NON-SELECTIVE OXIDATION OF ALUMINUM GALLIUM ARSENIDE HETEROSTRUCTURES FOR HIGH PERFORMANCE CURVED WAVEGUIDE SEMICONDUCTOR LASERS

A Dissertation

Submitted to the Graduate School of the University of Notre Dame in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy by Jusong Wang

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Non-selective oxidation of AlGaAs heterostructure under oxygen-enhanced wet thermal conditions has been combined with deep dry etching via reactive ion etching (RIE) to achieve a high index contrast (HIC) ridge waveguide (RWG). The HIC RWG provides laser diodes with both strong optical confinement due to the high index contrast, and strong electrical confinement by eliminating current spreading. The oxide also effectively passivates the active region sidewall exposed after etching through the WG core layers. More importantly, the roughness of the sidewall, which leads to strong optical scattering losses in an HIC waveguide, has been greatly reduced by the smoothing action of the non-selective oxidation process. With such a structure, high performance straight laser diodes have been demonstrated on both quantum well (QW) and quantum dot (QD) heterostructures. In particular, a 4 μm wide QD laser fabricated with this deep dry etch plus non-selective oxidation process shows a 1.8 times lower threshold current...
density \( J_{th} \) than similar HIC lasers passivated with deposited \( \text{SiO}_2 \), and 6.5 times lower than conventional (shallow etched) index guided lasers.

The use of a HIC structure is absolutely critical to the realization of low bend loss curved waveguides and laser resonators. With a specially designed half-racetrack ring resonator (\( R^3 \)) pattern, the dependence of the radiative bend loss on the bend radius and ridge width is carefully studied. By implementing e-beam lithography for the patterning process, a half-racetrack-ring resonator with a 3.1 \( \mu \text{m} \) ridge width and a record small bend radius of \( r=3 \ \mu \text{m} \) is demonstrated. A new experimental method is demonstrated for characterizing the radiative bend loss from analysis of efficiency data of half-\( R^3 \) lasers with multiple cavity lengths. The radiative bend losses are extracted from an inverse efficiency \( 1/\eta_d \) vs. length \( L \) plot for half-\( R^3 \) lasers with \( r=150, 100, 50, 25 \) and \( 10 \ \mu \text{m} \) and three different ridge widths. In addition to the expected bend loss dependence on ring radius, we observe a clear trend of increased bend loss with increasing RWG width and number of WG modes supported. Finally, a full-ring laser with a 150 \( \mu \text{m} \) radius is fabricated using the developed e-beam lithography, deep dry etch via RIE and non-selective oxidation processes. The device shows a low \( J_{th} \) of 719 A/cm\(^2\), 25% lower than the best reported full ring laser having the same ring radius and a similar deep-etched waveguide structure fabricated using a deposited insulator.
To Xiaoli Shi, my beloved wife
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ABBREVIATIONS

CPG: circular pattern generator

cw: continuous wave

CW: clockwise

CCW: counter-clock wise

DBR: distributed Bragg reflector

DFB: distributed feedback

DI: de-ionized

EBL: electron beam lithography

FP: Fabry-Perot

FSR: free spectrum range

FWHM: full width at half maximum

GRINSCH: graded index separate confinement heterostructure

HIC: high index contrast

IILD: impurity induced layer disordering

IPA: isopropyl alcohol

LED: light emitting diode

LD: laser diode

MEK: Methyl Ethyl Ketone (MEK)

MFC: mass flow controller
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
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<tbody>
<tr>
<td>MIBK:</td>
<td>Methyl Isobutyl Ketone</td>
</tr>
<tr>
<td>MMI:</td>
<td>multimode interference</td>
</tr>
<tr>
<td>MOSFET:</td>
<td>metal-oxide-semiconductor field effect transistors</td>
</tr>
<tr>
<td>PECVD:</td>
<td>plasma enhanced chemical vapor deposition</td>
</tr>
<tr>
<td>PICs:</td>
<td>photonic integrated circuits</td>
</tr>
<tr>
<td>ppm:</td>
<td>parts per million</td>
</tr>
<tr>
<td>QD:</td>
<td>quantum dot</td>
</tr>
<tr>
<td>QDH:</td>
<td>quantum dot heterostructure</td>
</tr>
<tr>
<td>QW:</td>
<td>quantum well</td>
</tr>
<tr>
<td>QWH:</td>
<td>quantum well heterostructure</td>
</tr>
<tr>
<td>RIE:</td>
<td>reactive ion etching</td>
</tr>
<tr>
<td>rpm:</td>
<td>revolution per minute</td>
</tr>
<tr>
<td>RWG:</td>
<td>ridge waveguide</td>
</tr>
<tr>
<td>SEM:</td>
<td>scanning electron microscope</td>
</tr>
<tr>
<td>SOI:</td>
<td>silicon on insulator</td>
</tr>
<tr>
<td>UVO:</td>
<td>ultra-violet ozone</td>
</tr>
<tr>
<td>VCSELs:</td>
<td>vertical cavity surface emitting lasers</td>
</tr>
<tr>
<td>WG:</td>
<td>waveguide</td>
</tr>
</tbody>
</table>
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CHAPTER 1:
INTRODUCTION

1.1 Brief Review of AlGaAs Native Oxides

The success of Si as a dominant material in the modern integrated electronics world can be largely attributed to its native oxide SiO$_2$ grown under wet-thermal conditions. The insulating property of the oxide serves as a perfect candidate for the gate region of transistors and helped speed the development of integrated circuits based on CMOS technology. Furthermore, SiO$_2$ also provides a lower refractive index of n~1.55 compared with n~3.4 of Si. Benefiting from the well-developed processing techniques for electronic devices, Silicon-On-Insulator (SOI) wafer technology [1] has also become important for the design and fabrication of waveguide-based photonic devices [2] such as wavelength multiplexers and de-multiplexers [3]. However, limited by the fact that Si is an indirect bandgap material, SOI wafers cannot be utilized to fabricate light sources, presenting an insurmountable barrier for full functionality photonic integrated circuits (PICs) [4].

Most III-V compound semiconductors have direct bandgaps. Light emitting diodes (LEDs) [5] and laser diodes (LDs) [6] have long been commercially available with wavelengths ranging from 400 nm to 1550 nm, made possible by the varied bandgaps of compound semiconductor alloys. During the evolution of modern photonics technology, the discovery of AlGaAs native oxide films grown under wet-thermal conditions at the
University of Illinois (Urbana-Champaign) in 1990 by John Dallesasse et al. [7] initiated a small yet significant revolution in the world of optoelectronics. This native oxide, grown at ~350-500 °C in water vapor created from a N₂ carrier gas flowing through a heated H₂O bubbler, is believed to be a mixture of (AlₓGa₁₋ₓ)₂O₃, AlO(OH) and GaO(OH) compounds [8], and is much more dense and stable than the Al and Ga hydroxides formed by atmospheric hydrolysis at room temperature.

Similar to native SiO₂ on Si, the AlGaAs native oxide also has insulating and low-index (n~1.55) properties and is very suitable for both electrical and optical confinement as required for passive or active waveguide-based optoelectronic devices. With AlGaAs native oxide, metal-oxide-semiconductor field effect transistors (MOSFETs) have been demonstrated [9]; the performance of vertical cavity surface emitting lasers (VCSELs) has been greatly improved [10]; and enhanced edge emitting lasers [11], distributed feedback (DFB) lasers [12], low-bend-loss buried channel waveguides [13] have all been reported. As further shown in this work, the development of ring-resonator lasers for photonic integrated circuits is readily accelerated by the adoption of native oxide materials.
1.2 Non-Selective Oxidation of AlGaAs

For the conventional selective wet oxidation of Al$_x$Ga$_{1-x}$As, interest is generally limited to high Al content ($\geq$80%) materials since the oxidation rate bears a strong dependence on the Al ratio (x) as shown in Figure 1.1 [14] where oxidation rate is plotted on a log scale versus inverse temperature.

Figure 1.1 Oxidation rate vs. temperature for different Al ratio (x) in Al$_x$Ga$_{1-x}$As [14].
In contrast to its ideal application in VCSEL devices [10], the high oxidation selectivity of AlGaAs poses processing limitations for edge-emitting laser heterostructures. Consider, for example, the fabrication of oxide-confined index-guided edge-emitting lasers in an AlGaAs-GaAs quantum well heterostructure (QWH), such as the structure shown in the scanning electron microscope (SEM) image of Figure 1.2 [14]. The detailed crystal structure is shown in Figure 1.3.

![SEM image of selectively oxidized AlGaAs-GaAs quantum well (QW) heterostructures](image.png)

Figure 1.2 SEM image of selectively oxidized AlGaAs-GaAs quantum well (QW) heterostructures [14].

In 2001, Dr. Yong Luo at the University of Notre Dame demonstrated that non-selective oxidation of AlGaAs [14] can be achieved by adding small amounts (<1%) of oxygen to the process gas during wet-thermal oxidation. The added trace quantities of O$_2$ (<1%) and commonly used N$_2$ flowing through a heated bubbler form a "mixed carrier
gas" introduced into the oxidation furnace. It was found that the oxidation rate of low Al content (x≤0.4) Al<sub>x</sub>Ga<sub>1-x</sub>As material under this condition is greatly enhanced [15]. This effect has been shown to allow deep oxidation (through a heterostructure waveguide normally impenetrable by the oxidation front) as shown in Figure 1.4 [14] (same crystal structure as Figure 1.3), allowing a possible new means for achieving a high lateral index step suitable for curved waveguiding structures.

<table>
<thead>
<tr>
<th>Layer Description</th>
<th>Concentration</th>
</tr>
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<tbody>
<tr>
<td>p-type 50 nm GaAs : Zn cap</td>
<td>&gt;1×10&lt;sup&gt;19&lt;/sup&gt; cm&lt;sup&gt;-3&lt;/sup&gt;</td>
</tr>
<tr>
<td>p-type 1 µm Al&lt;sub&gt;0.80&lt;/sub&gt;Ga&lt;sub&gt;0.20&lt;/sub&gt;As : Zn</td>
<td>9.5×10&lt;sup&gt;17&lt;/sup&gt; cm&lt;sup&gt;-3&lt;/sup&gt;</td>
</tr>
<tr>
<td>75 nm Al&lt;sub&gt;0.20&lt;/sub&gt;Ga&lt;sub&gt;0.80&lt;/sub&gt;As</td>
<td></td>
</tr>
<tr>
<td>10 nm GaAs</td>
<td></td>
</tr>
<tr>
<td>75 nm Al&lt;sub&gt;0.20&lt;/sub&gt;Ga&lt;sub&gt;0.80&lt;/sub&gt;As</td>
<td></td>
</tr>
<tr>
<td>n-type 1 µm Al&lt;sub&gt;0.80&lt;/sub&gt;Ga&lt;sub&gt;0.20&lt;/sub&gt;As : Si</td>
<td>1.8×10&lt;sup&gt;18&lt;/sup&gt; cm&lt;sup&gt;-3&lt;/sup&gt;</td>
</tr>
<tr>
<td>n-type 500 nm GaAs : Si</td>
<td>1-4×10&lt;sup&gt;17&lt;/sup&gt; cm&lt;sup&gt;-3&lt;/sup&gt;</td>
</tr>
<tr>
<td>GaAs : Si</td>
<td>1-4×10&lt;sup&gt;18&lt;/sup&gt; cm&lt;sup&gt;-2&lt;/sup&gt; Substrate</td>
</tr>
</tbody>
</table>

Figure 1.3 Crystal structure of the quantum well heterostructure for the sample oxidized and shown in Figure 1.2 [14].
Figure 1.4 Deep oxidation through a low Al content waveguide layer through non-selective oxidation [14].
1.3 Waveguide Loss Mechanisms

The first potential application for deep, non-selective oxidation of AlGaAs heterostructures lies in the fabrication of waveguides and lasers with non-straight geometries. Because such devices are a main objective of this dissertation, we here address more fully the important issue of waveguide loss and the significance of the large lateral index contrast ($\Delta n \approx 3.4-1.6 = 1.8$), which can be achieved through deep oxidation.

The optical losses of a typical rib waveguide, as is shown in Figure 1.5 [16], can be classified into three mechanisms--- scattering, leakage and absorption.

![Figure 1.5 Schematic loss mechanisms in typical rib waveguides include (1) the epi-layer roughness, (2) the substrate leakage, (3) the rib-sidewall roughness, and (4) the defect and impurity absorption [16].](image)

Basically, absorption losses are related to the material bandgap, free carriers and deep energy levels [17]. The scattering results primarily from rough interfaces (both epilayer
boundaries and the etched rib surface). One theoretical treatment and model was proposed by Tien [18], who gave a formula for the scattering loss $\alpha_s$ of symmetric planar (1-D) waveguides as

$$\alpha_s = \frac{4\sigma^2 h^3}{\beta(t + 2l_p)} = \frac{\sigma^2 k_0^2 h E_s^2 \Delta n^2}{\beta \int E^2 \, dx} \quad (1.1)$$

where $\sigma$ is the interface roughness, $t$ is the waveguide thickness, $k_0$ is the free-space wave number, $\beta$ is the modal propagation constant, $\Delta n^2$ is the squared difference in the dielectric constants between the guiding and cladding layers, $h$ and $p$ are the transverse propagation constants in the guide and cladding layers, respectively, and $(E_s)^2$ is the optical intensity at the guide-cladding interface. Models for scattering loss in ridge-structure (2-D) waveguides require a full two-dimensional treatment of the waveguide cross section, resulting in additional complexity. However, with employing the "effective index approximation" [19], one can describe the ridge waveguide as an equivalent 1-D transverse index distribution, which can be ideally treated by equation (1.1).

The last loss mechanism is the leakage, which usually is expressed in a distributed manner and can result from radiation losses even in the absence of scattering losses. The distributed loss caused by bent features (e.g., ring or S-bend) is analogous to leakage [20]. Theoretical models have been proposed for distributed loss in 1-D planar waveguides, and can be applied to ridge waveguide bends with the effective index method. Experimental data of distributed bend-loss ($\alpha_b$) have shown good consistency with the following formulas [20],
\[ \alpha_b = K \exp(-cR) \]  \hspace{1cm} (1.2)

\[ c \approx \beta \left( \frac{2\Delta n_{\text{eff}}}{n_{\text{eff}}} \right)^{3/2} \]  \hspace{1cm} (1.3)

where \( K \) is a constant depending on the guide thickness and indices, \( \beta \) is the modal propagation constant (given by \( \frac{2\pi n_{\text{eff}}}{\lambda} \)), \( \Delta n_{\text{eff}} \) is the difference between the modal effective index and the cladding index, and \( R \) is the feature’s radius of curvature.

Generally, from equation (1.1), we can see that scattering loss increases with the square of index contrast \( \Delta n \). However, in the leakage mechanism for curved features, the radiation loss decreases exponentially with increased \( \Delta n \) as shown in equation (1.2) & (1.3). So, it is clear that in the straight geometry devices, in which scattering loss plays a dominant role, a small \( \Delta n \) is preferred. However, in curved geometry applications in which leakage loss dominates, especially when the radius is smaller than 150 \( \mu \text{m} \), large \( \Delta n \) is undoubtedly more desirable.
1.4 Optoelectronic Devices with High Index Contrast Structure

As discussed in Section 1.3, high index contrast materials are very desirable for waveguide-based devices with bent features. Based upon our unique process for non-selective oxidation of the low-Aluminum content core section of AlGaAs heterostructures, two types of waveguide structures, which provide a high refractive index contrast, are shown in Figure 1.6 and Figure 1.7.

![Figure 1.6 Planar oxide for large refractive index contrast. (a) before oxidation (b) after non-selective oxidation.](image)

Figure 1.6 shows a planar geometry waveguide formed by oxidizing directly after lithographic definition of a SiNₓ mesa. While this represents the simplest process for fabricating a waveguide (WG) with high refractive index contrast, the oxidation time is comparatively long (usually ≥60 minutes at 450 °C). In an alternative design shown in Figure 1.7, the sample, again with a lithographically defined SiNₓ mesa, is first dry-etched with Cl₂+BCl₃+Ar plasma in a reactive ion etching (RIE) system to define a ridge
waveguide. This waveguide is then subjected to a short non-selective oxidation cycle (usually \(\leq 20\) minutes) to grow an oxide on the sidewalls and base. While the first planar oxide structure allows less control of waveguide dimensions, some previous research has suggested that AlGaAs native oxide may have a greater thermal conductance than un-oxidized semiconductors and be helpful to laser diodes operating under continuous wave (cw) conditions. For other applications, the structure shown in Figure 1.7 has advantages of greater performance because the WG dimension is mainly controlled by lithography and optimized dry etching techniques. The subsequent non-selective oxidation can insulate the exposed heterostructure sidewall and passivate the air-semiconductor interface simultaneously. While the thermal properties of III-V native oxides merit further investigation, the laser diode fabrication in this work focuses on the deep etch plus oxidation approach to waveguide formation shown in Figure 1.7.

![Figure 1.7 Etch + oxidation process to reach large refractive index contrast while retaining the side wall insulating property showing (a) after dry etch in RIE system and before oxidation and (b) after non-selective oxidation.](image-url)
1.5 Dissertation Structure

In this work, a deep dry etch plus non-selective oxidation process is further developed towards photonic integrated circuit applications. In Chapter 2, several important design issues and considerations for cleaved-facet free unidirectional output racetrack-ring-resonator laser are discussed. In Chapter 3, the oxidation system and laser diode fabrication process are discussed. Electron-beam lithography method is adopted to pattern curved geometry waveguide structures. Large scale (~1 cm²) e-beam exposure tactics for optical device applications are also included in Chapter 3.

In Chapter 4, the performance of laser diodes is carefully studied for characterizing properties of high index contrast (HIC) AlGaAs heterostructure ridge waveguides. Straight laser diodes are first studied on an AlGaAs-based graded-index separate confinement heterostructure (GRINSCH) wafer. Improved device performance is observed and attributed to an improvement in sidewall quality after oxidation coming from both surface passivation and reduced roughness. Both broad area (>50 µm) and narrow ridge waveguide laser diode results are reported. The relative importance of these two effects (surface passivation and oxidation smoothing) on improved performance is further understood through results from the first native oxide confined high index contrast (HIC) structure GaAs based quantum dot laser heterostructure diodes. Dramatic improvement in the performance is demonstrated, which suggests that sidewall roughness is greatly removed by non-selective oxidation.

In Chapter 5, bend loss in curved waveguides fabricated with the non-selective oxidation is studied. The S-bend shaped laser diodes first studied demonstrate a low bend loss. Laser diodes with half-racetrack ring resonators are subsequently adopted to
more thoroughly characterize the influence of bend loss on device performance. Half racetrack ring resonator laser diode with ultra small bend radius of 3 µm is demonstrated. Then, to quantify the dependence of bend loss on bend radius, specially designed half R$^3$ laser diodes are explored. Through modification of the loss equation for straight laser diodes, the bend loss is extracted from a careful study of the dependence of laser efficiency on total laser diode cavity length. In addition to a strong dependence on bend radius, the bend loss also shows a clear dependence on the waveguide ridge width and corresponding number of optical modes supported.

In Chapter 6, a full ring laser diode with a simple tangential straight waveguide is demonstrated. A greatly reduced threshold current density ($J_{th}$) is observed, to our knowledge the lowest $J_{th}$ for this type of full-ring laser diodes ever reported. This result confirms the advantages of the deep etch plus non-selective oxidation process for achieving low loss ring resonators with promise for application in fully functional PICs. Finally, a work summary and future potential research directions are included in Chapter 7.
2.1 Racetrack Ring Resonators with Output Coupler Waveguide

Since their first demonstration in 1980 [21], semiconductor ring lasers have received increasing attention [22, 23]. The beauty of this kind of device is largely its lack of any requirement for mirrors or grating feedback reflectors, and the potential for single wavelength operation without grating feedback, giving it great promise for application in photonic integrated circuits.

Figure 2.1 shows a schematic design of a straight-waveguide-coupled racetrack-ring resonator laser. Unlike conventional diode lasers needing carefully cleaved facets to form the Fabry-Perot (FP) resonator for wave oscillation, the beam propagates around and the optical power is stored in the racetrack region. Under steady current injection, only a certain amount of light will be transferred out through the coupling region. This feature eliminates the requirements for wafer lapping, cleavage and facet coating and can significantly reduce the cost for laser diode manufacturing. Moreover, the racetrack region also provides a wavelength filtering effect since the free spectral range (FSR) is inversely proportional to the round-trip length of the racetrack resonator ($L_{\text{total}}$). A short racetrack will lead to a large FSR and can potentially provide single wavelength
operation without the usually required waveguide grating structure. Equation 2.1 below shows the formula for calculating the FSR in a racetrack resonator,

\[
FSR = \frac{c}{L_{total}} = \frac{c_0}{nL_{total}} \quad (2.1)
\]

\[
L_{total} = 2 \times (L_c + \pi \times r) \quad (2.2)
\]

where \(c_0\) is the vacuum light velocity, \(n\) is the modal index of refraction, \(L_{total}\) (Equation 2.2) is the racetrack cavity roundtrip length, and \(L_c\) is the length of the coupling region (as shown in Figure 1.8).

![Figure 2.1 Schematic design of waveguide-coupled racetrack ring resonator laser.](image)

An InP-based device with a racetrack ring master laser cavity resonator was reported with a radius of 150 µm and a threshold current density of 2145 A/cm² [24]. Below we discuss a few considerations regarding the design and fabrication of such racetrack ring resonator diode laser devices. First of all, reaching a low bend loss in the half ring region is essential. As discussed in Section 1.3, a high lateral refractive index contrast (\(\Delta n\)) is needed to meet this requirement. For active device applications, where metal is deposited
for electrical contacts, a dielectric layer is required between the metal and semiconductor ridge sidewall to provide electrical isolation and prevent optical absorption by the metal. SiN\(_x\) (n~1.9) and SiO\(_2\) (n~1.55) are commonly used, resulting in a maximum \(\Delta n\) of \(\sim 3.5-1.55 = 1.95\).

As discussed in Section 1.4, non-selective oxidation of AlGaAs heterostructure in conjunction with a dry etch process can lead to a cross-section structure as shown in Figure 2.2. This structure has a large refractive index contrast \((\Delta n \sim 1.8)\) as desired for reducing the radiation loss in the bent region as discussed in Section 1.3. The primary focus of this dissertation is to explore the further application of non-selective oxidation to novel devices suitable for photonic integration. Initial studies of the adopted structure (Figure 2.2) and non-selective oxidation process were performed by another group member (Dr. Di Liang) and several papers were published [25, 26]. In this early work, valuable studies on the relation between electrical insulating properties and the oxide thickness [26], the oxidation smoothing phenomenon [27] and the interface-passivating effect were reported. Building upon these advantages, several further steps toward the realization of working ring oscillator devices have been made in the work reported here. One of the primary tasks in the development of the racetrack-ring-resonator (R\(^3\)) laser device shown in Figure 2.1 is to explore the optimal radius for the racetrack resonator possible with our unique processing technique, both in terms of device performance and size. In order to separate this issue from others, half-racetrack-ring lasers have been designed and characterized as discussed in Chapter 5.
A second $R^3$ laser design consideration involves the coupling region which plays an important role in the device operation as an output coupler, analogous to the cleaved mirrors formed in common Fabry-Perot straight lasers. Several coupler designs have been demonstrated, such as a Y-junction [28] or multimode interference (MMI) couplers [29]. More recently, an $R^3$ laser device utilizing a directional coupler with a shallow-etched coupling channel between two parallel waveguides has been reported [24]. The advantage of this design is that it avoids the stringent lithography demands of deeply-etched couplers, which require electron-beam-lithography (EBL) [30] to meet an accuracy requirement at the tens of nm level. Based on this design, and integrated with our unique non-selective oxidation process, a coupler design with a cross-section as shown in Figure 2.3 is here proposed. To minimize the abrupt structure-induced mode loss and maintain high mode confinement, the sidewall etch depth in the curved section
of the racetrack is kept at the $d_1$ depth as shown in Figure 2.2. However, to enhance the coupling efficiency, the coupling channel region is shallow etched to $d_2$, stopping above the waveguide (WG) layer. With this bi-level design [24], the gap ($w_{\text{gap}}$) can be widened to ~1-2 µm, which is much more practically realizable than a ~100 nm-wide deep-etched gap [30] due to greatly reduced fabrication tolerances and the ability to use a conventional optical lithography process.

![Figure 2.3 Cross-section of coupling region integrating bi-level dry etch and non-selective oxidation processes.]

To ensure that conventional µm-level optical lithography is suitable for such a design, simulations were performed via the beam propagation method using OptiBPM 7.0.1 from OptiWave System Inc. Figure 2.4 shows (a) a top view of two parallel waveguides, the cross-sections of (b) the left half (uncoupled, deeply etched) and (c) right half (coupled,
shallow etched), with (d) the corresponding propagating optical power distribution. The ridge width \(w\) is 5 \(\mu\)m, gap is 2 \(\mu\)m wide, \(d_1\) is 2.4 \(\mu\)m and \(d_2\) is 1.5 \(\mu\)m. With an input from WG1, Figure 2.4(d) clearly shows the strong coupling effect in the shallow-etched coupler and absence of coupling in the deep-etched gap, high index contrast region to be used for waveguide bends. In Figure 2.5, simulation results from OptiBPM of the coupling ratio versus coupler length are plotted. From Equation 2.3 [17], which tells the relation between coupler length \(L\) and coupling ratio, a coupling constant \(\kappa\) of \(~0.0035\ \mu\text{m}^{-1}\) for such a structure is reached.

\[
\text{CouplingRatio} = \sin^2(\kappa L) = \frac{\text{Power}_{WG2}}{\text{Power}_{total}} \quad (2.3)
\]

Beside the bend loss in the racetrack and the coupler design, a third important consideration is the suppression of bi-directional beam propagation in the racetrack, which could induce mode competition and an unstable output mode in the \(R^3\) laser. As shown in Figure 2.6, with enough injection current in the racetrack region, two beam modes will simultaneously propagate in the clockwise (CW) and counter-clockwise (CCW) directions within the resonator. Generally, there is no preferred direction in the resonator since these two modes experience identical loss and compete for the same injection current. This phenomenon leads to an unstable output for each individual mode and decreases the overall performance of the laser.
Figure 2.4 Simulation of coupler. (a) top view of two parallel waveguides (WG1 & WG2); (b) cross-section of left 500 μm long waveguide (w=5 μm, deep-etched 2 μm wide gap); (c) cross-section of right 500 μm long waveguide (shallow-etched 2 μm wide gap); (d) top view of optical power distribution in the waveguides.
Figure 2.5 Coupling Ratio vs. Coupler Length. Nine data points are plotted and connected with a smooth line.

Figure 2.6 Bi-directional beam propagations in the racetrack resonator.
Although not implemented in this work, one approach, which has been shown effective at suppressing bidirectional operation, is to introduce an S-bend in the racetrack region [31]. As shown in Figure 2.7, the S-bend can have little influence on the CW beam propagation, while partially converting the CCW propagated beam into a CW beam. In other words, the CW directional propagated beam is enhanced and the output beam in this direction thus becomes favored. Experimental results on racetrack ring resonators incorporating such a supplemental S-bend [32] have demonstrated 83% of the total laser power emitted from the preferred output direction.

![Figure 2.7 S-bend integrated racetrack resonator designed for single directional beam propagation.](image)

Based upon the design considerations outlined above, our design of a straight-waveguide-coupled racetrack-ring-resonator laser is shown schematically in Figure 2.8. This design has several advantages and unique features including:
• Only conventional high dimension optical lithography (>1 µm) is required, avoiding the need for costly and time consuming EBL.

• Following dry-etching, the self-aligned non-selective oxidation step will result in a high index contrast structure suitable for a small ring radius (≤150 µm) with a low processing cost.

• Incorporation of S-bend to achieve unidirectional operation.

Figure 2.8 Optimized design of straight-waveguide-coupled integrated S-bend racetrack-ring-resonator laser.
2.2 Oxide-Defined Distributed Bragg Reflectors

To further enhance the unidirectional output of an R³ laser with straight output coupler, a distributed Bragg-reflector (DBR) grating can be integrated on the straight waveguide to reflect back light outcoupled in the undesired direction, as shown schematically in Figure 2.9. Additionally, such a DBR structure can be used in a full ring laser diode design to improve mode stability and overall device performance [33].

![DBR reflector](image)

**Figure 2.9** An R³ laser design with DBR reflector to enhance single direction output and wavelength stability.

In general, the DBR, as shown in Figure 2.9, is designed like a reflection-type diffraction grating, where partial reflection can only be achieved when the Bragg reflection wavelength $\lambda_B$ in vacuum satisfies Equation 2.4 [34],

$$ q \frac{\lambda_B}{n} = 2 \Lambda $$

(2.4)

where $n$ is the effective refractive index of the guiding medium, $q=1, 2, \ldots$ is an integer representing the diffraction order, and $\Lambda$ is the corrugation period. To form a periodic DBR structure (Figure 2.10) typically requires a combined process with etching and
crystal regrowth, which is both complex and costly from a manufacturability standpoint. A simple and cheap alternative processing technique to form the required periodic feature would be very attractive commercially.

![Figure 2.10 Schematic cross section of an edge-emitting laser diode with distributed Bragg reflector for single wavelength operation [34].](image)

The native oxide can be used to achieve such a periodic structure. Figure 2.11 shows the desired periodic structure realized almost exclusively through the isotropic nature of the oxidation process itself (although there is some mask-related enhancement present [35]). A DBR structure based on this observation is shown schematically in Figure 2.12 [35]. The small \( \Lambda \) dimension required here can be realized by electron beam lithography or a nano-imprinting technique [36], but the required thin top cladding layer (thickness=\( \Lambda/2 \leq 100 \) nm) greatly weakens the feasibility of this proposed approach.

25
Figure 2.11 SEM picture of oxidation enabled periodic structure desired for a distributed Bragg reflector [35].

Figure 2.12 Schematic design of DBR structure based on isotropic property of oxidation process [35].

Here, an improved design as shown in Figure 2.13 is proposed. Here we take advantage of the added dimension control provided by incorporating a dry etch process step to overcome the thin cladding limitation. Unlike the planar approach of Figure 2.12, the new design overcomes limitations posed by the insulating property of the native oxide
which blocks current flow to the region beneath the DBR grating, where current injection to this region is denied. The design of Figure 2.13 shows that the periodic index variation can be achieved through local oxidation, which leaves open interpenetrating semiconducting regions for electrical contact while also providing isolation between the optical mode and any metal contact films filling the trench areas. A 3-D drawing of such a design is shown in Figure 2.14.

![Figure 2.13 Improved design of oxide-defined semiconductor grating structure.](image)

As an important practical fabrication concern, such a structure can be achieved simultaneously with the HIC waveguide structure as shown in Figure 2.2 without the additional cost and complication of an MOCVD regrowth step.
Figure 2.14 3-D schematic of DBR design with non-selective oxidation process (a) before oxidation and (b) after oxidation. Top masked with SiN$_x$ during oxidation.
3.1 Setup of Oxidation System

The research discussed in this work depends upon the III-V oxidation system as shown schematically in Figure 3.1. In Figure 3.2, a photograph of the system is presented. The oxidation system consists of a Lindberg/Blue-M 3-zone tube furnace (1100 °C STF 55346C) with a long flat constant temperature region (~12 cm with ± 1 °C variation). It has four gas channels: two for nitrogen, and two for oxygen. Each channel is controlled by a mass flow controller (MFC), which gives precise control of gas flow rate and mixture. Specifically, gas channel 1 is used to flow purge nitrogen before and after oxidation, while gas channel 2 is used to flow ultra-high purity nitrogen through a heated water bubbler to bring water vapor into the furnace. Gas channel 3 is generally used for dry oxidation or annealing studies. Gas channel 4 allows accurate control for mixing a small amount of oxygen (1000-8000 parts per million (ppm) relative to nitrogen) into the process gas stream. During wet oxidation, the flow rate of MFC 2 is set to 0.67 l/min, which is chosen for its equivalence to the 1.4 standard cubic feet per hour (scfh) flow rate used in original oxidation studies at the University of Illinois at Urbana-Champaign [7].
Figure 3.1 Schematic of III-V Oxidation System.
To ensure the system is well sealed and isolated from the outside air, the plumbing utilizes only welded tubing and VCR connection fittings to valves following standard semiconductor industry standards. For more convenient and easier processing control, supplemental circuits were designed to provide front panel control of each mass flow controller channel, remotely controlling an MKS Instruments Inc. Type 247 four-channel controller. For testing and maintenance considerations, leak testing ports are incorporated into the system. The overall design of the system [37] ensures accurate mixing of dilute O$_2$ with N$_2$/H$_2$O and eliminates sources of uncontrolled contamination to increase the reliability and reproducibility of experimental results.
3.2 Waveguide and Laser Processing Steps with Optical Lithography

Detailed procedures for fabrication of native-oxide-confined ridge waveguide semiconductor diode lasers are described below.

1) The sample is soaked in acetone and isopropyl alcohol (IPA) for several minutes (~3-5 min) each to remove the surface dirt, and then blown dry with nitrogen.

2) Silicon nitride is grown (1000-5000 Å, ~150 Å/min) with plasma enhanced chemical vapor deposition (PECVD).

3) The adhesion promoter HMDS and photoresist AZ 5214 are spun on at 5000 revolutions-per-minute (rpm) for 45 seconds.

4) A soft-bake of the photoresist is performed at 105 °C for 60 seconds.

5) Lithography of a mesa mask proceeds with an exposure for a total energy of about 120 mJ/cm².

6) The photoresist is developed in AZ 327 MIF developer for ~40-50 seconds and rinsed in de-ionized (DI) water. The resulting pattern is examined under a microscope.

7) A hard-bake of the photoresist is performed at 120 °C for 60 seconds.
8a) The PECVD SiNx is etched via reactive ion etching (RIE) using a CF$_4$/O$_2$ plasma. SiNx is used as a mask for the RIE etch and oxidation processes.

8b) The AlGaAs epilayers are etched via RIE using a Cl$_2$/BCl$_3$/Ar plasma. The etch time for the high index contrast lasers in this work is calibrated to etch entirely through the active region and into the lower cladding layer.

9) Residual photoresist is removed with acetone in an ultrasonic bath for 5 minutes, followed by a 200-watt oxygen plasma cleaning step in the RIE system for 5 minutes.

10) The GaAs native oxide is removed from the exposed sample surface by etching in HCl: H$_2$O (1:4 volume ratio) for 10 seconds, followed by a rinse in DI water.

11) The sample is slowly loaded into the oxidation system supplied with H$_2$O vapor carried by N$_2$ and a certain concentration of added oxygen (~5000-7000 ppm) for wet oxidation.

12) After oxidation, the sample is slowly unloaded to minimize thermal stresses.

13) The SiNx on the sample top is selectively removed via RIE in CF$_4$/O$_2$ plasma to expose the highly-doped GaAs cap layer.
14) Steps 3) to 6) are repeated with a pattern to provide a “lift-off” of metal between laser stripes for electrical isolation during bar testing.

15) 200 Å-thick titanium and 2000 Å-thick gold layers are deposited in a model FC-1800 electron beam vacuum coating system.

17) The sample is soaked in acetone under ultrasonic agitation for metal lift-off.

18) The oxidized sample is lapped to ~110 µm with diamond lapping films, then polished with a fine-particle alumina suspension to get a smooth (mirror-like) surface (roughness <1 µm).

19) The sample p-side is coated with 800 Å-thick AuGe (88% Au)/130 Å-thick Ni/1500 Å-thick Au contact layers in a Varian thermal metal evaporator, followed by an alloy anneal at 405 °C for 30 seconds on a graphite strip heater under an N₂ ambient.

20) The sample is carefully cleaved into laser diode bars to provide parallel mirror facets forming a Fabry-Perot resonator cavity.

Important oxidation parameters are described below [37].

- The temperature of water in the 2-liter bubbler is set to 95 °C.
• The temperature of heating tapes wrapped on the tubes between the bubbler and the furnace is set to above 102 °C to prevent water vapor condensation.

• The flow rate of the N₂ carrier gas is 0.67 l/min.

Un-bonded laser diodes are characterized with a test-bed based upon a Keithley Model 2520 pulsed-current laser diode testing system. Near-field images are characterized on a Si reticon line scan camera with a short focal length lens positioned for a magnification of ~125×.
3.3 E-beam Lithography for Optical Device Applications

In the later stage of this work, e-beam lithography was adopted for two reasons. First, e-beam results in a better resolution pattern (smoother sidewall before dry etch). Second, e-beam lithography enables flexible in-house pattern design, especially for curved waveguides such as racetrack and ring shaped patterns.

For successful e-beam lithography, the patterns designed in OptiBPM waveguide layout software and exported in .gds format must be properly transferred to the Elionix CAD software. Because the Elionix CAD software will transform a full-ring pattern into two concentric disks, as shown in the left part of Figure 3.3, two half-rings were used to form the full ring pattern, as shown on the right in Figure 3.3. During the e-beam exposure process, the half-ring pattern is fractured into a series of rectangles stacked to each other for e-beam writing as for any other larger shaped patterns.

As an alternative to transferring a ring pattern from a .gds file, the built-in circular pattern generator (CPG) in the Elionix CAD software was explored. In this method, a series of concentric circles are generated to form the desired ring pattern, and the e-beam writing path will follow these circles instead of using rectangles. This method may be considered as the most ideal method to write curved patterns, however it leads to additional complexity if used in combination with .gds transformed patterns particularly for assigning exposure doses. A test exposure was performed for these two ring pattern generation methods, and little difference was observed in the developed patterns as shown in Figure 3.4. So, for simplicity, all following patterns in this work were generated only via .gds format and subsequently transformed to the Elionix CAD format.
For both CPG and .gds converted patterns, the same 5 nm grid size is used, which is defined by the chip width (1.2 mm) and number of grid points on each axis (240000). The resulting roughness in curve edge can be greatly reduced by smoothing during the non-selective oxidation process [27].

Figure 3.3 Ring pattern transform comparison in Elionix CAD software.

Another issue worth mentioning here is that of the “chip” size and “stitching”. In the Elionix system, the “chip” represents the exposure area achievable without moving the sample stage. There are several options, as large as 2.4x2.4 mm². It is easy to understand that the bigger the chip size, the fewer the chips and number of “stitch” areas between chips. However, for the biggest chip size, 2.4x2.4 mm², the e-beam accelerating voltage
can only reach 25 KeV during the exposure (instead of the 75 KeV of other chip sizes). This influences the e-beam focusing (exposure e-beam dot size) and overall exposure resolution result. Therefore, for this work, the second biggest chip size of 1.2x1.2 mm² is adopted.

Figure 3.4 Ring patterns (w=10 µm, r=150, 50, 30, 10 µm) comparison. (a) ring patterns generated by CPG, (b) ring patterns transformed from .gds file.

As the total pattern area is in general around 5x5 mm², an easy solution to avoid problems when stitching between chips in case there is a pattern longer than 1.2 mm is to overlap each chip by 1 µm to others. Otherwise a gap will likely appear in the chip connection area and ruin the device.

In Figure 3.5, a demonstration of the intentional overlapping of chips is shown, with different chips represented by different colored squares. During design of laser diode patterns for e-beam lithography, chip overlapping is usually only necessary in a direction which contains a feature longer than the chip size, for example the x direction in Figure
3.5. By overlapping chips (e.g., Chip 1 and Chip 2), as long as the left 0.5 µm-wide part in the Chip 1 and Chip 2 overlapping region is exposed during Chip 1 exposure, and the right 0.5 µm-wide part exposed during Chip 2, there will not be any gap in the long straight stripe run through Chip 1 and Chip 2. Although this small overlapping area has the potential for being double exposed, the influence of this can be neglected with optimized dose values. After chip overlapping, there is no distortion and no pattern features are lost. With this method applied during the placing of chips on design patterns, “stitching” issues can be avoided during large area exposures of optical device patterns in the Elionix system.

![Figure 3.5 Illustration of chip placement with 1 µm overlap (in x direction).](image)

In Figure 3.6, the laser diode fabrication process using e-beam lithography is illustrated schematically.
Figure 3.6 Process flow for e-beam lithography of laser diode resonator waveguides.
The process steps and parameters used in this work to optimize e-beam lithography for application to photonic devices are listed below.

1) Apply MMA (8.5%) with spinner at 3500 rpm for 45 second, then bake at 175 °C for 3 minutes.

2) Apply PMMA (1.5%) with spinner at 3500 rpm for 45 second, then bake at 175 °C for 4 minutes.

3) Design waveguide pattern with OptiBPM or L-Edit CAD software, then export pattern to .gds format file.

4) Convert .gds file to Elionix readable format. When chip matrix is generated in Elionix CAD software, overlap each chip by 1 μm to prevent stitching problems during exposure.

5) To expose waveguide patterns of widths under 5-μm wide, a dose of 400 uC/cm² is used. For waveguides wider than 5 μm, a dose of 200 uC/cm² is used. It is noted that dose values must be calibrated to adjust for variations in the MMA and PMMA solutions and thickness.

6) After e-beam exposure, develop PMMA/MMA in a solution of IPA: Methyl Isobutyl Ketone (MIBK) (3:1) with 1.5% volume Methyl Ethyl Ketone (MEK) for 15-30 seconds, then rinse with IPA.
7) Descum in an ultra violet ozone (UVO) for 5-10 minutes or in Emitech oxygen plasma asher for 1-2 minutes.

8) Deposit ~10 nm chromium (Cr) with FC 1800 metal evaporator. Cr acts as a mask for SiNₓ etch in RIE.

9) Lift-off chromium in Acetone and rinse with IPA. Soak sample in 70 °C nanoacryl for 3 minutes if MMA residue is found on the chromium edges under microscope inspection.

After this step, the sample is ready for SiNₓ removal via in RIE (step 8 in Section 3.2). And, during the following etching of AlGaAs epilayers with Cl₂/BCl₃/Ar plasma, the chromium thin film deposited on top of SiNₓ (as shown in Figure 3.6 (d)) is stripped off simultaneously.
CHAPTER 4:

STUDY OF AlGaAs HETEROSTRUCTURE LASER DIODES

4.1 Study of AlGaAs Quantum Well Heterostructure Straight Laser Diodes

4.1.1 Broad Area Laser Diodes

The objective of this project is to apply a new non-selective oxidation process for AlGaAs to the fabrication of laser diodes to improve overall device performance and enable novel device designs. To achieve this goal, an AlGaAs based graded-index separate confinement heterostructure (GRINSCH) has been purchased from EpiWorks Inc. While the full details of the wafer structure are proprietary, the design is very similar to that in Ref. [38]. The basic structural features are shown in Figure 4.1.

To characterize the laser heterostructure quality, broad-area laser diodes are first fabricated. In general, a broad area laser has a \( \geq 50 \, \mu \text{m} \) ridge width (w), such that the effects of current spreading and scattering losses at the stripe edge can be considered negligible. The ridge used here is 100-\( \mu \text{m} \) wide and 2.6 \( \mu \text{m} \) deep and defined by dry etching through the waveguide, followed by a 20-minute oxidation at 450 °C with 7000 ppm O\(_2\) added to the carrier gas.
In Figure 4.2, V-I (Voltage vs. Current) and L-I (Optical Output Power vs. Current) curves of the fabricated broad area lasers are presented. The differential series resistance above the turn-on voltage of 1.5853 V is ~1.6 ohm which also includes the stage and contact resistance between the fine probe tip and laser diode. The threshold current $I_{th}$, is 138 mA, and the length $L$ and area $S=L\times w$ of the laser cavity are 417 µm and $4.17\times10^{-4}$ cm², respectively, giving a threshold current density $J_{th}=I_{th}/S$ of 331 A/cm². The differential responsivity $R_d=\Delta P/\Delta I$ above threshold is 1.1 W/A, and the photon energy $E_{ph}=1.24eV\cdot\mu m/\lambda(\mu m)$ is 1.535 eV (corresponding to $\lambda=0.808$ µm), giving an external differential quantum efficiency $\eta_d=R_d/E_{ph}$ of 71.7%. This indicates that above threshold, >71 additional coherent photons are emitted for every additional 100 injected electron hole pairs. The data shown in Figure 4.2 is measured under pulsed injection current with
a pulse period of 25 µs and duty cycle of 4.8%. The total optical output power is mathematically twice the measured power from a single facet.

In Figure 4.3, the threshold current density $J_{th}$ is plotted vs. inverse laser cavity length, $L^{-1}$. For FP resonator laser diodes, the internal quantum injection efficiency $\eta_i$ has
a relation to external differential quantum efficiency $\eta_d$ as given by Equation (4.1) [39], where $\alpha_i$ is the laser cavity internal loss, $L$ is the cavity length, and $R_1$ & $R_2$ are the reflectance of the two FP resonator mirrors. With a simple modification, Equation (4.2) is reached. In Figure 4.4, the broad area laser efficiency data is plotted according to the format of Equation (4.2) such that the intercept gives the inverse injection efficiency, $1/\eta_i$, and the slope equals the internal loss $\alpha_i$.

$$
\eta_d = \frac{\eta_i}{1 + 2\alpha_i L / \ln(1/R_1 R_2)} \quad (4.1)
$$

$$
\frac{1}{\eta_d} = \frac{1}{\eta_i} \left(1 + \frac{2\alpha_i L}{\ln(1/R_1 R_2)}\right) \quad (4.2)
$$

In Table 4.1, the data shown in Figures 4.3 and 4.4 are compared with reported InGaAs (980 nm) [40, 41], InGaAsP (808nm) [42] and GaAsP (808 nm) [43] high efficiency broad area lasers. By convention, cavity lengths of 1 mm are selected for the comparison, with $L=1$ mm data for this work interpolated from Figures 4.3 and 4.4. From Table 4.1, we can see that the fabricated broad area lasers of this work have low threshold and high efficiency values which compare favorably with those in the literature.
Figure 4.3 $J_{th}$ vs. inverse cavity length of broad area GRINSCH lasers.
Injection Efficiency and Loss of Broad Area Laser Diodes

\[
\frac{1}{\eta_i} = \frac{1}{1.192} = 83.9\%
\]

\[
\alpha_i = 1.507 \text{ cm}^{-1}
\]

Figure 4.4 Differential external quantum efficiency of broad area lasers. From the linear fitting of the data, \(\eta_i=83.9\%\) and \(\alpha_i=1.5 \text{ cm}^{-1}\) are determined.
<table>
<thead>
<tr>
<th>Material</th>
<th>λ (nm)</th>
<th>$I_{th}$ (L=1 mm)</th>
<th>$J_{th}$ (L=1 mm)</th>
<th>$R_d$</th>
<th>$\eta_d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>This Work</td>
<td>InAlGaAs 808</td>
<td>180 mA</td>
<td>180 A/cm²</td>
<td>1.18 W/A</td>
<td>77%</td>
</tr>
<tr>
<td>Ref. [40]</td>
<td>InGaAs 980</td>
<td>120 mA</td>
<td>120 A/cm²</td>
<td>0.47 W/A</td>
<td>37.5%</td>
</tr>
<tr>
<td>Ref. [41]</td>
<td>InGaAs 980</td>
<td>201.5 mA (L~1.3 mm)</td>
<td>155 A/cm² (L~1.3 mm)</td>
<td>1.17 W/A</td>
<td>88.7%</td>
</tr>
<tr>
<td>Ref. [42]</td>
<td>InGaAsP 808</td>
<td>420 mA</td>
<td>420 A/cm²</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Ref. [43]</td>
<td>GaAsP 808</td>
<td>279 mA</td>
<td>279 A/cm²</td>
<td>1.38 W/A</td>
<td>90%</td>
</tr>
</tbody>
</table>
4.1.2 Straight and Narrow Ridge Waveguide Laser Diodes

The performance of the broad area lasers described above demonstrates that the basic laser fabrication processes have been successfully developed at Notre Dame. To test the suitability of the proposed high index contrast ridge waveguide structure for ring resonator lasers, we next fabricated narrow ridge (w=5.5 µm) straight lasers using the same wafer and processing. A typical L-I curve is demonstrated in Figure 4.5. The nonlinearity exhibited towards higher drive currents is due to thermal effects and is typical for un-bonded laser diodes. The differential responsivity from threshold to ~100 mA is 1.01 W/A, which leads to $\eta_d=65.8\%$. Figure 4.6 shows the near-field pattern parallel to the epilayer plane measured at 110 mA cw and demonstrates single-mode laser operation with a full width at half maximum (FWHM) of ~ 2.4 µm. From simulations in a 3-D mode solver program (OptiWave Inc.), we find that such a ridge structure (5.5 µm wide and 2.6 µm deep) is capable of supporting six modes. The observation of lasing in only the fundamental mode is attributed to its lowest loss among all the modes, enabling it to reach the threshold operation condition (i.e., the round trip gain equals the round trip loss) first, at which point the gain is clamped and unable to further increase to higher levels required for other modes to oscillate.
Figure 4.5 L-I curve of narrow ridge straight laser diode. Ridge width $w$ is 5.5 $\mu$m.
Figure 4.6 Near-field pattern of the narrow ridge straight laser diode. Laser is biased at a drive current of 110 mA cw.

In Figure 4.7, $J_{th}$ is plotted versus $L^{-1}$, with data of broad area laser diodes included for comparison. From a plot of $1/\eta_d$ versus $2L/\ln(1/R_1R_2)$ in Figure 4.8, a quantum injection efficiency of $\eta_i=78.3\%$ and internal loss of $\alpha_i=9.513$ cm$^{-1}$ are determined.
Figure 4.7 Threshold current density vs. inverse laser diode cavity length of broad area and narrow ridge straight laser diodes.
In the above section, data of straight laser diodes fabricated from a quantum well heterostructure using a deep etch plus oxidation process were presented. A more detailed study of this unique waveguide structure enabled by the non-selective (O\textsubscript{2} enhanced) wet thermal oxidation process has been carried out by Dr. Di Liang in our group \cite{25, 26, 44}. Comparison of the laser diode performance for this HIC structure with other conventional structures (mainly based on J\textsubscript{th} vs. L\textsuperscript{-1}) has suggested that the quality of the exposed sidewall created by deep etching through the active region is greatly improved by the
non-selective oxidation process. The performance improvement has been attributed to two factors. The first is the passivation effect on the sidewall during oxidation, which is believed to neutralize the traps and recombination centers generated by damage caused during the deep dry etching process. These traps act as electron-hole recombination centers, increasing the number of injected carriers lost to non-radiative processes and thus leading to an increase in the laser diode threshold current density, $J_{\text{th}}$. The other influence of non-selective oxidation is the sidewall roughness oxidation smoothing effect [45]. Both of these effects contribute to the improved device performance, but are coupled in that higher losses require increased injection levels. This in turn may cause a decrease in the efficiency with which carriers are collected by the quantum well (injection efficiency), apart from a decrease in non-radiative processes normally associated with the internal quantum efficiency. It is generally believed that above threshold, $\eta_i$ measures only this injection efficiency because stimulated emission rates are much faster than non-radiative processes [17].
4.2 Quantum Dot Heterostructure Laser Diodes

To further explore the application of the non-selective oxidation process and in an effort to separate these above two effects, studies employing a laser diode heterostructure containing a quantum dot active region [46] were performed on material provided by Dr. Serge Oktyabrsky’s group at the University of Albany, State University of New York. The detailed epi-layer structure is shown in Figure 4.9. The gain medium consists of 7-layers of InAs shape engineered QDs in GaAs QWs separated by 29 nm of Al$_{0.2}$Ga$_{0.8}$As.

Figure 4.9 Schematic of QD epi-layer structure.
It has been widely realized that the use of InAs quantum dot gain media can provide superior performance with regard to several laser diode parameters and the possibility to fabricate long-wavelength lasers on GaAs [46]. With a QD heterostructure, where the energy levels are more quantized than in a QW heterostructure and the injected current and carriers are confined in three dimensions by the quantum dots, the performance of laser diodes are relatively immune to non-radiative recombination centers at the sidewall. Thus, high index contrast ridge waveguide lasers formed in QD heterostructures by deep etching have been demonstrated with conventional deposited oxide dielectrics, whereas for QW heterostructures they have not before the introduction of our non-selective oxidation technique.

In order to explore the non-selective oxidation of this QD heterostructure and the non-selective oxidation enabled HIC waveguide, three sets of laser diodes are fabricated as shown in Figure 4.10.

As shown in the above Figure 4.10, sample A was shallow etched via RIE and then oxidized. Sample B and sample C were both deeply etched in RIE. After that, sample B was coated with SiO₂ via PECVD, and sample C was oxidized simultaneously with sample A. Both the native oxide (in sample A and C) and deposited SiO₂ (in sample B) are ~ 400 nm thick and have similar refractive indices (~1.55). We note that the thickness of the “non-selective” native oxide in sample C is not as uniform as achieved in our previous GRINSCH QW structure due to larger differences in Al ratio among epi-layers and anodic rate enhancement effects which can occur due to built in fields present at hetero-interfaces [47]. The laser diodes have widths ranging from 4 to 100 µm, and lase at λ~1.2 µm.
Figure 4.10 Cross-section schematic and SEM pictures of QD heterostructure ridge waveguide lasers. Sample A: shallow etch, native oxide; Sample B: deep etch, PECVD SiO₂; Sample C: deep etch, native oxide.
Figure 4.11 shows a comparison of the threshold current density ($J_{th}$) for these three sets of laser diodes with a similar cavity length ($L \approx 1$ mm). It is clearly shown that sample C (deep etch + native oxide) exhibits the lowest $J_{th}$ of $\approx 300$ A/cm$^2$ for all stripe widths $\geq 8$ µm. For sample A (shallow etch + native oxide) and B (deep etch + PECVD SiO$_2$), the minimum $J_{th}$ values are $\approx 500$ A/cm$^2$ for the broad-area ($w \geq 50$ µm) LDs, 1.66X higher than for sample C. For the narrowest stripe width of $\approx 4$ µm, the $J_{th}$ of 480 A/cm$^2$ for sample C is 1.78 times lower than that of sample B (853 A/cm$^2$), and 6.5 times lower than that of sample A (3122 A/cm$^2$). It can be seen that both QD laser diodes with HIC structures (both samples B and C) demonstrate better device performance than a conventional low index contrast structure (sample A) due to the elimination of current spreading [48-50].

For further comparison of the two HIC structures B and C, Figure 4.12 shows the output power vs. current for broad area (50 µm-wide) and narrow stripe (~7-8 µm-wide) devices, Figure 4.13 the injection efficiency $\eta_i$ vs. stripe width, and Figure 4.14 the internal loss $\alpha_i$ vs. stripe width as derived from analysis of inverse $\eta_i$ vs. L data (not shown).
Figure 4.11 Comparison of $J_{th}$ vs. laser diode stripe width $w$ for samples A, B and C.
Figure 4.12 Comparison of L-I curves for sample B (deep etch + PECVD SiO$_2$) and sample C (deep etch + native oxide).

unbonded, p-side up
300K, pulsed (10 kHz, 1%)
$\lambda \sim 1.2$ $\mu$m
LD cavity length $\sim 1$ mm

sample C
(native oxide)
(a) $w \sim 50$ $\mu$m
(b) $w \sim 6.7$ $\mu$m

sample B
(PECVD SiO$_2$)
(c) $w \sim 50$ $\mu$m
(d) $w \sim 7.6$ $\mu$m
Figure 4.13 Comparison of injection efficiency vs. width for samples B and C.
Figure 4.14 Comparison of internal loss ($\alpha$) vs. width for samples B and C.

Figure 4.13 shows that the injection efficiency of sample C is 1.4X higher than that of sample B for laser diode widths $\geq 20\ \mu m$, and 1.5X higher for $w\sim7\ \mu m$. Clearly, sample C, fabricated by combination of deep dry etching and non-selective oxidation, exhibits superior laser performance over samples A and B. This can be attributed to more effective optical and electrical confinement and, especially, the reduced sidewall scattering loss (as is evident from Figure 4.14) achieved through smoothing of sidewall roughness during non-selective oxidation [45]. Figure 4.14 shows a reduction of internal...
loss by 2.15X (from 25 cm\(^{-1}\) for sample B to 11.6 cm\(^{-1}\) for sample C) for the w~7 \(\mu\)m wide LDs due to the non-selective oxidation process. Although not evident from the unsmooth oxidation front in the cross sectional image of Figure 4.10(c), this oxidation smoothing reduces the scattering loss because it occurs along the z direction of beam propagation, as schematically shown in Figure 4.15. This is the first experimental data directly demonstrating the efficacy of oxidation smoothing for reducing the scattering loss in III-V compound semiconductor high index contrast waveguides, as can be seen from the following discussion.

Figure 4.15 Oxidation smoothing schematics.

In assessing the relative importance of the native oxide’s two roles in improving device performance as mentioned above (low-defect electrical passivation vs. propagation loss reduction via oxidation smoothing), the following can be considered. For similar length high index contrast ridge waveguide lasers passivated by a native
oxide versus a deposited oxide, the L~1 mm, 4 µm wide quantum dot (QD) heterostructure lasers of Figure 4.11 show a performance ratio $J_{th}(\text{PECVD SiO}_2, 853 \text{ A/cm}^2)/J_{th}(\text{native oxide, } 481 \text{ A/cm}^2)$ of ~1.77. From Figure 4.20 of Ref. [51], the L~335 µm, w~5 µm quantum well heterostructure curves show a ratio of $J_{th}(\text{PECVD SiO}_2, 2140 \text{ A/cm}^2)/J_{th}(\text{native oxide, } 1380 \text{ A/cm}^2)$ of ~1.55. If the primary disadvantage of using a deposited oxide was the introduction of a greater number of interface traps, the QD heterostructure devices should show a much small performance ratio as defined above due to their aforementioned immunity to interface recombination. As this is not the case, we can conclude that the more important role played by the native oxide in improving device performance is that of reducing scattering losses through oxidation smoothing. Because no similar comparative studies of loss and efficiency for deposited versus native oxide HIC devices have been performed for the GRINSCH QW heterostructure, no further useful conclusions can be made here regarding differences in the degree of oxidation smoothing on interface quality achieved via the application of non-selective oxidation to QD heterostructure vs. QW heterostructure deep-etched RWG lasers.
CHAPTER 5:

RADIATIVE BEND LOSS OF HIGH INDEX CONTRAST WAVEGUIDES
FABRICATED VIA NON-SELECTIVE OXIDATION

5.1 Bend Loss Study with S-Bend Shaped Laser Diodes

The development of curved waveguides, essential for photonic integrated circuits (PICs), began to draw research attention as early as the 1960’s [20]. Work in the mid-1990s by Prof. Nick Holonyak, Jr.’s group at the University of Illinois at Urbana-Champaign on “deep oxide” confined waveguides realized by combining impurity induced layer disordering (IILD) and traditional wet oxidation represented a notable advance for curved waveguides, but the process has not proven to be viable for manufacturing due to complexity and dimension control issues. Both S-bend waveguides [13] and half-ring lasers [52] are explored in this chapter to evaluate our new deep-etch plus non-selective oxidation high-index-contrast (HIC) ridge waveguide process.

For photonic integrated circuits, S-bend shaped waveguides are very useful for routing signals on chip. They are designed to avoid discontinuities in the radius of curvature so as to minimize mode mismatch loss [53]. To reduce the radiation loss in the region of bending, it is clear that an HIC structure is desirable as discussed in Chapter 1. S-bend laser diodes are fabricated as a first study of the reduced bend loss provided by the HIC waveguide explored in this work.
The S-bend shape, as shown in Figure 5.1, is defined by Equation (5.1) [53]. The curvature $\kappa$ and the radius of curvature ($r$) along the transition curve are approximately given by Equation (5.2) [53] and Equation (5.3) respectively.

Figure 5.1 Schematic of S-bend waveguide.

$$y = f(x) = \left(\frac{D_{\text{off}}}{l_{\text{tran}}}\right)x - \frac{D_{\text{off}}}{2\pi} \sin\left(\frac{2\pi x}{l_{\text{tran}}}\right) \quad (5.1)$$

$$\kappa = \frac{2\pi D_{\text{off}}}{l_{\text{tran}}^2} \sin\left(\frac{2\pi x}{l_{\text{tran}}}\right) \quad (5.2)$$

$$r = \left\{\frac{1 + \left[1 - \cos\left(\frac{2\pi x}{l_{\text{tran}}}\right)\right]^2}{\frac{D_{\text{off}} \cdot 2\pi}{l_{\text{tran}}^2} \cdot \sin\left(\frac{2\pi x}{l_{\text{tran}}}\right)}\right\}^{3/2} \quad (5.3)$$

where $D_{\text{off}}$ is the offset distance in the y direction and $L_{\text{tran}}$ is the transition distance in the x direction.

For a given $D_{\text{off}}$ (100 $\mu$m) and $L_{\text{tran}}$ (200 $\mu$m), the radius of curvature along the S-bend is plotted in Figure 5.2, and the radius reaches its minimum value ($r_{\text{min}}=79$ $\mu$m) at
positions x=38 µm and 162 µm. The $r_{\text{avg}}$ is defined as the average radius for the S-bend, which is 141 µm for this curve. In Figure 5.3, $r_{\text{min}}$ and $r_{\text{avg}}$ are plotted vs. $L_{\text{tran}}$ for a fixed $D_{\text{off}}$ value of 100 µm.

Figure 5.2 Curvature along S-bend waveguide for $D_{\text{off}}=100$ µm and $L_{\text{tran}}=200$ µm.
Based on such a pattern, S-bend laser diodes are fabricated with a fixed $D_{\text{off}} = 100$ µm and varied $L_{\text{tran}}$ ranging from 140 to 340 µm. All the laser diodes have a 5.5 µm ridge width and lasing wavelength of 810 nm. The measured variation in threshold current density versus $L_{\text{tran}}$ is plotted in Figure 5.4. It shows that $J_{\text{th}}$ values lie between 550 A/cm² and 620 A/cm², which is close to the $J_{\text{th}}$ of straight laser diodes (460 A/cm²) and implies a low radiation loss from the S-bend region.

Figure 5.3 Radius vs. $L_{\text{tran}}$ with $D_{\text{off}}=100$ µm. Average radius ($r_{\text{avg}}$) and minimum radius ($r_{\text{min}}$) are plotted.
Figure 5.4 $J_{th}$ of S-bend LDs. The red solid line represents $J_{th}$ value for straight LDs on the same bar with S-bend LDs.
5.2 Performance of Half-Racetrack-Ring Laser Resonator Diodes vs. Bend Radius

To more fully study the impact of bend radius on the bend loss and device performance for the HIC RWG structure, half-racetrack ring laser diodes have been designed. With the same processing steps and ridge dimensions (w=5.5 µm & etch depth=2.6 µm), half-racetrack ring geometry laser diodes are fabricated. To get a half-ring laser diode, only one well-cleaved facet is required for lasing. As shown in Figure 5.5, using a racetrack pattern instead of a circular ring simplifies fabrication by allowing considerable deviation in the cleave position while still achieving facets normal to the waveguide as required for maximum feedback. After one cleave, a half-ring laser with a straight region is obtained (the right part of Figure 4.5). The total cavity length is calculated from the equation \( L_{\text{total}} = l \times 2 + \pi \times r \), where \( l \) is the straight region length and \( r \) is the ring radius. To compare the impact of radius on \( I_{\text{th}} \) and \( J_{\text{th}} \), the mask pattern has been designed to maintain the same \( L_{\text{total}} \) for different laser diodes formed on the same bar. With such a design, the area of the laser cavity \( (\text{area}=L_{\text{total}} \times w) \) is a constant within a laser diode bar and the performance variations from each laser with different radii of curvature are proportional to the measured \( I_{\text{th}} \) so that the radiation loss of the bend region can be readily compared. In Table 4.1, an example of a cleaved laser diode bar is demonstrated. The mask layout for optical contact lithography in a 2 cm × 2 cm square is shown in Figure 5.6, and was fabricated outside Notre Dame by Compugraphics Inc.
Figure 5.5 Mask layout of half-racetrack ring laser diodes.

Table 5.1

HALF-RING LASER CAVITY LENGTHS ON A CLEAVED BAR WITH SIX DIFFERENT RADII

<table>
<thead>
<tr>
<th>radius</th>
<th>25 µm</th>
<th>50 µm</th>
<th>75 µm</th>
<th>100 µm</th>
<th>125 µm</th>
<th>150 µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>length of</td>
<td>324 µm</td>
<td>285 µm</td>
<td>245 µm</td>
<td>206 µm</td>
<td>167 µm</td>
<td>127 µm</td>
</tr>
<tr>
<td>straight region</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( L_{\text{total}} )</td>
<td>726 µm</td>
<td>726 µm</td>
<td>726 µm</td>
<td>726 µm</td>
<td>726 µm</td>
<td>726 µm</td>
</tr>
</tbody>
</table>
Figure 5.6 Optical mask layout design for half-racetrack ring laser diodes.

In Figure 5.7, L-I curves of five half-ring lasers contained on the same cleaved bar ($L_{\text{total}}=726 \, \mu\text{m}$) are plotted. A clear increase of $I_{\text{th}}$ and decrease of slope efficiency $R_d$ is observed as the ring radius is reduced from 150 $\mu\text{m}$ to 25 $\mu\text{m}$, showing the effect of increased bend loss.

In Figure 5.8, $J_{\text{th}}$ is plotted versus ring radius for three different bars having devices of 586, 726 and 1360 $\mu\text{m}$ total length. The plot clearly shows a simple trend for each length as expected. In such a half-ring laser diode where the straight sections have a lower
distributed loss compared with the bend section, a greater $L_{\text{total}}$ will lead to a weaker impact from the half ring region on the overall distributed loss and result in a decrease in the $J_{\text{th}}$.

Figure 5.7 L-I curves of half-racetrack lasers with different bend radius on the same bar. Ridge width $w$ for all lasers is 5.5 $\mu$m.
Figure 5.8 $J_{th}$ vs. radius of half-racetrack ring laser diode. Three bars with total cavity lengths as 586 µm, 726 µm and 1360 µm are included.

Figure 5.9 shows an L-I curve from a 10 µm radius half-racetrack ring laser diode with threshold current of 85 mA and $\eta_d$ of 7.9%. The $r=100$ µm half-ring laser diodes fabricated here with non-selective oxidation have comparable performance to those fabricated at UIUC with the more complicated IILD plus oxidation process [52]. In Chapter 6, we will present a more detailed comparison for published half and full ring laser results.
Figure 5.9 L-I characteristic of half-racetrack ring laser diode with a radius of 10 µm. The ridge width is ~5.5 µm.
5.3 Ultra-Small Bend Radius and High Performance Half-Racetrack Ring Resonator Laser Diodes via E-Beam Lithography

As discussed in Chapter 2, e-beam lithography (EBL) can lead to a smoother waveguide sidewall and give more flexibility for testing a variety of pattern designs. In this section, we show that by using EBL to pattern half-racetrack ring laser diodes fabricated by the deep etch plus non-selective oxidation process, their performance is greatly improved.

Figure 5.10 shows the optical output power vs. current characteristics for (a) r=25 µm, (b) r=10 µm and (c) r=8 µm half-racetrack ring resonator (R^3) lasers. The inset shows a top view SEM image of a similar 8-µm radius half-R^3 laser with a 10-µm wide ridge. For the 25-µm-radius half-R^3 laser, the threshold current is 78 mA, corresponding to a threshold current density of J_th=751 A/cm^2 for the L~1.04 mm total cavity length device. Relative to comparable length optically-patterned devices fabricated on the same wafer, this represents a 21% J_th decrease for the 25 µm half-R^3 laser (from J_th=945 A/cm^2, data not shown), and is only 1.5X higher than the J_th for similarly fabricated L~1 mm straight lasers from the same wafer [44, 54]. In addition, the r=25 µm device of Figure 5.10 (a) demonstrates a slope efficiency at 2xI_th of R_d=0.25 W/A (differential quantum efficiency η_d=16%), and a single-facet (2 emitters) peak output power reaching 239 mW. For comparison, similar straight HIC RWG lasers with width w=7 µm and cavity length L=452 µm have a threshold current density of J_th=679.5 A/cm^2 with R_d=1.19 W/A (η_d=78% for emission at λ~813 nm) for both pulsed and cw operation [25]. The kinks in
the L-I curve above ~100 mW suggest mode competition effects in these wider w~10 μm devices. We have shown elsewhere (for w=7 μm stripe straight lasers) that despite the HIC structure for which simulations predict a w~1 μm single mode cutoff width, the fundamental (lowest order) mode generally dominates during the lasing operation even to relatively high output powers as lasing of the higher-order modes is believed to be suppressed by their higher loss [25].

Figure 5.10 L-I curve for e-beam lithography defined half-racetrack ring resonator laser diodes with r=8, 10 and 25 μm.
Due to the reduced sidewall roughness achieved through the use of EBL, the $r=10 \ \mu \text{m}$ device exhibits a 31% decrease in $J_{\text{th}}$ and 29% increase in $R_d$ relative to similar length optically-patterned devices of [44, 54], and the slope efficiency of 40-$\mu \text{m}$ radius EBL-patterned half-$R^3$ lasers (data not shown) has doubled from that of Refs. [44, 54]. Figure 5.12 also shows a $r=8 \ \mu \text{m}$ half-$R^3$ device with a threshold current of $\sim 143$ mA and $J_{\text{th}}=1462 \ \text{A/cm}^2$, only 3.3X higher than that of straight lasers of similar length [44, 54].

With the same process, a half-$R^3$ laser diode with a bend radius of only $r=3 \ \mu \text{m}$ has also been successfully fabricated, as demonstrated by the I-V and L-I characteristics shown in Figure 5.11. The differential series resistance is 4.3 ohm for the device. With a threshold current of $I_{\text{th}}=49$ mA, ridge width of 3.1 $\mu \text{m}$, and total cavity length as 980 $\mu \text{m}$, $J_{\text{th}}$ is only 1613 A/cm$^2$. The device shows a differential responsivity $R_d$ of 0.33 W/A, and corresponding external differential quantum efficiency of 21%, much better than the 10 $\mu \text{m}$ radius optically-patterned device presented in Figure 5.4. The observation of laser operation from a resonator containing such a small radius to our best knowledge sets a world record, and is made possible by our unique deep-etch plus non-selective oxidation process and the smooth and precise patterning achievable through e-beam lithography.
unbonded, p-side up
300K, pulsed (1 kHz, 1%)
\( \lambda \sim 810 \text{ nm} \)

Figure 5.11 L-I curve of EBL patterned half-racetrack ring resonator laser diodes, with high efficiency and record small \( r=3 \, \mu\text{m} \) bend radius.
5.4 Characterization of Bend Loss in Half-Racetrack Ring Resonator Laser Diodes

For straight laser diodes, the total optical loss for one round trip of propagation within the laser cavity can be described by Equation (5.4), from which follows Equation (5.5) for the overall distributed loss coefficient, $\alpha_r$. The loss coefficient $\alpha_r$ consists of the mirror loss $\alpha_m$ given by Equation (5.6) and $\alpha_i$ which represents all other internal losses due to scattering and absorption. Because the mirror loss in fact represents power emitted from the laser cavity, it can be used to relate (via Eqn 5.7) the external differential quantum efficiency $\eta_d$ (change in number of coherent photons emitted for change in number of injected electron hole pairs) to the overall distributed loss coefficient $\alpha_r$ and injection efficiency $\eta_i$ (fraction of additional injected carriers collected by the quantum well active region).

$$e^{-2\alpha_r L} = R_1 R_2 e^{-2\alpha_i L} \quad (5.4)$$

$$\alpha_r = \frac{1}{2L} \cdot \ln \frac{1}{R_1 R_2} + \alpha_i \quad (5.5)$$

$$\alpha_m = \frac{1}{2L} \cdot \ln \frac{1}{R_1 R_2} \quad (5.6)$$

$$\eta_d = \frac{\alpha_m}{\alpha_r} \cdot \eta_i \quad (5.7)$$

For half-R$^3$ laser diodes, Equation (5.8) gives an equation similar to Equation (5.4), adding a factor for the round-trip total loss $\exp[-\alpha_{bend} \theta]$ for two passes ($\theta=360^\circ$ or $2\pi$) through the half-ring region, where $\alpha_{bend}$ represents the radiation bend loss coefficient
From Equation (5.8), Equations (5.9), (5.10) and (5.11) can be similarly derived.

\[ e^{-2\alpha_i L} = R_1 R_2 e^{-2\alpha_i L} \cdot e^{-2\pi \alpha_{\text{bend}}} \quad (5.8) \]

\[ \alpha_r = \frac{1}{2L} \cdot \ln \frac{1}{R_1 R_2} + \alpha_i + \alpha_{\text{bend}} \cdot \frac{\pi}{L} \quad (5.9) \]

\[ \eta_d = \eta_i \cdot \frac{\alpha_m}{\alpha_m + \alpha_i + \alpha_{\text{bend}} \frac{\pi}{L}} \quad (5.10) \]

\[ \frac{1}{\eta_d} = \frac{1}{\eta_i} \cdot \left[ 1 + \frac{\alpha_{\text{bend}} \cdot 2\pi}{\ln \left( \frac{1}{R_1 R_2} \right)} + \frac{2\alpha_i}{\ln \left( \frac{1}{R_1 R_2} \right)} \cdot L \right] \quad (5.11) \]

\[ \frac{1}{\eta_i} = \frac{1}{\eta_i} \left[ 1 + \frac{\alpha_{\text{bend}} \cdot 2\pi}{\ln \left( \frac{1}{R_1 R_2} \right)} \right] \quad (5.12) \]

From comparison of Equations (4.2) and (5.11), it is evident that the plot of inverse \( \eta_d \) vs. \( L \) for half-\( R^3 \) lasers diodes should have the same slope as that of straight laser diodes. The excess bend loss in Figure 5.16 represents the power loss, which includes optical power from all of the modes supported by the waveguide. By comparing Equation (5.11) with Equation (4.2), a new intercept term \( (1/\eta_i') \) is defined in Equation
The bend loss will only give an additional factor to the $1/\eta_i$ value of Equation (4.2) and thus influence the y-axis intercept obtained by a linear fitting of the data. Thus, the bend loss can be extracted based on the offset of the linear fit intercept for half-R³ lasers from that of straight laser data.

Therefore, to determine the $\eta_i$ and $\alpha_i$ from an inverse $\eta_d$ vs. L plot, a series of half-R³ laser diodes with the same ring radius and varied total cavity lengths are required, for which the new EBL pattern shown in Figure 5.12 was designed. With a fixed distance shift (d) between each racetrack pattern, a set of laser diodes with multiple cavity lengths are obtained after cleaving. Straight waveguides for each of the widths studied are also included in the pattern (not shown).

Figure 5.12 Pattern design for half-racetrack ring laser diode to characterize the excess bend loss.
With such a design, three sets of half-R^3 laser diodes with laser aperture width of \( w=2.1 \ \mu m, 4.2 \ \mu m \) and \( 7.3 \ \mu m \) have been fabricated, and the complete data of \( 1/\eta_d \) vs. \( L \) is presented in Figures 5.13, 5.14 and 5.15, respectively.

![Graph](image)

Figure 5.13 L-I summary of \( w=2.1 \ \mu m \) half-racetrack laser diodes.
Figure 5.14 L-I summary of $w=4.2 \, \mu m$ half-racetrack laser diodes.
Figure 5.15 L-I summary of $w=7.3$ μm half-racetrack laser diodes.

Linear fits to the data in each plot are obtained through least squares regression analysis, and a summary of the slope and $1/\eta_d$ intercept values is presented in Table 5.2. Based on the data collected, Equation (5.12) was applied to determine the excess 360-degree bend loss (one round trip through the half-racetrack ring resonator), as plotted in Figure 5.16. The error bars for each data point are obtained through analysis of the standard errors in the linear fitting.
### TABLE 5.2
DATA SUMMARY FROM FIGURES 5.13, 5.14 AND 5.15

<table>
<thead>
<tr>
<th>r (µm)</th>
<th>slope of linear fitting (mm⁻¹)</th>
<th>w=2.1 µm</th>
<th>w=4.2 µm</th>
<th>w=7.3 µm</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>straight LD</strong></td>
<td>1/η_d value @ L=0</td>
<td>1.300 ± 0.157</td>
<td>0.925 ± 0.120</td>
<td>0.587 ± 0.047</td>
</tr>
<tr>
<td>r=150 µm</td>
<td>1.468 ± 0.116</td>
<td>1.211 ± 0.089</td>
<td>1.177 ± 0.035</td>
<td></td>
</tr>
<tr>
<td></td>
<td>slope of linear fitting (mm⁻¹)</td>
<td>1.379 ± 0.198</td>
<td>0.962 ± 0.159</td>
<td>0.610 ± 0.164</td>
</tr>
<tr>
<td></td>
<td>1/η_d value @ L=0</td>
<td>1.723 ± 0.171</td>
<td>1.987 ± 0.167</td>
<td>2.479 ± 0.145</td>
</tr>
<tr>
<td>r=100 µm</td>
<td>Slope of linear fitting (mm⁻¹)</td>
<td>1.351 ± 0.188</td>
<td>0.934 ± 0.238</td>
<td>0.661 ± 0.159</td>
</tr>
<tr>
<td></td>
<td>1/η_d value @ L=0</td>
<td>2.143 ± 0.174</td>
<td>2.462 ± 0.173</td>
<td>2.925 ± 0.130</td>
</tr>
<tr>
<td>r=50 µm</td>
<td>slope of linear fitting (mm⁻¹)</td>
<td>1.253 ± 0.174</td>
<td>1.000 ± 0.134</td>
<td>0.507 ± 0.188</td>
</tr>
<tr>
<td></td>
<td>1/η_d value @ L=0</td>
<td>2.859 ± 0.127</td>
<td>3.095 ± 0.097</td>
<td>3.791 ± 0.157</td>
</tr>
<tr>
<td>r=25 µm</td>
<td>slope of linear fitting (mm⁻¹)</td>
<td>1.406 ± 0.251</td>
<td>0.867 ± 0.184</td>
<td>0.615 ± 0.166</td>
</tr>
<tr>
<td></td>
<td>1/η_d value @ L=0</td>
<td>3.300 ± 0.161</td>
<td>3.704 ± 0.134</td>
<td>4.820 ± 0.111</td>
</tr>
<tr>
<td>r=10 µm</td>
<td>slope of linear fitting (mm⁻¹)</td>
<td>1.324 ± 0.758</td>
<td>0.980 ± 0.220</td>
<td>0.536 ± 0.161</td>
</tr>
<tr>
<td></td>
<td>1/η_d value @ L=0</td>
<td>3.747 ± 0.574</td>
<td>4.353 ± 0.143</td>
<td>5.362 ± 0.097</td>
</tr>
</tbody>
</table>
The excess bend loss is calculated from the data in Table 5.2 by the process described in the example that follows. For \( w=7.3 \ \mu m \) straight and \( r=10 \ \mu m \) half-racetrack laser diodes, the \( 1/\eta \) values (\( 1/\eta_d \ @ \ L=0 \)) are 1.177 and 5.362 respectively. By rearranging Equation (5.12), we get \( \alpha_{bend} \cdot 2\pi \) as shown in Equation (5.13), in which \( \alpha_{bend} \) represents the bend loss coefficient in units of inverse radians (rad\(^{-1}\)) such that \( \alpha_{bend} \cdot 2\pi = 8.521 \) is the exponent in the bend loss factor of Equation (5.8) corresponding to the total bend loss for 360° of bending. The loss coefficient in rad\(^{-1}\) can be converted to dB/rad by Equation (5.16), directly analogous to the conversion of attenuation coefficients in m\(^{-1}\) to dB/m [34]. Because the exponent term extracted via Equation (5.13) already includes the full bend revolution angle of \( 2\pi \), we find the total 360° bend loss in dB to be 4.343x8.521=37.013 dB.

\[
\alpha_{bend} \cdot 2\pi = 2\pi \left[ \frac{1}{\frac{1}{\eta_i} - 1} \right] \ln \left( \frac{1}{R_1 R_2} \right) \quad (5.13)
\]

\[
R_1 = R_2 = \left( \frac{3.4 - 1}{3.4 + 1} \right)^2 \approx 0.3 \quad (5.14)
\]

\[
\alpha_{bend} \cdot 2\pi = \left( \frac{5.362}{1.177} - 1 \right) \ln \left( \frac{1}{0.3^2} \right) = 8.521 \quad (5.15)
\]

\[
\alpha_{bend} \left( \frac{dB}{rad} \right) = \frac{10}{\ln(10)} \cdot \alpha_{bend} \left( rad^{-1} \right) = 4.343 \times \alpha_{bend} \left( rad^{-1} \right) \quad (5.16)
\]
As we can see in Figure 5.16, the excess bend loss follows two trends. First, it increases with decreased bend radius, in agreement with the discussion in Section 1.3 (Waveguide Loss Mechanism) and the data in Section 5.2, where the threshold current density $J_{th}$ increased and the external differential quantum efficiency $\eta_d$ decreased for a reduced bend radius value. The second observed trend, where the bend loss decreases with reduced ridge width, merits further discussion below.

Figure 5.16 Bend loss of half-racetrack ring resonator laser diodes for waveguide widths of 2.1, 4.2 and 7.3 μm.
We can explain the lower bend loss in narrower stripe width laser diodes as follows. Based on mode calculations in OptiBPM, the wider waveguides support more modes than the narrower waveguides. For example, the w=7.3 μm HIC waveguide supports 14 modes, the w=4.2 μm waveguide supports 7 modes and the w=2.1 μm waveguide supports 3 modes. These modes experience different degrees of radiation loss in the bend region. Higher order modes have a higher bend loss as they extend further into the cladding layer (the native oxide grown on the ridge sidewall) and thus experience more scattering due to sidewall roughness and absorption by the metal overcoat. Therefore, wider waveguides, because they support more higher order modes, exhibit greater bend loss in the ring region.

The linear fitting for straight laser diodes and half-racetrack ring laser diodes collected in Figures 5.13, 5.14 and 5.15 do not demonstrate perfectly matched slope values. However, the differences in slopes are less than 6.2% for w=2.1 μm lasers, less than 8.4% for w=4.2 μm lasers, and less than 13.5% for w=7.3 μm lasers. In addition, the data in Figure 5.16 follows an exponential relationship, where the bend loss increases exponentially with decreasing bend radius, as predicted by Equation (1.2).

In Figure 5.17, scattering loss (determined from straight lasers) and excess bend loss are combined together as the total loss, as given by Equation (5.17), and plotted vs. bend radius. This calculated loss is equivalent to the total round trip loss of a circular full ring resonator. By comparison with Figure 5.16, we can see that the total loss is dominated by scattering loss for ring lasers with large radius (~150 μm), where the ridge width is less important. For lasers with small radius (<50 μm), reducing the ridge width so as to reduce the number of modes is the most effective way to reduce overall loss. Based on
this understanding of the bend loss mechanism, a low bend loss ring laser should have a single mode structure, which necessitates a reduction in the ridge width to ~0.9 μm for the high index contrast structure in this work operating at a wavelength of λ~808 nm.

\[
\alpha_{total} = \alpha_b \left( dB / rad \right) \cdot 2\pi + \alpha_s \left( dB / cm \right) \cdot 2\pi r \quad (5.17)
\]

Figure 5.17 Calculated total bend loss plus scattering loss of full ring laser diodes.
In Chapters 4 and 5, straight laser diodes and half-racetrack ring laser diodes realized through a non-selective-oxidation enabled high index contrast ridge waveguide structure have been demonstrated. The structure provides both high confinement for the injected charge carriers by eliminating the current spreading and high confinement for the optical modes through its large lateral refractive index step (~1.7). The native oxide grown non-selectively on the heterostructure sidewall simultaneously passivates surface states to reduce non-radiative recombination and significantly smoothes roughness to reduce scattering optical loss. As a result, greatly improved device performance has been demonstrated.

For future photonic integrated circuits (PICs), eliminating the facet cleaving step central to the fabrication of conventional Fabry-Perot resonator diode lasers is a key requirement for full functionality monolithic integration. As discussed in Chapter 1, a full ring laser diode can serve such a purpose and such a device has been an important driving motivation for this work.

Figure 6.1 illustrates a simple full ring laser pattern design implemented here by e-beam lithography. The full circular ring pattern is placed in direct connected with a straight waveguide for the optical output. To better collect the output beam, end facets are still cleaved to achieve a smooth surface. However, such surfaces provide a certain level of undesired optical reflection and feedback. With two cleaved facets (A and B), as
shown in Figure 6.1, the straight output waveguide biased with injected current can operate like a straight laser diode in competition with the ring resonator if they are not isolated. To prevent this, two design considerations are incorporated. First, the straight output waveguide was tilted 7° from normal to the cleaved facets [55, 56]. This can greatly reduce the reflectance of the output facet so as to reduce the feedback [57]. Second, the ring resonator was electrically isolated from the output waveguide. By only injecting current into section containing the ring, the straight waveguide will not have enough electrical pumping to reach the minimum gain required for lasing. A schematic diagram and a microscope image of the ring laser diode implementing these design considerations are presented in Figure 6.2. These full ring patterns were exposed simultaneously with the half-racetrack pattern described in Section 5.3. As this EBL layout and exposure preceded the analysis of bend loss and its dependence on waveguide width as presented in Chapter 5, only ring patterns with non-optimal 6 µm wide waveguides were fabricated.

Figure 6.1 Schematic of full ring laser diode design.
Figure 6.2 Schematic diagram and microscope image of a full-ring laser diode. The straight output waveguide is electrically separated from the ring resonator.

Figure 6.3 shows the L-I characteristic for a full ring laser diode with ring radius of 150 μm and ridge width of 6 μm. The device has a threshold current of ~57 mA. As shown in Figure 6.2, the total biased region includes the ring resonator and the contacted section of straight waveguide, a total electrically-pumped length of ~1322 μm (2πr+380 μm), giving a threshold current density of ~719 A/cm². For this device, the two separate unbiased output sections are 40 μm and 270 μm long. The optical power was measured through the shorter and thus less absorbing 40 μm section. It has been shown by others [22] that two such electrically isolated straight sections can be reverse biased to act as photodiodes [22] to characterize the optical power in the CW versus CCW directions. Such a test was not included in our study of the general ring laser diode performance characteristics (I_th, J_th, η_d).
As the output waveguide only tangentially touches the ring resonator, only a small fraction of the oscillating laser power is coupled out for detection purposes. Thus, the slope efficiency $R_d$ of 38.5 mW/A is low as expected, corresponding to an external differential quantum efficiency $\eta_d$ of 2.6%. It is anticipated that the quantum efficiency can be increased by further optimization of the output coupler or use of a unidirectional output design [58].

![Graph](image)

Figure 6.3 L-I curve of a full ring laser diode.
In the following Table 6.1, we compare data from this work (for both half-racetrack and full ring laser diodes) with other reported results on full ring laser diodes. In comparison to published results on full ring laser diodes with a similar heterostructure and high index contrast structure (deep etch with same ridge width) [59], our device demonstrates a ~25% lower threshold current density \( J_{th} \) (719 vs. 960 A/cm\(^2\)) for the same radius (150 \( \mu \)m) and ridge width (6 \( \mu \)m). We attribute this excellent performance to our unique process which combines a deep etch plus non-selective oxidation to form the high index contrast ridge waveguide structure, providing greatly reduced sidewall roughness and effective sidewall passivation.

Additionally, from the study in Chapter 5, especially Section 5.3, we expect that the bend and overall loss in the ring region can be further reduced by reducing the ridge width to achieve operation in the single mode regime.
### TABLE 6.1
COMPARISON WITH REPORTED HALF-RING AND RACETRACK RING LASERS

<table>
<thead>
<tr>
<th>Material</th>
<th>Radius (µm)</th>
<th>Ridge Width (µm)</th>
<th>I&lt;sub&gt;th&lt;/sub&gt; (mA)</th>
<th>J&lt;sub&gt;th&lt;/sub&gt; (A/cm²)</th>
<th>R&lt;sub&gt;d&lt;/sub&gt; (W/A)</th>
<th>η&lt;sub&gt;d&lt;/sub&gt;</th>
<th>Uniqueness</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>This Work</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>InAlGaAs (810 nm)</td>
<td>3</td>
<td>3.1</td>
<td>49</td>
<td>1613</td>
<td>0.33</td>
<td>21%</td>
<td>Non-selective oxidation of AlGaAs, half-R&lt;sup&gt;3&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>5.5</td>
<td>40</td>
<td>1000</td>
<td>0.39</td>
<td>26%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>6</td>
<td>57</td>
<td>719</td>
<td>0.039</td>
<td>2.6%</td>
<td>full ring</td>
</tr>
<tr>
<td><strong>Ref. [52]</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AlGaAs-GaAs (829 nm)</td>
<td>100</td>
<td>5</td>
<td>13</td>
<td>860</td>
<td>0.38</td>
<td>25%</td>
<td>HILD plus oxidation, half ring</td>
</tr>
<tr>
<td><strong>Ref. [59]</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>InAlGaAs (~850 nm)</td>
<td>150</td>
<td>6</td>
<td>-</td>
<td>960</td>
<td>-</td>
<td>-</td>
<td>HIC, ring, output coupler</td>
</tr>
<tr>
<td><strong>Ref. [24]</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>InGaAsP (~1598 nm)</td>
<td>150</td>
<td>2.5</td>
<td>66</td>
<td>2145</td>
<td>-</td>
<td>-</td>
<td>bi-level etching</td>
</tr>
<tr>
<td><strong>Ref. [58]</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>InAlGaAs</td>
<td>150</td>
<td>6</td>
<td>95</td>
<td>930</td>
<td>0.11</td>
<td>7.8%</td>
<td>racetrack, unidirectional</td>
</tr>
<tr>
<td><strong>Ref. [33]</strong></td>
<td></td>
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<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- (1001 nm)</td>
<td>200</td>
<td>5</td>
<td>52</td>
<td>508</td>
<td>0.017</td>
<td>2.1%</td>
<td>unidirectional output</td>
</tr>
<tr>
<td><strong>Ref. [22]</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>InAlGaAs</td>
<td>200</td>
<td>6</td>
<td>87</td>
<td>960</td>
<td>0.052</td>
<td>3.7%</td>
<td>full ring, unidirectional</td>
</tr>
<tr>
<td><strong>Ref. [23]</strong></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>InGaAs (980 nm)</td>
<td>225</td>
<td>50</td>
<td>-</td>
<td>80</td>
<td>0.26</td>
<td>20.4%</td>
<td>broad area</td>
</tr>
<tr>
<td><strong>Ref. [60]</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>InGaAs (980 nm)</td>
<td>225</td>
<td>50</td>
<td>52</td>
<td>105.87</td>
<td>0.285</td>
<td>22.4%</td>
<td>broad area</td>
</tr>
<tr>
<td><strong>Ref. [61]</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>InGaAs (1020 nm)</td>
<td>1000</td>
<td>3</td>
<td>360</td>
<td>117</td>
<td>-</td>
<td>-</td>
<td>unidirectional output</td>
</tr>
<tr>
<td><strong>Ref. [62]</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>InAs (1240 nm)</td>
<td>1000</td>
<td>3</td>
<td>923</td>
<td>300</td>
<td>-</td>
<td>-</td>
<td>quantum dots</td>
</tr>
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</table>
CHAPTER 7:
SUMMARY AND FUTURE DIRECTIONS

The application of non-selective heterostructure oxidation to photonic devices has been carefully studied. A robust fabrication process involving e-beam lithography has been developed at the University of Notre Dame for novel photonic device applications. In particular, pattern generation, chip matrix positioning and related “stitching” problems, and circular pattern exposure options have been explored in depth.

By combining a deep etch process via reactive ion etching with non-selective oxidation of an AlGaAs heterostructure, straight laser diodes with a high index contrast ridge waveguide structure have been fabricated on both quantum well and quantum dot heterostructures. The improved device performance shows that sidewall roughness and recombination centers resulting from dry etching damage have been greatly reduced. QD laser diodes fabricated with this process exhibit more than a two times reduced internal loss ($\alpha_i$) when compared with PECVD SiO$_2$ coated HIC devices, attributed mainly to the sidewall roughness smoothing effect.

Beyond simply improving the performance of straight laser diodes, the greatest feature demonstrated here for the high index contrast structure realized in this work for enabling future integrated photonic devices is its simultaneous provision of low bend loss and low scattering loss. A half-racetrack ring laser diode with a bend radius as small as 3 $\mu$m has been achieved. From measurements on fixed total cavity length half-racetrack
ring laser diodes, the dependence of bend loss on bend radius has been observed by way of a decreasing threshold current density $J_{th}$ and increasing external differential quantum efficiency $\eta_d$ with increasing radius from 25 to 150 µm.

By incorporating the bend loss factor into diode laser equations, we have proposed and demonstrated a new experimental method for characterizing bend loss from an analysis of the slope efficiency versus length data for half-racetrack ring resonator lasers. The technique is applied to half-racetrack ring resonator laser diodes with widths of $w=2.1$ µm, 4.2 µm and 7.3 µm to demonstrate that the bend loss decreases as the stripe width and corresponding number of supported waveguide modes decreases.

Building upon the notable improved device performance of straight laser diodes and half-racetrack ring laser diodes, and moving towards future application in photonic integrated circuits, a simple full ring laser diode ($r=150$ µm, $w=6$ µm) has been fabricated. Even without optimal ridge width or output coupler design, the full ring laser exhibits a threshold current density 25% lower than published results for a comparable laser diode heterostructure. Improved performance is expected with further design optimization, particularly a transition to a single-mode waveguide dimension.

Aiming towards more advanced racetrack ring resonator laser diodes, the design for a output coupler using bi-level etching (i.e., a shallow etched trench in the coupler region) has been simulated using the beam propagation method. In addition, a simple surface-etched distributed Bragg-reflector (DBR) grating made possible by non-selective oxidation has also been proposed. The DBR can be achieved simultaneously with the HIC waveguide fabrication without the need for the traditional regrowth process. Low loss S-bend waveguides, a useful component for promoting unidirectional oscillation and
optical output from an R3 device, have also been demonstrated during initial bend loss characterization studies.

With well-developed processes for high index contrast ridge waveguide laser diode fabrication featuring e-beam lithography, deep reactive ion etching and non-selective oxidation of AlGaAs heterostructures, a bright path towards future integrated optoelectronic devices and photonic integrated circuits (PICs) has been illuminated at Notre Dame.
BIBLIOGRAPHY


