of this thesis, which is to develop and optimize a set of robust laser fabrication process using available in-house facilities to demonstrate electrically injected, CW, and room temperature BRL.

1.5 Thesis Overview

The main focus of this thesis will be on the fabrication of AlGaAs based BRL and DFB lasers, with an ultimate goal to produce a self-pumped, on-chip source suitable for integrated photonic applications. The lasers will make use of nonlinear property such as second harmonic generation (SHG) to generate 1.55 µm output suitable for telecommunication application, that is otherwise not possible with AlGaAs based design. This thesis is divided into the following sections: Chapter 2 will be split into two parts: device and fabrication. Background relating to BRW and BRL will first be covered, then knowledge regarding common fabrication techniques will be introduced. Chapter 3 will
Figure 1.6: (a) SEM of the latest attempt on fabricating DFB laser. Due to differential etching from the small surface opening, current recipe for AlGaAs RIE is insufficient to produce a straight etch profile. (b) Poor quality of fabricated ring laser due to buffered oxide etch (BOE) attacking the oxide used during planarization, resulting in severe cracks and damages. With permission to reproduce from [4].

Figure 1.7: Output spectra of the previously fabricated DFB laser showing the undesired multi-mode characteristic, with permission to reproduce from [4].
then entail the fabrication process developments in the area of electron beam (e-beam) lithography, dry etch and metal contact evaporations in order to successfully fabricate the desired laser devices. Chapter 4 will focus on the characterization of FP diode lasers in terms of its electrical, optical and thermal performances. Finally, summary and future directions will be discussed in Chapter 5.
Chapter 2

Background

Bragg reflection waveguide (BRW) [86] provides a promising platform for monolithic integration of nonlinear processes with active laser by utilizing the $\chi^2$ nonlinear property of AlGaAs. Benefits such as wide wavelength tunability, portability and low power consumption makes Bragg reflection laser (BRL) an ideal candidate as portable trace gas sensor in laser spectroscopy or as frequency converter for DWDM in optical communication. This chapter will first half discuss backgrounds related to BRW, its use as diode laser and current performances, follow by introduction of the major techniques utilized during our semiconductor laser fabrications.

2.1 Bragg Reflection Waveguide Platform

2.1.1 Bragg Reflection Waveguide

BRW consists of an active core layer sandwiched between claddings that are comprised of transverse Bragg reflectors (TBR). TBRs are alternative layers of $Al_xGa_{x-1}As$ grown by metal organic chemical vapor deposition (MOCVD) with different Al concentration, $x$. Due to the Bragg stacks in the claddings, BRW looks very similar to VCSEL structurally. However, BRW is not surface-emitting like VCSEL, but rather pertains the edge-emitting
nature of conventional diode lasers. Distributed reflections from the Bragg mirrors confine the light propagation within the core layer and travels in the orthogonal direction to the Bragg stack. Such propagation is called Bragg mode and differs from conventional total internal reflection (TIR). A typical BRW structure is illustrated in Figure 2.1 [86].

BRW is essentially an one-dimensional (1D) photonic crystal where the dispersion behavior, hence mode profile, can be tailored through the design of TBR. A set of matching layers could also be added at the interfaces between core and TBR to relax the constraint on the core layer thickness. Thereby, providing additional freedom in terms of dispersion and nonlinear properties tailoring. In addition, the thicknesses of TBR layers can be designed precisely a quarter wavelength of the desired guided mode. This is known as the quarter-wave BRW (QtW-BRW) condition, and is a special case where the optical confinement in the core is maximized by placing the guided mode in the center of stop band through the constraints imposed by the quarter wavelength condition. The thickness of the TBR can then be calculated by [87]
Chapter 2. Background

Figure 2.2: $\chi^2$ three-wave mixing.

\[ \frac{d_{h(l)}}{\sqrt{n_{h(l)}^2 - n_{eff}^2}} = \frac{\lambda}{4} \]  
(2.1)

where $d$ and $n$ are the thickness and refractive index, respectively. $\lambda$ is the wavelength of the Bragg mode and the effective refractive index, $n_{eff}$, of the guided mode is given by [88]

\[ n_{eff} = \sqrt{n_c^2 - [(2m - 1)\lambda/2d_c]^2}, \quad (m = 1, 2, 3...) \]  
(2.2)

where $m$ is the mode order. The key property which enables BRW for frequency conversion is through three-wave mixing of second-order nonlinearity process, $\chi^2$, as illustrated in Figure 2.2. We are particularly interested in the difference frequency generation (DFG) process as it enables applications such as wavelength conversion and wide wavelength tuning. In DFG process, two light sources, namely pump and signal, are injected into the nonlinear medium and an output idler is generated. The frequency of the generated idler will be the difference between signal and pump according to the governing interaction. The design utilized for this thesis is a type-II DFG where the 775nm pump propagates in Bragg mode while the 1550nm signal and idler are in TE TIR mode and TM TIR mode, respectively.

Nonlinear process must satisfy the energy conservation and phase matching condition
in order to facilitate effective interactions. For energy conservation:

\[ E_p = E_s + E_i \]  \hspace{1cm} (2.3)

\[ \hbar \omega_p = \hbar \omega_s + \hbar \omega_i \]  \hspace{1cm} (2.4)

\[ \omega_p = \omega_s + \omega_i \]  \hspace{1cm} (2.5)

where \( E_{p,s,i} \) and \( \omega_{p,s,i} \) are the energy and frequency of pump, signal and idler, respectively. As for phase matching condition:

\[ k_p = k_s + k_i \]  \hspace{1cm} (2.6)

where \( k_{p,s,i} \) are the propagation constants of pump, signal and idler. Several phase matching techniques are available for phase matching III-V compounds, but not all are suitable. For example, in conventional birefringence phase matching (BPM) scheme, one can inject light with different polarizations to achieve phase matching. This is because anisotropic material experiences change in refractive index that depends on the polarization and propagation direction of light. Which in turn creates a difference between ordinary and extraordinary refractive index. However, due to the isotropic nature of AlGaAs, conventional BPM is not possible, but rather form birefringence phase matching has to be utilized, which requires breaking the core AlGaAs active layer with additional \( Al_2O_3 \) layers [89]. Unfortunately, the inclusion of such oxide layer is not compatible in achieving our goal of electrically injected nonlinear laser.

An alternative scheme which can provide the necessary phase matching is quasi-phase matching (QPM) [90]. QPM is not a complete phase matching method, but rather allows some phase mismatch over small propagation distance and then reverse it. This is accom-
plished by periodically modulating the nonlinear susceptibility. However, even though high nonlinear conversion could be achieved, large losses and fabrication complexity limits its application in III-V system.

Finally, modal phase matching (MPM) [91] can achieve phase matching by utilizing higher order mode which has lower refractive index. Such scheme could be exploited to our advantage since Bragg mode has lower effective refractive index than its fundamental TIR mode counterpart. Therefore, through careful design considerations, our group proposed the exact MPM of the Bragg mode with TIR mode to achieve efficient nonlinear conversion [86]. Subsequently, nonlinear frequency conversion applications such as sum frequency generation (SFG) [83], second harmonic generation (SHG) [82] and difference frequency generation (DFG) [84] have been successfully demonstrated. Parametric process, such as DFG, can be utilized to generate coherent light in mid-IR regimes [92]. Several advantages of BRW include large modal volumes [93][94], high gain coefficient [95] and strong mode discrimination [96][97]. Not to mention the possibility of monolithic integration with diode laser for unique and interesting applications such as electrically injected, self-pump DFG laser in near-IR and mid-IR spectrum.

2.1.2 Bragg Reflection Lasers

BRL is essentially an electrically injected BRW light source, but with quantum wells inserted inside the core to provide gain for the laser. Both the double-sided [85], and single-sided [98] arrangements have been proposed. Aside from all the aforementioned advantages of BRW from last section, BRL also has a much more relaxed constraint for core thickness without comprising the strong modal gain and single mode operation compared to conventional QW laser. For conventional QW lasers, optical confinement factor (OCF) decreases with increasing core thickness, thereby reducing modal gain. However, this is not an issue for BRL, thereby loosening the constraint on the core thickness.
A schematic of BRL is illustrated in Figure 2.3. With a very similar structure to BRW, BRL consists of a low index core with refractive index $n_c$ and thickness $d_c$. TBRs are comprised of alternating concentration of $Al_xGa_{x-1}As$ with different refractive indices $n_l$ and $n_h$ and thicknesses $d_l$ and $d_h$, respectively. The lowest refractive index material in the entire system is the core, where $n_c < n_l < n_h$, to ensure operation in Bragg mode. The output power of the diode laser at injected current $I$, $P_{out}(I)$, is given by [3]:

$$P_{out}(I) = (I - I_{th}) \cdot \eta_d \cdot \frac{hc}{\lambda_p} \cdot e^{(2.7)}$$

where $I_{th}$ is the threshold current and $\eta_d$ is the differential efficiency, or external quantum efficiency. $\eta_d$ is related to the internal quantum efficiency, $\eta_i$, by

$$\eta_d = \eta_i \cdot \frac{\alpha_m}{g_{th}} \quad (2.8)$$

where $\alpha_m$ is the mirror loss and $g_{th}$ is the threshold gain. Since $I = J \cdot L \cdot W$, Eq. (2.7) can be further modified to

$$P_{out}(J) = \frac{LW \cdot \eta_i}{\lambda_p} (J - J_{th}) \cdot \frac{hc}{e} \cdot \frac{\alpha_m}{g_{th}} \quad (2.9)$$
finally, gain equals loss at threshold, so $g_{th} = \alpha_p L + \alpha_m$, where $\alpha_p$ is the propagation loss. So Eq. (2.9) becomes:

$$P_{out}(J) = \frac{LW \cdot \eta_i}{\lambda_p} (J - J_{th}) \cdot \frac{hc}{e} \cdot \frac{\alpha_m}{\alpha_m + \alpha_p L}$$  \hspace{1cm} (2.10)

Temperature dependency had also been characterized and is shown in Figure 2.4. As can be seen, increasing temperature results in lower output power and higher threshold current.

As early as 2009, our group had demonstrated proof of concept on the feasibility of BRL. Figure 2.5 (a) shows the LI performance where current threshold density as low as $157 \text{ A/cm}^2$ was achieved. In addition, Bragg mode operation was verified through near-field profile as shown in Figure 2.5 (b). However, despite the low threshold current density achieved for this type of laser, phase matching between Bragg and TIR modes proved quite challenging and was unsuccessful. More recently, parametric fluorescence [99] and self-pumped SPDC [100] have been reported. However, the reported laser in [100] not only suffered high threshold current density of $3.3 \text{kA/cm}^2$ but only pulse mode operation was demonstrated.
Figure 2.5: (a) LI curve for BRL at 500 $\text{mum}$ (solid line), 580 $\text{mum}$ (dashed red line) and 970 $\text{mum}$ (dashed blue line) cavity lengths. (b) Simulated vs. measured (just above threshold and 50x threshold) near-field (NF) profile of the Bragg mode. With permission to reproduce from [3].

As a result, nonlinear properties in BRL was only demonstrated recently as shown by the generated idler in Figure 2.6 (a). Yet, there was still discrepancy between design simulation and actual device performance. For instance, in order to achieve phase matching, external optical pump had to be used instead of the desired self-pump design. Figure 2.6 (b) illustrates the generated idler power against external optical pump wavelength. External pump had to be used because electrically injected BRL pump was lasing at around 790nm as shown in Figure 2.6 (c) instead. Furthermore, phase matching degeneracy point of the actual vs. simulated performance also differed by quite a bit. According to simulation from Figure 2.6 (d), the degeneracy point was designed to be 775nm such that an idler at 1550nm would be generated. However, the degeneracy point based on measured DFG tuning curve shown in Figure 2.6 (d) can be extrapolated to be around 825nm instead. This was mainly attributed to uncertainty and lack of accurate modeling in the indium and aluminum concentrations in the quantum wells. A new design had been submitted based on this most recent learning and a new wafer stack had been grown in hopes to successfully demonstrate truly electrically injected, self-pumped, and continuous-wave DFG laser.

In addition to design optimization, robust and high quality fabrication process is
Figure 2.6: (a) Demonstrated DFG using BRL with the generated idler peak at 1725 nm. (b) External optical pump at 816.5 nm. (c) Normalized optical spectrum of BRL with 40mA (black solid line) and 100mA (dashed blue line) current injection. (d) Simulated DFG tuning curve of the designed BRL. (e) Measured DFG tuning curve. With permission to reproduce from [4].
crucial to achieving high power BRL. This is clearly evident from the simulation shown in Figure 2.7, where the Bragg mode loss modulates according to etch depth. Mode loss increase drastically with a sharp slope outside the 200 nm process window between 2 $\mu$m to 2.2 $\mu$m. Since our design does not include any etch stop layer, ensuring precise control of AlGaAs etching within low loss window is crucial to the laser performance.

![Figure 2.7](image)

Figure 2.7: Bragg mode loss varies with AlGaAs etch depth, with permission to reproduce from [4].

Furthermore, a problem typically associated with any FP laser is the degradation...
of single mode operation with increasing current, as shown in Figure 2.8. As can be observed, BRL becomes increasingly multi-moded as current is increased beyond 85mA. Such phenomenon then limits the maximum current injection, which results in weaker laser. Hence the usefulness of single mode DFB lasers.

2.2 Fabrication Techniques

2.2.1 E-beam Lithography

Lithography is essentially a method of printing on a flat surface. It was originally used to pattern on limestone hundreds of years ago, but more recently it had been widely adopted for the semiconductor industry. An obvious difference between the two applications is the feature dimensions, where micro- or nano-scales are required in modern semiconductor manufacturing. Several lithography techniques such as photolithography [102], nanoimprint [103], electron beam (e-beam) lithography [104], just to name a few, are capable of patterning with such precision. E-beam lithography is of particular interest not only because of its superior resolution, but also for its direct-write capability. By scanning and guiding a highly focused electron beam, it can create arbitrary pattern without the need of a mask. However, due to its nature of scanning exposure rather than flood exposure (as in photolithography), it suffers from the issue of low throughput. Nevertheless, it’s a great technique for prototyping and research environment where flexibility and high resolutions are favored over speed. Some key considerations of e-beam lithography include choice of resist and the associated developer solutions, electron beam energy, current and dose, and also development time and temperature.

E-beam lithography consists of steps shown in Figure 2.9. First, an electron-sensitive polymer layer (e-beam resist) is spin coated onto the substrate. Things to take into consideration during spin coating of resist include spin speed (in rotations per minute, RPM), spin time and acceleration. Higher spin speed results in thinner resist whereas
Figure 2.9: Steps of e-beam lithography.

lower spin speed results in thicker resist. Subsequently, the resist is exposed and then developed.

During exposure, an electron beam, generated by thermal field emission gun inside an electron column, is scanned across the resist. It is focused and guided by a series of electromagnetic lenses and electrostatic deflector within the column as shown in Figure 2.10. Writing of the patterns is accomplished by essentially changing the solubility of the exposed resist. Depending on the type of resists (positive or negative), the physicochemical changes resulting from the inelastic collisions between electrons and resist will either soften or harden the resist. For positive e-beam resist, the scission of long polymer chains breaks it into smaller fragments, making the exposed area more soluble in developer solution [105]. Inversely, for negative e-beam resist, cross-linking of smaller polymers when exposed makes it less soluble in developer solvent [106]. As electrons enter the resist, forward scattering from low energy elastic collisions could broaden the beam slightly. More importantly, proximity effect [107][108] caused by backward scattering from large angle collisions of electrons that penetrated deeply into the substrate could result in over-exposure and pattern distortion. However, this can be minimized by applying proximity effect correction (PEC), which is an algorithm correction to account for such undesired effect.

After exposure, the resist is developed by immersing in a developer solvent to remove the exposed portion of positive resist, or non-exposed portion of negative resist. The developer essentially penetrates and surrounds resist fragments to form a gel-like layer
around it. The fragments then detach from the rest of resist once fully surrounded and
diffuse into the solvent. As such, the longer the development time, the more fragments
will be removed. Excessively long development could then result in smaller dimensions
than desired. Aside from time, temperature during development is also an important
factor for consideration. Colder temperature could limit the development of those resist
partially exposed by scattered electrons, since they would not have enough energy and
would be frozen instead. Therefore, resolution could be enhanced for positive tone resists.
Table 2.1 summarizes the important parameters of e-beam lithography and its impacts
on process [109].

Some commonly available positive tone e-beam resists include polymethyl methacrylate (PMMA) [105] and ZEP [110]. On the other hand, hydrogen silsesquioxane (HSQ) [106] and ma-N [111] are some of the most popular negative tone resists. The resists utilized in this thesis are ZEP-520A and a bi-layer MMA/PMMA. ZEP-520A is chosen to define the ridges and opening of via for its high resolution and dry etch resistance. Meanwhile MMA/PMMA is chosen to create the under-cut profile desired for lift-off to
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Process Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exposure energy</td>
<td>Resolution, sensitivity, proximity</td>
</tr>
<tr>
<td>Exposure dose</td>
<td>Pattern quality</td>
</tr>
<tr>
<td>Pattern density</td>
<td>Proximity, pattern quality</td>
</tr>
<tr>
<td>Resist material</td>
<td>Sensitivity, resolution, contrast</td>
</tr>
<tr>
<td>Resist thickness</td>
<td>Sensitivity, resolution, pattern quality</td>
</tr>
<tr>
<td>Developer</td>
<td>Sensitivity, resolution, development window</td>
</tr>
<tr>
<td>Development temp.</td>
<td>Sensitivity, resolution, exposure window</td>
</tr>
<tr>
<td>Development time</td>
<td>Sensitivity, resolution, exposure window</td>
</tr>
</tbody>
</table>

Table 2.1: Process parameters of e-beam lithography and its effect on process.

define the metal contacts.

2.2.2 Reactive Ion Etching

Etching refers to the removal of materials from the sample surface. It can be categorized into two distinct types, namely wet [112] and dry etching [113]. Wet etching uses chemical solution suitable for eroding materials of interest. For example, hydrofluoric (HF) acid is a typical solution for removing silicon dioxide (SiO2). In particular, a diluted HF solution commonly referred to as buffered oxide etch (BOE), is used to remove native or thin layers of oxide. The chemical reaction is given by:

\[
SiO_2 + 6HF \rightarrow H_2 + SiF_6 + 2H_2O
\]  \hspace{1cm} (2.11)

The advantages of this type of etching lies in its simplicity, cheap cost and high selectivity. However, wet etching results in an isotropic etch, whereby the etch expands in all direction as shown in Figure 2.11 (a). Such phenomenon is not favorable where directionality is desired. On the other hand, dry etching can be optimized to provide anisotropic etch with a typical profile illustrated in Figure 2.11 (b). As the name implies, dry etching does not involve wet chemical solution, but rather relies on the reaction of etchant gases, or the physical bombardments of ions, with the substrate materials to be removed.
Dry etching can then be further categorized into physical (low pressure, high energy), chemical (high pressure, low energy) or hybrid. Whereas physical etching utilizes highly energetic ion bombardments, typically Ar, to physically mill away the desired material \cite{114}, chemical etching uses chemically reactive etchant gas to react and form volatile by-products with target materials to be removed \cite{115}. There are trade-offs between the two methods. While physical etching provides anisotropic etch with high directionality, it suffers from low selectivity and significant surface damages due to its physical nature. On the other hand, chemical etching has a higher selectivity and minimal surface damage, but has an isotropic etch profile similar to wet etching. Then comes the hybrid method, which strikes a fine balance between both worlds to achieve anisotropic etching with high etch rate and selectivity, while also minimizing surface damage. Such method is called reactive ion etching (RIE) \cite{116}.

A typical RIE chamber is shown in Figure 2.12 (a). An important component of RIE is the plasma chamber. Plasma is essentially a neutral gas comprised of ions, free electrons, radicals and other neutral species. It is generated by applying industry standard radio frequency (RF) electromagnetic field (13.56 MHz) to the bottom electrode while the top electrode acts as ground. Electrons react to the alternating electric field and oscillate between the top and bottom electrode while the heavier ions remain more or less stationary in such a rapidly changing electric field. Collisions between electrons and the
inflowing etchant gas create reactive species such as radicals and positive ions. Positive radical ions then strike the sample substrate due to the build up of negative charges at the base plate, or so called self-bias voltage, $V_b$. Chemical reactions from the diffusion and absorption of the ionized radicals onto sample substrate surface form volatile byproducts, which is subsequently desorbed and removed from the chamber by vacuum pump. Energetic ions bombardments, on the other hand, helps with enhancing the absorption of radicals onto the surface and also dissociation of volatile products [117]. Increasing the RF power results in higher energy collision and thus, higher etch rate. However, a drawback with capacitive RIE system, such as the one just described, is the surface damage induced by high RF power. Alternatively, plasma could be generated remotely with inductively coupled plasma (ICP)-RIE as illustrated in Figure 2.12 (b). In this case, an additional ICP RF power is applied to circular coil to generate a varying magnetic field. This then induces electric field that contains the generated plasma within the vicinity of the coils and away from the table where samples are located. Such design can provide separate controls for the ion flux and incident ion energies, thereby generating higher density plasma (higher etch rate) at lower ion energies (reducing surface damage).
Plasma density could be as much as three orders of magnitude higher than conventional RIE system [117]. As a result, ICP-RIE can achieve superior etch performance with high etch rate and selectivity.

Obviously, composition of the etchant gas is an important consideration of the RIE process since the ionized molecules have to react efficiently with the materials desired to be etched. Thus, different compositions are required for etching of different materials. In this work, both SiO2 and AlGaAs will be etched using ICP-RIE system. As such, more details regarding the etching mechanisms, particularly the gas chemistry compositions, will be discussed in following sections.

**Oxide RIE**

Fluorocarbon gases such as CF4, CHF3 or C4F8 are typically used for oxide RIE. Chemically reactive carbon ions bond with oxygen while fluorine ions bond with silicon to form by-products such as CO, CO2 and SiF4. In the case of CHF3, hydrogen atoms also react with fluorine to form stable HF gas. The fluorine to carbon (F/C) ratio plays important role in SiO2 etching, where higher F/C ratio results in higher SiO2 etch yield [118]. However, it is known that the use of fluorocarbon gases will also introduce polymer formation, which could be redeposited back onto the sample and chamber walls to create problems such as contaminations and inconsistencies. To suppress polymer formation, common additives such as O2 could be utilized as it combine with carbon ions to increase F/C ratio. Alternatively, Ar could also be added to reduce polymer formation. Since it’s inert, it does not change the chemistry of the plasma. But unfortunately, both will result in an increase in resist removal rate, hence lower selectivity.

**AlGaAs RIE**

The most commonly used gas mixture to etch AlGaAs is chlorine-based chemistries such as Cl2, BCl3, HCl and SiCl4 [119][117]. Chlorine ions form volatile reaction with most III-
V materials, including AlGaAs. Some examples of the volatile by-products formed include GaCl3, GaCl, AlCl3 and AsCl3 [120]. Yet, pure Cl2-based plasma often faces difficulty breaking through the thin native oxide formed by the exposed GaAs/AlGaAs surface. This problem is exacerbated particularly for high Al concentration layers. Hence, BCl3 is often used in conjunction with Cl2 to breakthrough the thin oxide layer. Furthermore, since BCl3 getters water vapor, it minimizes oxidation of AlGaAs to achieve equi-rate etching of GaAs and AlGaAs [121]. Similar to oxide RIE, inert gases such as Ar are also frequently used to enhance etch rate and desorption of volatile by-products [117]. Lastly, non-volatile chloride layer, such as GaCl3, forms on the sidewall which minimizes lateral etching to achieve a straight profile.

2.2.3 Thin-film Deposition

Thin-film deposition is the exact opposite process of etching. It adds layer(s) of material(s) rather than remove them. It can also be separated into two general categories similar to the mechanisms discussed in previous section, namely, chemical and physical deposition. Chemical vapor deposition (CVD) relies on the chemical reaction between the inflowing gas and substrate material whereas physical vapor deposition (PVD) involves vaporizing a solid source (target), whereby the evaporated atoms (or molecules) will condensate onto the sample substrate surface. There are numerous variations of both CVD and PVD, and it would not be feasible to review all of them. As such, the two variations that are related to this work, plasma-enchanced chemical vapor deposition (PECVD) and electron beam evaporation, will be discussed in more details.

Plasma-enhanced Chemical Vapor Deposition

Conventional CVD requires very high temperature to thermally activate the required chemical reaction to deposit SiO2, typically in excess over 1000°C. On the other hand, PECVD uses plasma to provide the necessary energy for chemical reaction, thereby
Chapter 2. Background

significantly reducing the deposition temperature to less than $400^\circ$ [122]. This is due to the acceleration of ions towards sample substrate surface by the plasma as discussed in previous section. A schematic illustrating the chamber of PECVD is shown in Figure 2.13 (a). To further understand the process of CVD, Figure 2.13 (b) illustrates the sequence of chemical reactions [123]. Inflowing gas precursors are first diffused through the boundary layer to the substrate interface and absorbed to the surface. Chemical reaction then occur on the surface of substrate material. By products are then desorbed and diffused back to the main flow region and eventually pumped away. Choice of precursor is thus very important. SiO2 is of particular interest in this work, and the chemical reaction of SiO2 is shown below [124].

$$SiH_4 + 2N_2O \rightarrow SiO_2 + 2N_2 + 2H_2$$

(2.12)

E-beam Evaporation

Evaporation is a type of PVD technique for thin film deposition. Materials to be deposited are vaporized, either through sublimation or evaporation, by heating it up to
Figure 2.14: Schematic of e-beam evaporator chamber, with permission to reproduce from [125].

high temperature. Evaporated gas particles then traverse through the chamber to condense on sample substrate. The system is pumped to high vacuum with pressure on the order of $10^{-6} \sim 10^{-7}$ to minimize contaminations. Furthermore, there are two types of evaporations, using either thermal or e-beam sources. For thermal, materials to be deposited are placed in a resistive boat and electrical current is used to heat up the boat and whatever is inside it. The main concern with thermal evaporation is contaminations because the boat container material will evaporate along with the source placed inside it. Furthermore, it only works for metals and other low melt-point materials. On the other hand, e-beam evaporation uses electron beam to heat up materials situated inside a crucible. A schematic illustration of e-beam evaporation is shown in Figure 2.14. Electrons are generated from an e-beam column underneath the crucible, then guided around in a 270° turn using magnetic field to bombard and heat up the material inside the crucible. A rotating water-cooled hearth hosts up to a maximum of 4 crucibles, so that up to 4 different metals can be deposited sequentially. Contamination for e-beam evaporation is much reduced compared to thermal evaporation and it can deposit both metal and
dielectric. As such, e-beam evaporation is chosen to deposit the necessary metal contact stacks.
Chapter 3

BRL Fabrication Process Development

Thanks to the mature microelectronics industry, fabrication processes used to make semiconductor lasers had been available for quite some times. Many tools and recipes can be leveraged with modifications catered for III-V compounds. Similarly, the processes used in this work are of typical industry practice and all fabrications were carried out using facilities hosted by TNFC. However, extensive development efforts were required to optimize a robust process flow for the reasons articulated earlier in this thesis. New e-beam lithography and oxide RIE recipe were thus developed. Furthermore, a robust e-beam evaporated metal contact deposition for GaAs laser was not available at University of Toronto when I began my graduate study. Therefore, one of my main task was to establish a reliable metal evaporation recipe with high yield. These process developments were also necessary to enable a better performance diode laser and functional ring and DFB lasers. This chapter will first present an overview of laser fabrication process flow, followed by the process development of each new recipe and its associated challenges. A full step-by-step fabrication flow with recipe details is also enclosed in Appendix A.
3.1 Laser Fabrication Process Flow

In general, laser fabrication can be broken into 3 major stages depicted in Figure 3.1. Stage 1 essentially forms the passive device by defining the ridge, while the next 2 steps are for making active (laser) devices. Each stage is actually comprised of many more steps as illustrated in Figure 3.2. Due to the multiple lithography and etching steps involved, the entire process could take up to two weeks, provided that there are no additional complications such as tool downs.

During stage 1, an oxide thin film is deposited via PECVD, which will later be used as hard mask for AlGaAs etching. Waveguide ridge pattern is then defined through e-beam lithography. The pattern is then transferred to the oxide layer using a CHF3-based oxide RIE process. Resist is then stripped and de-scummed via oxygen ashing. Finally, a chlorine-based AlGaAs RIE (mixture of Cl2/BCl3/Ar) is utilized to define the ridge etch depth.

Subsequently in stage 2, electrical isolation is desired to prevent unintended current leakage path. The high quality and conformal coverage of PECVD oxide makes it a great candidate for such a task. A via is then defined on top of the ridge through another set of e-beam lithography and oxide RIE to allow current injection through the entire wafer stack.
Figure 3.2: Schematic illustration of detailed process flow for each stage.
Finally in stage 3, the p-contact window is defined again with e-beam lithography using lift-off technique. P-contact metal consists of e-beam evaporated Ti/Au, where the Ti helps with adhesion of Au. After lift-off, back-side polishing of the sample thins the total sample thickness to around 150 µm. This step is necessary to facilitate cleaving of shorter laser bars, as from experience the minimal length of cleaving is roughly 3x the sample thickness. N-contact, which is comprised of Au/Ge/Ni/Au, is then deposited on the polished back side again via e-beam evaporator. Finally, the sample is ready for characterization after cleaving into 0.5mm wide laser bars.

3.2 New Electron Beam Lithography Resists

E-beam lithography is carried out using Vistec EBPG 5000+ as shown in Figure 3.3. It is capable of high resolution patterning down to 10nm with a stitching and overlay accuracy of 20nm [6]. Layout to be patterned is first designed in GDSII (graphic data system) file format using KLayout Editor. This can also be accomplished with any other standard layout design software. It is then fractured and converted to GPF file format using GenISys BEAMER. Specifications such as exposure fields and resolution are fed into the EBPG system. Proximity effect correction (PEC) is also incorporated to correct for the electron scattering effect mentioned previously.

In order to strike a fine balance between minimizing sidewall roughness and optimizing write time, the exposure is separated into sleeve and bulk sections as illustrated in Figure 3.4. The sleeve regions are for critical patterns such as waveguide definitions. As such, a combination of higher resolution and lower dose is used. On the other hand, bulk regions are for non-critical patterns that are further away from the waveguides. Therefore, lower resolution and higher dose are utilized for faster throughput.

As evident from the process flow, multiple lithography steps are required. But despite serving the same purpose of patterning, they actually have very different requirements.
Figure 3.3: Vistec EBPG 5000+ hosted in the basement of Wallberg building of University of Toronto [6].

Figure 3.4: Bulk and sleeve layers are utilized to minimize sidewall roughness. (a) Pattern is separated into bulk (red) and sleeve (green) layers. (b) An overlap of 200nm between bulk and sleeve is used to ensure sufficient no stitching issues.
The resist in stage 1 and 2 needs to withhold subsequent dry etching to preserve the integrity of protected oxide. Conversely, resist in stage 3 is meant for lift-off of the metal deposited on top of it. Therefore, two different positive tone e-beam resists, ZEP-520A and PMMA/MMA, are utilized to fulfill their respective roles. ZEP-520A is used in stage 1 and 2 for its high resolution and resilience to oxide RIE. Meanwhile, a bi-layer PMMA/MMA is used to create under-cut profile to facilitate easier lift-off process, which is something quite difficult to achieve with conventional positive resist. In addition, PMMA has a poor resistance to dry etching, therefore it’s not an ideal candidate for defining the ridges. Resists are spun via spinner located inside a VPFX-6 wetbench as shown in Figure 3.5. Process details for each type of resist will be discussed in more details in next sections.

3.2.1 ZEP-520A

A thicker resist is desired when defining the ridge to ensure sufficient process margin during subsequent oxide RIE. Figure 3.6 depicts the relationship between rotation speed
Chapter 3. BRL Fabrication Process Development

Figure 3.6: Figure of ZEP520A resist spin speed vs. thickness.

<table>
<thead>
<tr>
<th>Spin Speed</th>
<th>Spin Time</th>
<th>Acceleration</th>
<th>Pre-bake Time</th>
<th>Pre-bake Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000 RPM</td>
<td>1 min</td>
<td>584</td>
<td>3 mins</td>
<td>180°C</td>
</tr>
</tbody>
</table>

Table 3.1: Spinning parameters for ZEP520A

and resist thickness for ZEP-520A [126]. A rotation speed of 2000 RPM was chosen to obtain 500nm thick resist. Sample cleaning prior to spin coating helps to improve resist adhesion. So the sample is rinsed with acetone and IPA and followed by a quick sonic clean for 1 minute. It is then blow dried with nitrogen gun and baked at 180°C to de-moisturize. Table 3.1 details of the critical spin coating parameters. Baking the resist at 180°C evaporates any potential moisture trapped inside the resist.

An initial dose test was performed in the quest to identify optimal dose for ZEP-520A. A range of dose was systematically swept from 120µC to 150 µC and the results are shown

<table>
<thead>
<tr>
<th>Exposure Dose</th>
<th>Beam Current</th>
<th>Fracture Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sleeve</td>
<td>180 uC</td>
<td>1 nA</td>
</tr>
<tr>
<td>Bulk</td>
<td>230 uC</td>
<td>10 nA</td>
</tr>
</tbody>
</table>

Table 3.2: E-beam lithography exposure parameters for ZEP-520A
in Figure 3.7. The light green and blue strips near the sidewalls are residues from under-exposure for doses below 140\(\mu\)C. In fact, even 150\(\mu\)C still had tiny traces of residue near the sidewalls if examined carefully. Therefore, a 2\textsuperscript{nd} dose test was performed from 160\(\mu\)C to 190\(\mu\)C and the SEM cross-sections are captured in Figure 3.8. All 4 conditions provided adequate results with similar width, straight sidewall profile and no residue. The final process condition of 180\(\mu\)C was chosen to give the process enough margins such that there won’t be residue due to under-exposure but also won’t significantly change the waveguide width due to over-exposure in the event of slight dose variations. Critical process parameters are summarized in Table 3.2.

After exposure, the sample is dismounted from the sample holder and developed in a solvent solution to complete the patterning process. Sample is developed in ZED-N50 at \(-5^\circ\)C where the cold temperature development enhances resolution as discussed previously. Then it is rinsed in a 9:1 MIBK:IPA solution for 30 seconds to stop the development. Finally, post-baking the sample at 100\(^\circ\)C for 5 minutes hardens the resist, which will improve selectivity in subsequent oxide etching.

### 3.2.2 PMMA/MMA

Similar protocol is developed for the bi-layer PMMA. First, a layer of MMA is spin coated onto the sample at 5000RPM and baked at 180\(^\circ\)C for 3 minutes. Then the PMMA layer is spin coated on top of MMA with the same condition. Because MMA actually develops faster than PMMA, an under-cut profile can be created as shown in Figure 3.9. Critical parameters for bi-layer PMMA spin coating and exposure are summarized in Table 3.3 and Table 3.4. It is worth noting that the required dose for PMMA at 1200 \(\mu\)C is much higher compared to ZEP-520A. In addition, since the resolution requirement for lift-off is quite lenient, separating into bulk and sleeve is not necessary, so everything is exposed in one setting. Furthermore, a larger current is also utilized for faster throughput. After exposure, sample is developed in 1:3 MIBK:IPA at room temperature and rinsed in IPA.
Figure 3.7: Optical images of the dose test samples ranging from (a) 120\(\mu\)C, to (b) 130\(\mu\)C, to (c) 140\(\mu\)C and (d) 150\(\mu\)C.

Figure 3.8: Dose test from 160 \(\mu\)m to 190 \(\mu\)m.
to stop the development.

![SEM cross-section of the under-cut profile of MMA/PMMA bi-layer](image)

Figure 3.9: SEM cross-section of the under-cut profile of MMA/PMMA bi-layer.

<table>
<thead>
<tr>
<th>Layer 1: MMA</th>
<th>Layer 2: PMMA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spin Speed</td>
<td>Spin Speed</td>
</tr>
<tr>
<td>5000 RPM</td>
<td>5000 RPM</td>
</tr>
<tr>
<td>Spin Time</td>
<td>Spin Time</td>
</tr>
<tr>
<td>1 min</td>
<td>1 min</td>
</tr>
<tr>
<td>Acceleration</td>
<td>Acceleration</td>
</tr>
<tr>
<td>584</td>
<td>584</td>
</tr>
<tr>
<td>Pre-bake Time</td>
<td>Pre-bake Time</td>
</tr>
<tr>
<td>3 mins</td>
<td>3 mins</td>
</tr>
<tr>
<td>Pre-bake Temperature</td>
<td>Pre-bake Temperature</td>
</tr>
<tr>
<td>180°C</td>
<td>180°C</td>
</tr>
</tbody>
</table>

Table 3.3: Spinning parameters for PMMA

<table>
<thead>
<tr>
<th>Exposure Dose</th>
<th>Beam Current</th>
<th>Fracture Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>1200 uC</td>
<td>50 nA</td>
<td>25 nm</td>
</tr>
</tbody>
</table>

Table 3.4: E-beam lithography exposure parameters for PMMA/MMA

### 3.3 Oxide RIE Recipe Developments

Initial work on oxide etch development was carried out using the Oxford PlasmaPro Estrelas 100 DRIE tool. A C4F8-based recipe was developed and the process details is outlined in Table 3.5. GaAs acts as an etch stop layer since fluorine based chemistry does
not form volatile products with it. Drastic improvements in terms of oxide etch quality was immediately evident as shown in comparison between Figure 3.10 (a) and (b). SEM cross-section in Figure 3.10 (a) shows severe resist damages and rough sidewall using the existing oxide etch recipe available within our group. In contrast, Figure 3.10 (b) shows the newly developed C4F8 recipe to have minimal damages and smoother sidewall profile. However, there still remained the issue of scattered redeposition as shown in 3.10 (c), whereby the etched trenches are left with either un-etched residues or redeposition back onto the substrate. This ultimately translates to micro-grass post AlGaAs etch. A temporary solution was to prolong the surface cleaning using buffered oxide etch (BOE). However, excessive BOE cleaning is not the ideal solution and optimization of the oxide etch recipe was deemed necessary to fully resolve this issue.

The gas composition of the RIE etch was revisited in order to optimize for a residue free recipe. SF6 was removed since it is more predominantly used for silicon etch. In order to minimize residue, a small amount of oxygen was added to reduce the amount of carbon available to form polymer films. In addition, the RF power was increased to enhance etch rate. New recipe details is summarized in Table 3.6 and 3.10 (d) shows the improvements with minimized residues. Unfortunately, this was not the final oxide etch recipe because the Estrelas tool had been broken since February 2017. Luckily though, a new RIE tool, Oxford PlasmaPro 100 Cobra, was commissioned shortly after so that our work could still be continued. However, the same C4F8 recipe produced drastically different result shown in Figure 3.11 (a). Extremely severe residues coupled with a positive etch profile shown in Figure 3.11 (b), which is wider than the designed waveguide, suggest significant redepositions. Amount of O2 was increased to 5sccm but situation did not improve. As a result, alternative recipe must be developed.

<table>
<thead>
<tr>
<th>ICP Power</th>
<th>RIE Power</th>
<th>Pressure</th>
<th>C4F8</th>
<th>SF6</th>
<th>Chiller</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000W</td>
<td>25W</td>
<td>7 mT</td>
<td>110 sccm</td>
<td>50 sccm</td>
<td>5°C</td>
</tr>
</tbody>
</table>

Table 3.5: C4F8-based oxide RIE process parameters
Chapter 3. BRL Fabrication Process Development

Figure 3.10: SEM cross-section of the (a) original oxide etch recipe where significant resist damages translated to rough sidewall, (b) newly developed C4F8 recipe where there is no resist damages and smoother sidewall is clearly evident, (c) scattered residue remaining on etched surface, (d) new C4F8 recipe with reduced residues.

Figure 3.11: (a) SEM of the same C4F8 recipe on new Cobra tool which suffered severe redeposition. (b) Positive profile where the bottom width is wider than designed in layout.
Table 3.6: Newly optimized gas composition of C4F8-based oxide RIE recipe details.

<table>
<thead>
<tr>
<th></th>
<th>Exp#1</th>
<th>Exp#2</th>
<th>Exp#3</th>
</tr>
</thead>
<tbody>
<tr>
<td>ICP Power</td>
<td>1500W</td>
<td>1500W</td>
<td>1500W</td>
</tr>
<tr>
<td>RIE Power</td>
<td>50W</td>
<td>50W</td>
<td>50W</td>
</tr>
<tr>
<td>Pressure</td>
<td>7 mT</td>
<td>7 mT</td>
<td>7 mT</td>
</tr>
<tr>
<td>C4F8</td>
<td>45 sccm</td>
<td>45 sccm</td>
<td>45 sccm</td>
</tr>
<tr>
<td>O2</td>
<td>2 sccm</td>
<td>2 sccm</td>
<td>2 sccm</td>
</tr>
<tr>
<td>Chiller</td>
<td>5°C</td>
<td>5°C</td>
<td>5°C</td>
</tr>
</tbody>
</table>

Table 3.7: Experiments of different CHF3-based oxide RIE recipes to examine etch rate and selectivity.

<table>
<thead>
<tr>
<th></th>
<th>Exp#1</th>
<th>Exp#2</th>
<th>Exp#3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure</td>
<td>30mT</td>
<td>30mT</td>
<td>30mT</td>
</tr>
<tr>
<td>RIE Power</td>
<td>200W</td>
<td>200W</td>
<td>200W</td>
</tr>
<tr>
<td>CHF3</td>
<td>12sccm</td>
<td>17sccm</td>
<td>25sccm</td>
</tr>
<tr>
<td>Ar</td>
<td>38sccm</td>
<td>33sccm</td>
<td>25sccm</td>
</tr>
<tr>
<td>Etch Rate (SiO2)</td>
<td>50nm/min</td>
<td>54nm/min</td>
<td>47nm/min</td>
</tr>
<tr>
<td>Etch Rate (Resist)</td>
<td>72nm/min</td>
<td>75nm/min</td>
<td>63nm/min</td>
</tr>
<tr>
<td>Selectivity</td>
<td>0.71</td>
<td>0.72</td>
<td>0.76</td>
</tr>
</tbody>
</table>

Figure 3.12: SEM cross-section of a (a) low mag, and (b) high mag image of the improved oxide RIE recipe using new CHF3/Ar recipe.

Final development work is carried out by optimizing a CHF3-based recipe instead. A combination of CHF3/Ar is chosen based on recommendation from Oxford Instrument and literature review [127]. Significant improvement in oxide etch quality is clearly evident as shown in Figure 3.12. The effect of Ar to CHF3 ratio on SiO2 etch rate and selectivity to resist were examined. Table 3.7 summarizes the experiment details. It is worth noting that the improvement in selectivity obtained by decreasing Ar to CHF3 ratio was negligible. This was quite counter-intuitive since decreasing Ar made the etch less physical, which should have improved selectivity. A more rigorously designed design
of experiment (DOE) may be useful in the future to further explore this phenomenon.

3.4 **Metal Contacts Evaporation**

Metal contact recipe development was carried out on the new Angstrom NEXDEP evaporator, shown in 3.13. E-beam evaporation is chosen over thermal evaporation for its versatility and low contaminations to form high quality contacts. Two contacts, a p-type and a n-type, are required for our process and each needs a different metal stack to engineer the work function to form good ohmic contact with p-GaAs and n-GaAs, respectively. There are many literatures reviews of making ohmic contact to GaAs [128][129]. For p-contact, Ti/Au is typically used where Au is the main conducting layer and a thin layer of Ti is deposited first to improve adhesion between GaAs and Au. As for n-contact, an alloy of AuGe/Ni/Au is commonly used. Quite often though, an additional thin layer of Ni will be deposited first to improve adhesion. After annealing at around 400°C, Ge diffuse into GaAs which reduces the width of depletion layer and forms a tunneling contact. The first Ni layer also reacts with GaAs to form NiAs(Ge) whereas the 2nd Ni layer along with the thick Au over-layer suppress the AuGe layer from balling up to achieve smooth surface. A $\beta$-AuGa layer is then formed on the top surface. [130].

The deposition thickness and rate of Ti and Au are tabulated in Table 3.8 for p-contact whereas the same for Ge, Ni and Au are summarized in Table 3.9 for n-contact.

Graphite crucibles are used for all metal sources as it provides good thermal isolation between the melted sources and water cooled hearth. It is worth noting that Ni is a particularly tricky metal to evaporate, as it adheres to crucible liner walls and could easily crack the crucible from stress induced by thermal expansion and contraction. Therefore,
Figure 3.13: Image of the new Angstrom NEXDEP evaporator.

<table>
<thead>
<tr>
<th>Metal</th>
<th>Thickness</th>
<th>Deposition Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Au</td>
<td>45 nm</td>
<td>2 A/s</td>
</tr>
<tr>
<td>Ge</td>
<td>25 nm</td>
<td>0.2 A/s</td>
</tr>
<tr>
<td>Ni</td>
<td>30 nm</td>
<td>0.2 A/s</td>
</tr>
<tr>
<td>Au</td>
<td>120 nm</td>
<td>2 A/s</td>
</tr>
</tbody>
</table>

Table 3.9: N-contact metal deposition process parameters
temperature ramp profile is extremely important optimization parameter for Ni specifically. A safe ramp time for Ni was determined to be at least 400s after numerous cracked crucibles while 180s was sufficient for all other metals.

### 3.4.1 Oblique Angle Deposition

A particular challenge with e-beam evaporation lies in its directional deposition nature, where line of sight is required. This is due to very few collisions will occur in a high vacuum system, $10^{-6}$ Torr pressure, such as this one; and thus, evaporated metal atoms
will reach the substrate in almost a straight line. As a result, step coverage of evaporated
deposition is very poor. This turns out to be very problematic for our process since a
conformal coverage of metal along the sidewall is required to bridge the pad and via
opening for current injection, as illustrated in Figure 3.14 (a). Initial attempt resulted
in poor sidewall coverage of the deposited Ti/Au as evident from the SEM cross-section
shown in Figure 3.14 (b), thereby rendering the probing pads disconnected and useless.
Typically, this problem could be resolved with a planetary rotational substrate holder to
enhance step coverage. Unfortunately, such holder is very expensive and not available
in our tool. Alternatively, planarization technique could be employed to alleviate the
need for depositing metals on the sidewalls. However, suitable planarization material
has to be carefully chosen since it has to be able to sustain subsequent high temperature
annealing process at 390°C to alloy the metal. HSQ [4], BCB (benzocyclobutane) [131]
and polyimide [132] are all common materials for planarizing III-V semiconductor lasers.
Yet, challenges associated with planarization often include added fabrication complexity,
which typically involves spin coating the polymer layer, followed by annealing to re-flow
and solidify the layer, and then the finally, layer has to be etched back to expose the
device top surface. Since end point detection is required, a tool with in-situ etch depth
monitoring is required. Furthermore, such etch back method is prone to variations in
either device height or variation in the spin coated polymer thickness, both of which could
decrease yield [133]. Therefore, an alternative solution that does not involve substantial
increase in fabrication complexity is desired. Oblique angle deposition (OAD) [134][135]
could be a simple and elegant solution with correct optimization. Figure 3.14 (b) shows
the schematic of the concept of oblique angle deposition where the sample is tilted relative
to the crucible. As a result of the tilt angle, more materials will be deposited on the
sidewall due to increased line of sight. However, this comes at the cost of reduced
deposition rate on the flat surface, so typically a maximum of 45° is recommended. A
20° tilt was utilized and improved step coverage is evident from SEM cross-section shown
in Figure 3.14 (c) shows the improved step coverage with a 20° tilt angle.

### 3.4.2 Transmission Line Measurement

Low resistance ohmic contact is crucial for a high quality laser. The most common method used to characterize contact quality is through transmission line measurement (TLM), as originally proposed by Shockley [136]. To derive necessary understandings, consider simple scenario of a semiconductor resistor with two metal contacts on each side as shown in Figure 3.15. The total resistance, $R_T$, is given by

$$R_T = 2R_m + R_{semi} + 2R_C \tag{3.1}$$

where $R_m$ is the metal resistance, $R_{semi}$ is the semiconductor resistance and $R_C$ is the contact resistance between the metal and semiconductor. However, since the metal resistance is much smaller than other resistances in question, it can be neglected. Furthermore, $R_{semi}$ can be further expressed as $R_{sh} \cdot L/W$, and so Equation 3.1 further becomes

$$R_T = R_{semi} + 2R_C = R_{sh} \frac{L}{W} + 2R_C \tag{3.2}$$

where $R_{sh}$ is the sheet resistance. From above equation, it is evident that contact resistance can be estimated when $L$, the distance between contacts, becomes zero. Similarly, TLM allows one to extrapolate the contact resistance from measured I-V of different spacing rectangle pads as shown in Figure 3.16 (a). However, standard TLM with rectangular contacts suffers from current crowding, where the current flows are not uniformly distributed and heavily shifted to one edge. Figure 3.16 (b) illustrates such phenomenon. This problem can be alleviated through the use of circular TLM (CTLM), where circular contact pads are used instead of the conventional rectangular pads [137]. I-V measurements are now taken between the inner and outer circular contacts with variable gaps.
Figure 3.15: Schematic of a simple semiconductor resistor with two metal contacts on each side. The basic governing equations of TLM can be deduced from this setup.

between them. Figure 3.16 (c) and (d) illustrates the structure of CTLM and current flows. For CTLM, the total resistance can be approximated as [137]

\[
R_T = \frac{R_{sh}}{2\pi L} (d + 2L_T)C \tag{3.3}
\]

where \(C\) is the correction factor and \(L_T\) is the transfer length, which is the average distance travelled by electron (or hole) in the semiconductor. Both \(C\) and \(L_T\) can be further written as

\[
C = L \ln(1 + \frac{d}{L}) \tag{3.4}
\]

\[
L_T = \sqrt{\frac{\rho_c}{R_{sh}}} \tag{3.5}
\]

where \(\rho_c\) is the specific contact resistivity in units of \(\Omega \cdot cm^2\). It can be further described as

\[
\rho_c = R_c(\pi L_T^2) \tag{3.6}
\]
Figure 3.16: (a) Partial layout schematic of conventional TLM. (b) Illustration of current crowding due to layout geometry. (c) Partial layout schematic of CTLM. (d) Illustration of current distribution, no current crowding because of symmetry.

Figure 3.17 is a plot of the total resistance and gap distances. Corrected resistances are calculated by applying the correction factor to the raw resistances. Using a linear fit, we can extrapolate both $R_C$ and $L_T$. When the gap is zero, the corresponding resistance is $2R_C$, whereas when the resistance is zero, the corresponding gap is $2L_T$. Based on the extrapolated values from Figure 3.17, $R_C = 3\Omega$, $L_T = 3.5\mu m$ and the calculated $\rho_c = 1.15 \times 10^{-6} \Omega cm^2$. The measured specific contact resistivity was an order of magnitude better than the previously reported within our group ($\rho_c = 4.2 \times 10^{-5} \Omega cm^2$). This value is in-line with what’s typically reported in literatures for p-contact on GaAs ($\sim 10^{-6} \Omega cm^2$).

### 3.5 AlGaAs RIE Optimization for DFB Laser

Optimization of AlGaAs RIE recipe for DFB laser was motivated by the problem encountered of previous group member shown previously in Figure 1.6 (a). Such imperfection is due to a well known phenomenon in RIE process called micro-loading effect, where large surface openings consume more etchant than small opening areas [138]. As a result, etch rate is dependent on local pattern density. Narrower width opening results in shallower
etch depth and vice versa. For the proposed DFB structure illustrated in Figure 3.18, one can then reasonably suspect inside the trenches in-between gratings near the ridge to be severely impacted by loading effect due to the surrounding walls on all 3 sides. Therefore, AlGaAs RIE recipe developed for straight waveguide was insufficient to successfully define a straight etch profile.

The influence of various RIE process parameters such as power, pressure and various gas composition flow rate were examined and summarized in Table 3.10. Process of record (POR) represents the original AlGaAs RIE recipe and figure of merit (FOM) is the ratio of the tapered footing relative to the total etch depth. A smaller ratio means a straighter etch profile and therefore, less micro-loading effect. Figure 3.19 shows the SEM cross-section images of the experiments tabulated in Table 3.10. No significant changes were observed for Exp#1 and Exp#2 when either the RF and RIE power was increased, as the ratio still measured more than 30%. For Exp#3, although the FOM ratio was significantly improved by increasing BCl₃ and Cl₂ flow rate, it resulted in
severe erosion of the gratings, as evident from Figure 3.19 (d). We suspect this to be due to increased lateral etching from the chemical etching nature of BCL$_3$ and Cl$_2$. On the other hand, increasing Ar flow rate independently, Exp#4, did not improve micro-loading effect; but when combined with increased pressure, Exp#5, then the FOM was reduced to 18% without damaging the gratings. This is hypothesized to the physical nature of Ar and more abundant supply of gas flow to re-fill the consumed etchant gas from nearby area. Thereby, resulting in a better FOM ratio. In order to take advantage of this observation, various combination of pressure and Ar flow rate were experimented but the improvements remained more or less the same. The best condition was determined to be Exp#6 with a pressure of 15mT and Ar flow rate of 20sccm and had achieved a FOM ratio of 15%. The SEM cross-section image is shown in Figure 3.19 (f).

The observed improvements by increasing gas flow rate matches with what’s available in literature [138]. However, despite achieving a considerable reduction of FOM ratio by slightly over 50%, micro-loading effect was not completely resolved. The current tool utilized (Trion Minilock RIE etcher) had been servicing TNFC for more than 10 years and has severe stability issue such as unstable reflected RIE power during operation.
Figure 3.19: SEM cross-section image of (a) Exp#1 where the RF power was increased to 250W, (b) Exp#2 where RIE power was increased to 100W, (d) Exp#3 where BCl3 and Cl2 were increased to 8sccm, (f) Exp#4 where Ar was increased to 15sccm, (e) Exp#5 where pressure was increased to 10mT and Ar was increased to 15sccm, and finally, (f) Exp#6 where pressure was increased to 15mT and Ar was increased to 20sccm.
Further improvements based on current facility proved to be extremely challenging. That said, further improvements may be accomplished by introducing an etch stop layer, or perhaps access to a better RIE system for AlGaAs etching.

### 3.6 Process Integration

After developing the recipe for each process module, the entire process flow is integrated to produce the final laser device. Improvements of the fabricated laser is clearly evident from Figure 3.20 (a) to (e). Initial laser shown in Figure 3.20 (a) suffered from poor quality with rough sidewall and severe micro-grass. After optimizing e-beam lithography and oxide RIE recipes, significantly improved physical integrity of passive device is shown in Figure 3.20 (b). Yet, there still remained several challenges along the way from passive to active devices. Two of the most problematic issues encountered during process integration were related to the use of BOE. It was discovered that BOE attacked high Al concentration layers of the exposed Bragg stack like in Figure 3.20 (c). Furthermore, excessive BOE right before contact deposition compromised the sidewall oxide quality as shown in Figure 3.20 (d). These problems were resolved thanks in part by optimizing the oxide RIE recipe for residue-free surfaces, but also minimizing BOE time to less than 5 seconds where necessary. Finally, Figure 3.20 (e) shows a typical quality of the latest process conditions where good electrical isolation of the oxide and conformal metal
Figure 3.20: SEM cross-section image of (a) Initial laser suffered from poor sidewall quality and severe micro-grass in the etched area due to un-optimized e-beam lithography and oxide RIE recipes. (b) Good passive device with optimized e-beam lithography and oxide RIE recipes. (c) BOE attacked high Al concentration layers, resulting in the cascaded profile as shown. (d) Sidewall oxide damaged from excessive BOE and also suffered from poor step coverage of evaporated metal. (e) Most recent optimized process showed good fabrication quality.
contact step coverage yield robust semiconductor lasers.

3.7 Summary of Fabrication Process Developments

Process developments with respect to various aspect of laser fabrication processes were presented. New e-beam lithography resist recipes were developed where high resolution patterning was achieved by applying proximity effect correction and the use of bulk and sleeve exposures. Improvements in oxide RIE quality was then demonstrated. Particularly, the development of CHF3-based recipe enabled straight etch profile with no resist damages and a residue-free surface. Furthermore, a robust metal contact evaporated deposition recipe was developed in-house for diode laser for the first time. The challenge of poor step coverage was resolved through the elegant optimization of oblique angle deposition, which not only simplified the overall fabrication process but also accomplished high yield of over 90%. Contact quality was also verified through the measurement from TLM, and found to be comparable with what’s available in literatures. A new AlGaAs RIE recipe was further optimized specifically for DFB laser. However, despite reducing the micro-loading effect by half, the developed process recipe was still imperfect. An introduction of etch stop layer might be required in order to fully resolve this problem. Another possibility might be to explore the potential access of a better AlGaAs RIE system, as the Trion Minilock had many tool constraints such as unstable reflected RIE power. A detailed step-by-step fabrication processes, including recipe details, is outlined in Appendix A. Finally, improvements in the fabricated laser quality was demonstrated through a series of SEM-cross sections.
Chapter 4

Characterization of BRL Diode Laser

Electrical and optical performances of the fabricated BRL diode laser are presented in this chapter. Using the developed fabrication processes outlined in previous chapter, BRL diode lasers are fabricated and characterized. First, the wafer design will be introduced, followed by laser characterization where the laser output power and current-voltage characteristics are examined. Characterization of the fabricated BRL diode laser was carried out by other group members, Greg Iu and Dr. Bilal Janjua.

4.1 Wafer Design

A new wafer stack, BRL8, was designed by Dr. Nima Zarein based on previous learnings. This will be the wafer used throughout this work. The main difference between BRL8 and its predecessor, BRL7, is reduced thicknesses of the Bragg stacks, matching layers and core layers to blue-shift the generated DFG idler. In addition, QW is also slightly modified as well. This new design is illustrated in Figure 4.1. The GaAs/AlGaAs layers are grown by metal-organic chemical vapor deposition (MOCVD). Starting with a n-type GaAs substrate, a 100nm buffer layer is grown before the bottom Bragg stack. The
Chapter 4. Characterization of BRL Diode Laser

Figure 4.1: Schematic of BRL8 wafer stack details

The bottom Bragg stack is comprised of 5 periods of $\text{Al}_{0.25}\text{Ga}_{0.75}\text{As}/\text{Al}_{0.7}\text{Ga}_{0.3}\text{As}$ while the top Bragg stack consists of 4 periods instead. P-I-N junction is formed by doping the top and bottom Bragg stack with C and Si, respectively. Two InAlGaAs quantum wells (QW) separated by three 10 nm $\text{Al}_{0.28}\text{Ga}_{0.72}\text{As}$ barriers are designed for Bragg mode to lase at 780nm and a phasematching point with TIR mode at 786nm. Finally, the wafer is capped off with 100nm of GaAs for protection. An etch depth target of 1.8$\mu$m to 2$\mu$m is desired. The refractive indices of each wave and the field profiles for BRL8 wafer are shown in Figure 4.2 (a). The simulated IV and LI are shown in Figure 4.2 (b) and (c), respectively.
Figure 4.2: (a) Simulation of the effective refractive indices of each wave on the top, and the field profiles of Bragg mode in red and TIR mode in black. Simulation of (b) the IV curve and (c) the LI curve with respect to current density. With permission to reproduce from [7].
4.2 Laser Performance

Experimental setup used to characterize the laser performances is shown in Figure 4.3. Laser sample is placed on top of a copper block that is connected to ground. Since the n-contact is on the bottom of the laser sample, copper block then grounds the n-contact. Current is applied on the p-contact with an electrical probe through a laser diode current source (Keithley 2510) in either pulsed or continuous-wave (CW) mode. Furthermore, a temperature controller (Keithley 2520) is connected to the copper block to control the stage temperature. Output power is measured by a large area silicon photodetector from one side of the facet. Then from the other side of the facet, either a 20x objective lens is used in conjunction with a camera for viewing the mode profile or an optical fiber coupled to an Ando 6310C optical spectrum analyzer (OSA) for spectrum and loss measurements. Luminescence-Current-Voltage (LIV) are measured to demonstrate the light output and current-voltage characteristics of the tested laser.
4.2.1 Light-current-voltage Characteristics and Spectrum

LIV essentially contains two parts: LI and IV. Whereas LI represents the optical property of the laser to show how efficiently the injected current can be converted into output photons, IV, on the other hand, shows the electrical characteristic of the laser of how much series resistance does the laser experience and the maximum amount of current it can take.

Initial BRL8 laser suffered from poor physical quality due to sub-optimal processing conditions. An examination of the SEM cross-section in Figure 4.4 (a) showed that sidewall oxides were damaged due to excessive BOE cleaning. This could lead to higher scattering losses and would increase threshold current and reduce the output power. Indeed, from the pulsed mode LI (red line) shown in Figure 4.4 (c), high threshold current of 44mA and a mere 2mW output power at 100mA injection current were measured. With a width and length of 1.88\(\mu\)m and 950\(\mu\)m, respectively, this translated to a high threshold current density of 2263A/cm\(^2\). The external efficiency of the laser was calculated from the slope of the LI curve to be 5.6%. Such high threshold current density and low efficiency confirmed the increased loss from imperfect fabrication processes. Furthermore, the directionality of e-beam evaporated deposition resulted in poor metal contact step coverage. This then translated directly to increased resistance as evident in the steep slope of the IV curve (blue line) after turn on in Figure 4.4 (c).

Enhanced laser performance was observed as fabrication quality improved. SEM cross-section of a typical BRL8 laser fabricated using latest process condition is shown in Figure 4.4 (b). As can be seen, structural integrity of both the oxide and metal contact sidewall were much improved compared to initial results. Pulsed mode LIV measurement shown in Figure 4.4 (d) was taken on a laser with a width of 1.9\(\mu\)m and a length of 0.989mm. With a threshold current of 26mA, the respective threshold current density achieved was 1383A/cm\(^2\). Such significantly improved threshold current density meant loss was much reduced so that not as much current injection was needed for gain
Figure 4.4: (a) SEM cross-section image of the initial laser characterized where it suffered from oxide sidewall damages and poor metal sidewall coverage. (b) SEM cross-section image of typical laser quality fabricated using the optimized process recipes. (c) Pulsed LIV with a 5% duty cycle of the initial laser characterized. A threshold current of 44mA, turn on voltage of 1.4V, and an output power of 2mW at 100mA current input were measured. (d) Pulsed LIV with a 5% duty cycle of BRL8 laser fabricated using optimized process recipes. A threshold current of 26mA, turn on voltage 1.6V, and an output power of 6mW at 100mA current input were measured.
to equal loss. Output power was also drastically improved from the LI curve (red line), where single facet output power of 6mW was measured with 100mA input current and more than 12mW with 160mA input current. External efficiency of 11.5% was achieved. The improvements in contact quality is clearly evident from the IV curve (blue line) since the near flat slope after turn on represented a significant improvement in the series resistance. Namely, sidewall coverage was good enough to not limit current spreading and that the interface between the metal contact and GaAs surface is good. As a result, dynamic resistance of less than 5Ω was measured. Furthermore, a turn on voltage of 1.6V is very close to the band gap of 1.589eV at 780nm emission meant that there was no leakage paths.

Aside from pulsed operation, performance of CW mode was also examined. Figure 4.5 (a) shows the LIV and dynamic resistance of BRL8 laser operating in CW mode. Unstable LI curve (red line) and the kinks could be due to either heating effect or mode switching, but the smooth IV curve (blue line) again confirmed the high quality contacts with low dynamic resistance of 5Ω. Furthermore, close to 9mW output power was achieved with 130mA input current. The lasing spectrum is then shown in Figure 4.5 (b). At just above threshold the diode laser operated as single mode laser and at two times threshold it became multi-moded. Such behavior are well known characteristics for this type of FP
4.2.2 Thermal Sensitivity

Thermal stability is an important consideration for semiconductor lasers. Characteristic temperature reflects the thermal sensitivity and measures the changes in threshold current and external differential efficiency of the device with increasing temperature, and are denoted by $T_0$ and $T_1$, respectively. Increasing temperature results in more non-radiative recombination such as Auger recombination, and also increases thermal leakage and phonon-phonon scattering which induces Joule heating. As a result, threshold current increases and differential efficiency decreases from the increased losses. Characteristic temperature, $T_0$ and $T_1$, are governed by Eq. (4.1) and (4.2). From this, we can observe that a higher characteristic temperature results in less sensitivity to change in temperature and therefore as high of value for $T_0$ and $T_1$ are desired.

\[ I_{th}(T) = I_{th,0} \cdot e^{(T/T_0)} \]  

\[ \eta(T) = \eta_0 \cdot e^{-T/T_1} \]  

where $I_{th}(T)$ and $\eta(T)$ are the threshold current and efficiency at temperature T, respectively. Whereas $I_{th,0}(T)$ is the threshold current as absolute zero, similarly, $\eta_0(T)$ is the efficiency at absolute zero. Experimentally, $T_0$ and $T_1$ can be obtained by measuring the change in threshold current and differential efficiency. As such, bonded BRL8 laser was operated in CW mode and the temperature controller of the stage was raised from 20°C to 55°C. The measured LI curve is shown in Figure 4.6. Then from these curves, Figure 4.7 (a) and (b) can be plotted to extract $T_0$ and $T_1$, respectively. $T_0$ was measured to be 77K whereas $T_1$ was measured to be 71K. For comparison, typical characteristic temperature for edge emitting diode laser ranges from 60K to 150K [139],
Chapter 4. Characterization of BRL Diode Laser

Figure 4.6: LI curve for temperature ranging from 20°C to 55°C in CW mode.

Figure 4.7: Change in (a) threshold current, and (b) slope efficiency with temperature.
so the measured characteristic temperature falls within expected range. However, this value is lower than previously reported value of \( \sim100\text{K} \) from previous generation. It is also worth noting that the current design is focused on nonlinear performance and not particularly well designed to minimize carrier leakages. Heat dissipation can be improved to minimize thermal sensitivity. One potential solution is to use silicon nitride instead of silicon dioxide as electrical isolation layer, where the better thermal conductivity of nitride could improve heat dissipation [140]. Alternatively, electro-plating a thick metal contact layer could also significantly reduce heating issues.

### 4.2.3 Loss Measurement

Loss can be measured by leveraging the dependence of efficiency with respect to cavity length. External differential efficiency, \( \eta_D \), is the ratio of increase in emitted photons to increase in injected carriers. It is therefore the efficiency of the entire system and can be extrapolated from the slope of LI curve of individual laser. The dependence of differential efficiency to cavity length can be expressed by:

\[
\frac{1}{\eta_D} = \frac{\alpha_{\text{int}}}{\ln(1/R) \cdot \eta_{\text{int}}} \cdot L + \frac{1}{\eta_{\text{int}}}
\]

(4.3)

where \( \eta_{\text{int}} \) is the internal efficiency, \( R \) is the reflectivity of the facet, \( L \) is the cavity length and \( \alpha_{\text{int}} \) is the internal loss. From this equation then, internal loss and internal efficiency can be measured experimentally by testing lasers with varying cavity lengths. Figure 4.8 plots the inverse external differential efficiency against cavity lengths. From the linearly fitted line, the slope and y-intercept can be used to extrapolate \( \eta_{\text{int}} \) and \( \alpha_{\text{int}} \) to be 0.58 and 8.9cm\(^{-1}\), respectively. Both represents significant improvement from results reported from previous generations [4].
Chapter 4. Characterization of BRL Diode Laser

4.3 Tapered Diode Laser

Tapered diode lasers have been under extensive study for its potential in generating higher fundamental mode power and its relative ease in design and fabrication [141][142][144][146]. The design utilized in this work takes the shape of a bow-tie like shown in Figure 4.9. The bow-tie laser has a total length, L, that scales with the tapering length, L_t. The full width, W, is determined by the half angle, θ. The center ridge waveguide is 2µm and filters higher order mode. Such design takes advantage of the increased output power from larger ridge width but filters out the higher order mode that’s associated with it. In addition, increased effective area allows for higher injection current before thermal rollover.

The main design consideration for tapered design is to ensure adiabatic operation where the fundamental mode is well confined [147]. Essentially, the widening of waveguide sidewalls has to be slower than the diffraction spreading of the first-order mode. For angles that are too large, significant radiation loss will hinder device performances or
Figure 4.9: Schematic illustration of bow-tie design.

Figure 4.10: CW mode LIV of (a) 0°, (b) 1°, (c) 2°, (d) 3° and (e) 4° bow-tie diode laser.
the laser will exhibit strong multi-moded behavior. Typically, this condition is ensured for a full angle of 6° or less [148]. With that in mind, tapered BRL8 lasers with half angle of 0°, 1°, 2°, 3° and 4°, and, total length of 0.25mm, 0.5mm, 0.75mm and 1mm are fabricated and characterized to examine its electrical performance. The CW mode LIV was measured for lasers with length of 0.705mm and a half angle ranging from 0° to 4°. The results are shown in Figure 4.10 (a) to (e) for 0° to 4°, respectively. As a result of increased effective area, higher injection current can be pumped into the tapered lasers to demonstrate higher power. In particular, 1° achieved highest peak power of 18mW with 200mA input power which was not observed before in FP diode lasers as it suffers catastrophic facet damages usually above 150-160mA. The improvement in peak power is related to increased gain area of the tapered design. The flatness of IV curve corresponds to dynamic resistance of less than 5Ω despite drastically increased effective area. This was an even more concrete evidence of the robustness of the newly developed metal contacts.

Since the effective area is significantly different, comparing injection current is not the most direct comparison. A better metric would then be to compare the output power with current density instead. Figure 4.11 shows the single facet output power with increasing current density by normalizing the input current by effective area of each laser. As expected, tapered lasers generate higher power given the same current density due to its increased area. The reduction in threshold current density is also immediately evident. Whereas the 0° straight laser exhibited a threshold current density of 1383A/cm², it is reduced by almost half to 712A/cm² for 1° tapered laser as a result of better electron utilizations. Furthermore, the spectrum of the bow-tie lasers are examined to see if the lasers are operating in single or multi-mode. Figure 4.12 (a) shows the 2° tapered laser behaving similar to the straight FP laser where at just above threshold, the laser are single moded, but at 2 times the threshold current, the laser becomes multi-moded. Yet, the 4° tapered laser shown in Figure 4.12 (b) reveals that it is multi-moded even just above threshold. This is inline with expectation from literature as most tapered design
are limited to less than 3° half angle [148].

![LI curve for various degree tapering by current density.](image)

Figure 4.11: LI curve for various degree tapering by current density.

![Spectrum of (a) 2° tapered bow-tie and (b) 4° tapered bow-tie.](image)

Figure 4.12: Spectrum of (a) 2° tapered bow-tie and (b) 4° tapered bow-tie.

### 4.4 Summary of Diode Laser Characterization

This chapter has presented the characterization results of BRL8 laser diode using the newly optimized fabrication processes. The wafer structure is first described then followed
by details of electrical, optical and thermal performances. Table 4.1 summarizes the important laser properties of the fabricated straight diode laser and comparison to results from previous generation laser, BRL7.

<table>
<thead>
<tr>
<th>Device</th>
<th>J_{th}</th>
<th>avg. R</th>
<th>\alpha_{int}</th>
<th>\eta_{int}</th>
<th>T_0</th>
</tr>
</thead>
<tbody>
<tr>
<td>BRL7</td>
<td>1705 A/cm²</td>
<td>\sim 14Ω</td>
<td>14.1cm^{-1}</td>
<td>0.14</td>
<td>105 K</td>
</tr>
<tr>
<td>BRL8</td>
<td>1383 A/cm²</td>
<td>\sim 7Ω</td>
<td>8.9cm^{-1}</td>
<td>0.58</td>
<td>77 K</td>
</tr>
</tbody>
</table>

Table 4.1: Comparison of important device characteristics of BRL8 to BRL7.

In terms of threshold current density, a reduction of \sim 20\% was demonstrated comparing to BRL7. This is attributed to the enhanced fabrication quality to reduce scattering loss. Etch depth is also optimized by leveraging from previous learnings. The lower loss is reflected in the reduction of \alpha_{int} and improvement in \eta_{int}. Furthermore, 50\% reduction in the average dynamic resistance serves as evidence of better metal contact quality and contact interface. Comparing to similar laser available from literature which was only able to achieve pulsed-mode operation, we are able to not only demonstrate CW-mode operation but also show a 50\% reduction in threshold current density [100].

Lastly, thermal sensitivity of the laser is examined and found to be lower than previously reported results. This represent room for improvements in the thermal dissipation of these lasers. Overall though, the newly developed fabrication processes promises robust and high performance lasers with good yield.

Finally, tapered bow-tie lasers are fabricated and characterized for the first time on BRW platform. The increased effective area of tapered design allows for higher injection current without damaging the device. This is confirmed from the experimental characterization result where 1° tapering produced single facet power of 18mW at 200mA input which was not achievable with straight laser. In addition, significant reduction in threshold current density from 1383A/cm² to 712A/cm² is also demonstrated. Spectrum analysis demonstrated similar multi-mode behavior for smaller tapering angle lasers while for the largest 4° bow-tie it showed multi-mode behavior immediately after reach-
ing threshold. As a result, we conclude that the tapering angle should be limited to less than $3^\circ$, which is inline with literature findings.
Chapter 5

Conclusion and Future Directions

The focus of this thesis revolves around the fabrication of robust and better performance BRL diode laser. New recipes for e-beam lithography, oxide RIE, contacts evaporation and AlGaAs RIE have been developed and integrated to produce functional lasers. Furthermore, fabrication flow has been simplified by eliminating the complex planarization scheme. Oblique angle deposition during e-beam evaporator deposition is demonstrated to be an elegant solution with reliable and superior performance to achieve significantly lower contact resistance. It is worth noting that the development of contact deposition process presented in this work enabled complete in-house fabrication capabilities of semiconductor diode lasers. Thus, eliminating time consuming and expensive outsourcing and offering more control over fabrication quality. Finally, electrical, optical and thermal performances of the fabricated diode lasers are then presented and compared to previous generation results.

The details of process developments are presented in Chapter 3. For e-beam lithography resist, rather than just exposing the entire pattern using one dose, the pattern is broken down to sleeve section for small features that require high resolution and bulk section for big patterns for lower resolution. Such setting allows for minimizing writing time while preserving accurate dimensions and good sidewall quality. In terms of oxide RIE,
a CHF$_3$-based recipe is developed to produce a residue free etch. Significant improvement in the etch quality both in terms sidewall roughness and residue is demonstrated. E-beam evaporated p- and n-type contacts for semiconductor diode laser are developed for the first time. A tilt angle of 20-45° is utilized for oblique angle deposition to produce high quality contacts. Lastly, the optimization of AlGaAs RIE recipe for DFB laser is attempted to minimize the micro-loading effect. Significant improvement is demonstrated by increasing pressure and Ar flow rate. Such phenomenon can be attributed to more etchant gases available for the much needed chemical reaction inside the small surface opening. However, due to tool constraint this problem is not completely resolved and footing in the bottom 10-15% of the ridge is still observed. Lastly, the improvements in physical integrity of the diode lasers are demonstrated through a series of SEM images.

The fabricated diode lasers are experimentally characterized in Chapter 4. BRL8 diode laser has demonstrated threshold current density of 1383A/cm$^2$, more than 12mW output, and an external efficiency of 11.5%. Combined with an internal loss of 8.9cm$^{-1}$ and internal efficiency of 0.58, this represented reduction in propagation loss from the improved fabrication processes. Furthermore, robust metal scheme accomplished by oblique angle deposition and better contact interface is demonstrated by comparing the average dynamic resistance of 7Ω of BRL8 to 14Ω of BRL7, a 50% reduction. Thermal sensitivity of the laser is examined where the characteristic temperature measured, $T_0$ and $T_1$, is 77°K and 71°K, respectively. Using the newly developed process, tapered bow-tie lasers are demonstrated for the first time using BRW platform. Benefits from the increased effective area to allow for higher injection current above 150mA which would normally damage FP diode lasers. An output power of 18mW at 200mA input is demonstrated from 1° tapered bow-tie laser. Furthermore, significant reduction in threshold current density from 1383A/cm$^2$ to 712A/cm$^2$ is also shown. It is also shown from spectrum analysis that tapering angle larger than 3° is not desirable due to the multi-moded nature even just above threshold.
5.1 Future Direction

With a robust process for high performance diode lasers, the fabricated BRL8 lasers will be used to demonstrate self-pump DFG by phasematching the Bragg and TIR modes. As a result, it’s important to explore the nonlinear properties of the laser to identify phase-matching point. Furthermore, high fundamental power and tunability are important characteristics desired for a successful self-pump DFG laser. With these in mind, other types of semiconductor lasers such as ring, tapered and DFB designs will be fabricated and studied. Below lists the future work that will be carried out:

- Lower characteristic temperature exhibited by the current devices can be improved by designing for better heat dissipation. One possible solution might be to switch the isolation layer material from SiO$_2$ to SiN$_x$. Another solution might be to design a heat dissipation pad or electroplate thick copper layer to channel the generated heat.

- Further examine the fabricated BRL8 diode laser for its nonlinear property and demonstrate CW electrically injected self-pumped DFG laser.

- Fabricate ring lasers using established process flow to demonstrate higher fundamental mode power.

- Challenges still remain with micro-loading effect for DFB AlGaAs etching despite significant improvement. An alternative DBR design could be used to achieve single frequency and single mode lasing. For this design, the active ridge and passive gratings can be fabricated separately with independent etch depth control. Micro-loading effect will also be significantly reduced without the grooved regions as with current design.
Appendix A

Detailed step-by-step fabrication process

Stage 1: Defining ridge waveguides

1. Cleave wafer into desired sample size using diamond scriber.

2. Blow dry the sample with nitrogen gun to remove any particles from cleaving. Then rinse the sample with acetone and iso-propanol (IPA) and ultrasonic clean in acetone and IPA sequentially for 3 minutes each. Then the sample is blow dried with nitrogen gun.

3. Bake the sample at 180°C for 5 minutes to remove any remaining moistures.

4. Prepare the Oxford Plasmalab 100 for PECVD deposition by turning on the tool according to instructions. Physically clean the chamber, if necessary, and set the table temperature to 300°C. Be careful with the external temperature controller and follow the instruction carefully to prevent damaging the tool.

5. Run the O2 clean recipe for 15mins at 300C.
6. Place samples on a Si carrier wafer and surround it by scrap Si pieces to minimize edge effects. Place the carrier wafer into loadlock and initiate pump down process.

7. Deposit PECVD oxide at 300°C for 2min50s using the recipe SiO$_2$ Eric (300C). Recipe details: 30W RF power, 1000mT pressure, 170sccm 5%SiH$_4$/N$_2$, 710sccm N$_2$O.

8. Inspect the samples under optical microscope to ensure no defects are observed.

9. Run the clean recipe and follow shutdown procedure for the Oxford Plasmalab 100 PECVD tool.

10. Prepare the samples for e-beam lithography by rinsing it with acetone and IPA, then baking at 180°C to de-moisturize.

11. Spin coat 1 layer of ZEP-520A resist at 2000RPM and 584 acceleration for 1min each. Then bake the sample at 180°C for 3mins to reflow the resist.

12. Inspect for defects or bubble under optical microscope.

13. Expose the resist using following parameters: Bulk: 25nm resolution, 230uC/cm$^2$ dose, 10nA current. Sleeve: 5nm resolution, 180uC/cm$^2$ dose, 1nA current.

14. Develop the sample in ZED-N50 developer solution for 65s. Then, immediately immerse the sample in MIBK:IPA (9:1) solution for 30s to stop the development. Finally, blow dry the sample with N$_2$ gun.

15. Inspect the exposed area under optical microscope. If pattern is under-developed, dip in the developer solution again for 5s. If the pattern is over-developed or the via opening is mis-aligned, repeat the e-beam lithography process.

16. Post-bake the sample at 100°C for 5 mins to harden the resist. This step improves selectivity to subsequent dry etching.
17. Prepare the Oxford PlasmaPro 100 Cobra ICP-RIE for oxide etching by running a 2 step clean recipe with Si carrier wafer: 3min SF$_6$ etch back followed by 10min O$_2$ clean.

18. Condition the chamber by running the oxide etch recipe. Recipe details: 200W RIE power, 30mT pressure, 38sccm Ar, 12sccm CHF$_3$, 10sccm He, 20°C table temperature.

19. Unload the Si carrier wafer and apply tiny drop of thermal paste, then affix the sample. Make sure thermal paste does not overflow. Blow dry the sample gently with N$_2$ gun.

20. Place carrier wafer into loadlock, pump to vacuum, load into chamber and run the CHF$_3$ oxide etch recipe for 5min15s.

21. Unload the carrier wafer to remove sample. Wipe the carrier with IPA and place back into chamber to run O$_2$ clean for 5min.

22. Condition the chamber and repeat the oxide etching process for next sample if necessary. Otherwise, unload the wafer and log off the tool.

23. Inspect the sample under optical microscope for any defects.

24. Strip resist by immersing sample in ZDMAC resist stripper at 90°C for 2 hours. A quick 5s sonicate clean can help to remove any resist residue. Then rinse the sample with acetone, followed by IPA, and blow dry with N$_2$ gun.

25. The sample is de-scummed in TePla Technics 100-E Oxygen Plasma Asher for 180s at 100W power and 0.3T pressure. Adjust the O2 knob until pressure of 0.3T is achieved.

26. Prepare the Trion Minilock RIE etcher for AlGaAs etch by turning on the Cl$_2$ and BCl$_3$ gas cylinders in the back (support area). Also, power on the roughing pump,
Appendix A. Detailed step-by-step fabrication process

27. Prepare the chamber by placing the Al carrier into chamber and run H2 clean, followed by O2 clean. Then switch to graphite carrier and repeat O2 clean. Reduce chiller temperature to 5°C and condition the chamber by running the AlGaAs etch recipe. Recipe details: 5mT pressure, 200W ICP power, 50W RIE power, 5sccm BCl₃, 4.5sccm Cl₂, 8sccm Ar, and etch time 120s. For DFB laser: 15mT pressure, 200W ICP power, 50W RIE power, 5sccm BCl₃, 4.5sccm Cl₂, 20sccm Ar, and etch time 105s.

28. After conditioning, load the sample and run the same recipe again. Limit each etch to 30s and leave 3 mins of cool down time in between, or else sample will over heat and be damaged.

29. Inspect the sample under optical microscope for defects/damages.

30. Run the O2 recipe using graphite carrier. Then, repeat etching if there are more samples, otherwise, follow shut down procedure.

31. Do not put sample in BOE after AlGaAs etch if there is high Al concentration layers in Bragg stack. It will cause the high Al % layer to be etched.

Stage 2: Electrical Isolation and Via Opening

1. Prepare the Oxford Plasmalab 100 for PECVD deposition by turning on the tool according to instructions. Physically clean the chamber, if necessary, and set the table temperature to 300°C. Be careful with the external temperature controller and follow the instruction carefully to prevent damaging the tool.

2. Run the O2 clean recipe for 15mins @ 300C.

3. Place samples on a Si carrier wafer and surround it by scrap Si pieces to minimize edge effects. Place the carrier wafer into loadlock and initiate pump down process.
4. Deposit PECVD oxide at 300°C for 2min50s using the recipe SiO₂ Eric (300°C). Recipe details: 30W RF power, 1000mT pressure, 170sccm 5%SiH₄/N₂, 710sccm N₂O.

5. Inspect the sample under optical microscope to ensure no defects are observed.

6. Run the clean recipe and follow shutdown procedure for the Oxford Plasmalab 100 PECVD tool.

7. Prepare the sample for e-beam lithography by rinsing it with acetone and IPA, and then baked at 180°C to de-moisturize.

8. Spin coat 2 layers of ZEP-520A resist at 2000RPM and 584 acceleration for 1min each. Then bake the sample at 180°C for 3mins in-between each layer to reflow the resist.

9. Inspect for defects or bubble under optical microscope.

10. Expose the resist using following parameters: Bulk: 25nm resolution, 230uC/cm² dose, 10nA current. Sleeve: 5nm resolution, 180uC/cm² dose, 1nA current

11. Develop the sample in ZED-N50 developer solution for 65s. Then, immediately immerse the sample in MIBK:IPA (9:1) solution for 30s to stop the development. Finally, blow dry the sample with N₂ gun.

12. Inspect the exposed area under optical microscope. If pattern is under-developed, dip in the developer solution again for 5s. If the pattern is over-developed or the via opening is mis-aligned, repeat the e-beam lithography process.

13. Post-bake the sample at 100°C for 5 mins to harden the resist. This step improves selectivity to subsequent dry etching.
14. Prepare the Oxford PlasmaPro 100 Cobra ICP-RIE for oxide etching by running a 2 step clean recipe with Si carrier wafer: 3min SF$_6$ etch back followed by 10min O$_2$ clean.

15. Condition the chamber by running the oxide etch recipe. Recipe details: 200W RIE power, 30mT pressure, 38sccm Ar, 12sccm CHF3, 10sccm He, 20°C table temperature.

16. Unload the Si carrier wafer and apply tiny drop of thermal paste, then affix the sample. Make sure thermal paste does not overflow. Blow dry the sample gently with N$_2$ gun.

17. Place carrier wafer into loadlock, pump to vacuum, load into chamber and run the CHF3 oxide etch recipe for 8mins.

18. Unload the carrier wafer to remove sample. Wipe the carrier with IPA and place back into chamber to run O2 clean for 5min.

19. Condition the chamber and repeat the oxide etching process for next sample if necessary. Otherwise, unload the wafer and log off the tool.

20. Inspect the sample under optical microscope for any defects.

21. Strip resist by immersing sample in ZDMAC resist stripper at 90°C for 2 hours. A quick 5s sonicate clean can help to remove any resist residue. Then rinse the sample with acetone, followed by IPA, and blow dry with N$_2$ gun.

22. The sample is de-scummed in TePla Technics 100-E Oxygen Plasma Asher for 180s at 100W power and 0.3T pressure. Adjust the O2 knob until pressure of 0.3T is achieved.

**Stage 3: Contact Deposition**
Appendix A. Detailed step-by-step fabrication process

1. Prepare the sample for e-beam lithography by rinsing it with acetone and IPA, and then baked at 180°C to de-moisturize.

2. First spin coat a layer of MMA at 5000RPM and 584 acceleration for 1min, then bake at 180°C for 3mins. Next, spin coat the PMMA-A5 layer using same condition, followed by another bake at 180°C for 3mins.

3. Inspect for defects or bubbles under optical microscope.

4. Expose the bi-layer PMMA resist using following parameters: 25nm resolution, 1200uC/cm² dose, 50nA current.

5. Develop the sample in MIBK:IPA (1:3) for 60s at room temperature, then immerse the sample in IPA for 30s to stop the development. Finally, blow dry the sample with N₂ gun.

6. Inspect the exposed area under optical microscope. If pattern is under-developed, dip in the developer solution again for 5s. If the pattern is over-developed, repeat the e-beam lithography process.

7. Dip sample in BOE for 5s to ensure good interface inside the via opening. Rinse the sample with DI water and bake it at 100°C for 5 mins.

8. Vent the Angstrom NEXDEP evaporator chamber. Remember to open the latches before venting, as the door will pop open once vented. Load the necessary crucibles and affix samples onto substrate holder. For oblique angle deposition, use 3 layers of scrap Si wafer as base, then affix sample by leaning against it with double sided carbon tape. Pump down the chamber after placing the substrate holder back into the chamber.

9. Wait 1 hour for the chamber to reach base pressure ∼2x10⁻⁶.
10. Deposit p-contact using recipes in following sequence - Ti: 20nm thickness, 1A/s dep rate, \( \sim 9\% \) power. Au: 400nm thickness, 2A/s dep rate, \( \sim 11\% \) power.

11. Wait 30mins after deposition before venting to let the crucible cool down. Open latches and vent chamber. Unload samples and crucible and pump down chamber.

12. Lift-off the metal by immersing the sample in warm acetone (60\(^\circ\)C) for 10mins. Agitate the sample inside warm acetone using a pipette. If the metal does not peel off after 15-20mins, then sonicate in warm acetone for 5s. Then rinse the sample in acetone and IPA and blow dry with \( N_2 \) gun.

13. Prepare the setup for sample thinning. First, heat the sample holder stub to 110\(^\circ\)C and melt mounting wax on it. Affix sample face-down to the stub, and then remove stub from hot plate. Flatten the sample using tweezer and wait 5mins for the wax to cool and solidify.

14. Set lapping fixture to a setting of 0.175 and attach sample holder stub to fixture with screw. Install a new silicon carbide polishing disc with 320 grit on the lapping machine.

15. Continuously flow water and begin rotation with a voltage setting of 40V.

16. After contacting the polishing disc, gently press down the fixture to apply some pressure. Rotate the fixture to allow for more uniform thinning. Measure the thickness of the sample periodically.

17. Then set lapping fixture to a setting of 0.16 and attach sample holder stub to fixture with screw. Install a new silicon carbide polishing disc with 1200 grit on the lapping machine.

18. Continuously flow water and being rotation with a voltage setting of 20V.
19. Repeat thinning process and measure the thickness of the sample periodically until desired thickness.

20. Remove sample holder stub from fixture and heat it to 110°C to melt the mounting wax on it. Carefully remove the thinned sample and immerse it in acetone for 10 mins. Rinse with acetone and IPA and gently blow dry with N₂ gun.

21. Vent the Angstrom NEXDEP evaporator chamber. Remember to open the latches before venting, as the door will pop open once vented. Load the necessary crucibles and affix samples onto substrate holder. Pump down the chamber after placing the substrate holder back into the chamber.

22. Wait 1 hour for the chamber to reach base pressure \( \sim 2 \times 10^{-6} \).

23. Deposit p-contact using recipes in the following sequence - Au: 45nm thickness, 2A/s dep rate, \( \sim 11\% \) power. Ge: 25nm thickness, 0.2A/s dep rate, \( \sim 5\% \) power. Ni: 30nm thickness, 0.2A/s dep rate, \( \sim 8\% \) power. Au: 120nm thickness, 2A/s dep rate, \( \sim 11\% \) power.

24. Wait 30 mins after deposition before venting to let the crucible cool down. Open latches and vent chamber. Unload samples and crucible and pump down chamber.

25. Cleave the sample by using the manual scriber in Pratt cleanroom. Place the sample on a blue adhesive tape, and scribe at the desired location. Then use a plastic non-adhesive layer to cover the sample to confine it. Finally, roll the sample over a round or sharp edge, the cleave marks should propagate along the crystalline axis.

26. Inspect the cleaved sample under an optical microscope, and then place in a mildly adhesive gel-pak.
Bibliography


