QUANTUM WELL INTERMIXED TWO SECTION

SUPERLUMINESCENT DIODES

BY

NICHOLAS S. LEESON

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By

NICHOLAS STEPHEN LEESON, B.ENG

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Abstract:

Superluminescent diodes have become important for various applications, such as for biomedical imagining, due to their broad spectral width and high power.

This thesis demonstrates two-section superluminescent diodes fabricated using quantum well intermixing with strained $Ga_{0.75}In_{0.25}As$ quantum wells, grown on a GaAs substrate. A 100 nm capping layer of $Ga_{0.515}In_{0.485}P$ grown at low temperature and having an excess of phosphorus, was removed from one section of the device to produce a relative bandgap shift between sections after rapid thermal annealing. The devices emitted at a wavelength of ~1 µm with 60 nm of spectral width, and up to 38 mW of power at 20°C, depending on the currents applied to each section.

The combination of the spectral output from the two quantum well intermixed sections resulted in the broad spectral width. Angled facets at 7 ° were used to prevent the device from lasing. Additional power improvements were seen following the thermal anneal when a SiO₂ capping layer was used on both sections. Depending on the applied currents, each section required 1.5 V to 3.0 V; and failed at 5.3 V \pm 0.5 V.

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CHAPTER 1. Introduction

Superluminescent diodes (SLDs), also sometimes called superluminescent light emitting diodes, are semiconducting light sources that are an intermediate between light emitting diodes (LEDs) and laser diodes (LDs).^{1,2,3,4} Broad spectrum and high power characterize such devices, which are attractive for many applications, such as biomedical imaging.

Similar to the laser diode, SLDs are edge emitting, have a high output power and emit like a point source. Similar to the LED, they have a broad output spectrum and low coherence. This is achieved by removing the optical feedback mechanism of a LD, preventing wavelength selectivity and gain narrowing.

The SLDs of this work were built on GaAs substrates, using Ga_{0.75}In_{0.25}As quantum wells for light emission, surrounded by Ga_{0.75}In_{0.25}As_{0.49}P_{0.51} barriers. In these SLDs, quantum well intermixing (QWI) is used to produce a two-section device, each operating at different wavelengths, for the purpose of producing a broad spectral output. The QWI is accomplished by growing a 100 nm thin layer of low temperature Ga_{0.515}In_{0.485}P (LT-GaInP) over the entire structure, removing it from one of the two sections, and then giving the entire device a rapid thermal anneal.^{5,6} The result is an exchange of material between the quantum wells and neighboring barriers, but because of the differences between the two sections, the amount of intermixing between the two sections are different. This produces a peak wavelength difference between the output optical spectra of both sections. By electrically pumping the sections separately, a broad spectral output results. High power is achieved by preventing the device from lasing,

which is accomplished by using titled facets, angled at 7 degrees. This is demonstrated in figure 1-1.



Figure 1-1: The SLDs of this thesis have angled facets, for the purpose of removing the optical feedback. This prevents the device from lasing.

A brief review is given on superluminescent diodes, upon which a discussion of the theory is presented in Chapter 2, processing and analysis techniques in Chapter 3, experimental results in Chapter 4 and a conclusion in Chapter 5.

1.1 Superluminescent Diodes (SLDs)

A superluminescent diode (SLD) is a pn junction based device that emits optical radiation based on superluminescence, also known as amplified spontaneous emission (ASE). This occurs when there are more carriers existing in excited states than there are in the lower bound states, which is called a population inversion. Like LDs, an SLD's main radiative recombination mechanism occurs through stimulated emission, although it is achieved without any wavelength selectivity.⁷

SLDs are modified LD structures that behave as edge emitting LEDs, which is accomplished by removing the optical feedback. They are characterized by their high power, which is similar to that of LDs, but come with a large spectral width, which is similar to that of LEDs. The edge-emitting device contains an active region, barrier materials and cladding, which serve two purposes. The first purpose is to generate the light (via the active region), and the second is to act as a waveguide. Similar to LDs, SLDs emit like a point source. This is advantageous, as light can be better coupled into fibers, as demonstrated in Fig. 1-2.



Figure 1-2: Emission characteristics of LEDs, LDs, and SLDs.

The broad spectral width of an SLD is advantageous since it produces a very low coherence length l_t . This is desirable for applications where interference fringes are undesirable. If the optical path difference between two beams of light is less than the coherence length, interference fringes are observed. The coherence length is calculated as follows,

$$l_t = \frac{\lambda^2}{n \cdot \Delta \lambda} \tag{1.1}$$

where *n* represents the index of refraction, and λ is the free space wavelength, and $\Delta\lambda$ is the full width half maximum (FWHM).

Literature Review

There are many different methods to fabricate an SLD. Quantum wells^{8,9,10,11} (QW) and quantum dots^{12,13} (QD) are both used for the creation of the desired peak wavelength. For structures utilizing QWs, the large spectral width is achieved through use of either asymmetric quantum wells,¹⁴ or multi-section quantum well intermixing¹¹ (QWI); whereas QD structures achieve a large spectral width by controlling the dot composition and geometry.¹² The high power of an SLD is made possible by preventing the device from lasing, which is accomplished through use of an antireflection coating,^{8,9,11} angled facets,¹⁰ an un-pumped absorption region at the rear facet,^{10,13} or an etched deflector.^{15,16}

The materials used to fabricate these devices range from different AlGaInAsP compositions, fabricated on either a GaAs or InP substrate.

SLD peak wavelengths currently exist in the near infrared regime; their spectral widths are seen to range between 18 and 170 nm,^{16,17} and the optical powers range between one and over a hundred milliwatts.^{10,12} Three recently reported SLDs emitting at the same target wavelength of devices in this thesis (i.e., 980 nm), are summarized in table 1-1.

Ref.	λ(nm) l	WHM (nm)	Power (mW)
8	980	24	1.4
9	980	18	5
16	980	18	67

Table 1-1: Recently reported SLDs emitting at 980 nm

Although a number of different commercial SLD companies exist, such as Exalos AG, Dense Light Semiconductor Pte Ltd., Volga Technology Ltd., etc, none of these

currently offer SLDs in the 980 nm regime. Three companies that do offer these wavelengths however, are Superlum Diodes Ltd., QPhotonics LLC, and Gtran Inc. Their SLDs are summarized in Table 1-2.

Company	λ (nm)	FWHM (nm) Power (mW)
Superlum Diodes Ltd.	970	30	7.5
Superlum Diodes Ltd.	960	30	60
Superlum Diodes Ltd.	1025	110	10
Qphotonics LLC	975	35	2
Qphotonics LLC	1020	30	1.5
Gtran Inc.	992	50	0.5
Gtran Inc.	1002	31	5

Table 1-2: Commercially available SLDs at approximately 980 nm

Applications

The SLD is a light source with a variety of applications. For example, it can be used as an optical amplifier for communications. SLDs can also be used to test optical fibers, such as measurements of the chromatic dispersion. Perhaps the most important application however, is in biomedical imaging.

SLDs have become useful tools for optical coherence tomography (OCT), which is used for non invasive imaging of human tissue, such as the cornea and retina.¹⁸ This takes advantage of the SLD's low coherence length, which allows different depths within a tissue to be examined by isolating the interference pattern created by the split beams. One beam is directed to the tissue, and the other is directed to a reference mirror, both of which are reflected and recombined to create interference. By scanning the beam across the sample and changing the position of the reference mirror to examine different depths within the tissue, the creation of a 3-dimensional image is possible. With a small coherence length, a large amount of data can be gathered within depths of about 2 to 3 mm. The scan's resolution is typically 1 to 15 μ m, which is one to two orders of magnitude better than conventional ultrasounds.¹⁸

Chapter 2. Theory

2.1 Material Properties of Bulk and Strained Ga_xIn_{1-x}As_yP_{1-y}

When designing laser, light emitting or superluminescent diodes, a number of different parameters need to be considered. The choice of substrate is first considered, as subsequent layers (except the QWs) deposited on it must match its lattice constant. The materials comprising the device are determined by desired emission wavelength and indices of refraction. The relation between lattice constant and energy bandgap is seen in Fig. 2-1 for different materials. For QWs however, strain and quantum confinement must also be considered in conjunction with these parameters.



*Figure 2-1: Energy Bandgap and Wavelength Emission of Semiconductor Materials vs. Lattice Constant*¹⁹

2.1.1 Lattice Constants for Bulk Materials

Listed in table 2-1 are the room temperature lattice constants of the binary materials that make up any GaInAsP composition. $Ga_{0.51}In_{0.49}P$ is lattice matched to a GaAs substrate and is a commonly employed ternary material.

Material	Lattice Constant
InAs	0.60583 nm
InP	0.58687 nm
GaAs	0.56533 nm
GaP	0.54505 nm
Table 2-1. Lat	tice Constants 20,21

Table 2-1: Lattice Constants^{20,21}

Table 2-2 lists the equations used to determine the lattice constants for any GaInP or GaInAsP composition.

Material	Lattice Constant (Å)			
Ga _x In _{1-x} P	5.8687-0.4182x			
$Ga_x In_{1-x} As_y P_{1-y}$	5.8688-0.4176 <i>x</i> +0.1896 <i>y</i> +0.0125 <i>xy</i>			
Table 2-2: Lattice Constant Equations ²⁰				

Equation 2.1 lists the relationship between the gallium (x) and arsenic (y) concentrations, in order for $Ga_xIn_{1-x}As_yP_{1-y}$ to be lattice matched to an InP substrate.³

$$x = \frac{0.1896y}{0.4176 - 0.0125y} \tag{2.1}$$

١

An equation describing the relation between the gallium (*x*) and arsenic (*y*) compositions of a $Ga_xIn_{1-x}As_yP_{1-y}$ material, lattice matched to GaAs, could not be found in the literature. However, an equation can be derived from the equation listed in table 2-2 by matching it to the GaAs lattice constant. For example, this is done in Eq. 2.2.

$$x = \frac{0.2155 + 0.1896y}{0.4176 - 0.0125y} \tag{2.2}$$

2.1.2 Energy Levels for Bulk Materials

Table 2-3 lists the material properties of GaAs, InP, GaP, and InAs, such as their lattice constants, energy bandgaps, and valence and conduction band edges measured relative to the vacuum level. Also included is $Ga_{0.51}In_{0.49}P$, which is lattice matched to GaAs.

Material	Energy Band-Gap @ T=300K	Valence Band Edg	e Conduction Band Edge
InAs	0.354 eV	-5.254 eV	-4.90 eV
InP	1.344 eV	-5.724 eV	-4.38 eV
GaAs	1.424 eV	-5.494 eV	-4.070 eV
GaP	2.260 eV / 2.780 eV	-6.060 eV	-3.80 eV / -3.28 eV
Ga _{0.51} In _{0.49} P	1.849 eV	-5.929 eV	-4.08 eV

Table 2-3: Material Properties of InAs, InP, GaAs, GaP et al.^{20,21}

The conduction band edge is determined by finding a material's electron affinity. The valence band edge is then calculated by subtracting the energy band gap from the conduction band edge. In the case of GaP, which is an indirect bandgap material, the direct Γ -valley energy gap is 2.78 eV, but the band gap minimum is 2.26 eV. This places

its Γ -valley conduction band edge at -3.28 eV, and its X-valley conduction band edge at -3.80 eV.





*Figure 2-2: Schematic of an E-k diagram*²⁰

Figure 2-3: E-k diagram of GaAs²²

Figure 2-2 illustrates a schematic band structure of each of the binary semiconductor materials, with Fig. 2-3 giving a more in-depth example of GaAs. Table 2-4 lists all the appropriate values associated with these diagrams. Note that because GaP's *E-k* X-Valley is lower than the Γ valley, its diagram will look slightly different.

Material	$Eg_{\Gamma}(eV)$	Eg _x (eV)	Eg _L (eV)	E _{so} (eV)
InAs	0.35	1.37	1.08	0.41
InP	1.34	2.19	1.93	0.11
GaAs	1.42	1.9	1.71	0.34
GaP	2.78	2.26	2.6	0.08
$Ga_{0.51}In_{0.49}P$	1.849	2.26	2.0	0.11

Table 2-4: Energy Bandgaps^{20,21}

To estimate most parameters of $Ga_x In_{(1-x)} As_y P_{(1-y)}$, denoted as b(x,y), a linear approximation based on the appropriate parameters of the binary compounds are used. This is known as Vegard's law and is shown in Eq. 2.3.

$$b(x, y) \cong (1-x)y \cdot b_{InAs} + (1-x)(1-y) \cdot b_{InP} + xy \cdot b_{GaAs} + x(1-y) \cdot b_{GaP}$$
(2.3)

Since Vegard's law is just an approximation, a linear extrapolation in the case of E_g is subject to inaccuracies; hence, the equations in Table 2-5 were developed to give a better representation of the true bandgap for any specific material composition (*x*,*y*).

Material	Bandgap Equation (eV)		
$Ga_x In_{1-x}P$	$Eg=1.34+0.69x+0.48x^2$ x<63%		
$Ga_xIn_{1-x}As_yP_{1-y}$	$Eg=1.35+0.668x-1.068y+0.758x^{2}+0.078y^{2}-0.069xy-0.332x^{2}y+0.03xy^{2}$		
Table 2-5: Energy Bandgap Equations ²⁰			

The following discrepancies are noted. The equation to calculate the energy bandgap of $Ga_xIn_{1-x}P$ at x=51% is calculated to be 1.817 eV, yet is measured at 1.849 eV.²⁰ Also, the $Ga_xIn_{1-x}As_yP_{1-y}$ equation calculates it to be 1.888 eV. This would suggest that the two equations in Table 2-5 are subject to inaccuracies, as compared to the measured values, however, they are still a better than Vegard's law, which gives 1.752 eV.

2.1.3 Effective Mass for Bulk Materials

Representing the mass of an electron as an effective mass is a technique that allows one to apply classical equations of motion while ignoring the periodic potential. This is based on the effective mass tensor,²³ defined as,

$$m_{i,j}^{*} = \frac{\hbar^{2}}{\left(\frac{d^{2}E}{dk_{i}dk_{j}}\right)}$$
(2.4)

where \hbar is the reduced Planck's constant, *E* represents Energy, *k* represents reciprocal space in units of π/a , where *a* is the lattice constant, and *i*,*j* represent the indices of directions. Assuming the curvature of the *E*-*k* diagram is symmetric, this equation can be reduced to:

$$m^* = \frac{\hbar^2}{d^2 E / dk^2} \tag{2.5}$$

Table 2-6 lists the various effective masses for all four binary compounds used to create $Ga_xIn_{1-x}As_yP_{1-y}$. It also lists $Ga_{0.51}In_{0.49}P$, which is lattice matched to a GaAs substrate.

Material	<i>m*</i> Γ	<i>m*</i> _x	<i>m*</i> _L	m* _{hh}	m* _{lh}	
InAs	0.023	0.64	0.29	0.41	0.026	
InP	0.080	0.66	0.63	0.60	0.089	
GaAs	0.063	0.85	0.56	0.51	0.082	
GaP	0.090	0.79	0.76	0.79	0.140	
Ga _{0.51} In _{0.49} P	0.088 ± 0.003	0.7263	0.6963	0.5814	0.1155	
$T_{able 2} 6$, Effective $M_{agges}^{20,21}$						

Table 2-6: Effective Masses^{20,21}

For electron-hole recombination, the effective mass in the Γ -valley (m^*_{Γ}) only has to be considered from the conduction band, whereas the effective masses from the X and L valleys can be ignored. For an unstrained valence band, at k=0, a combination of the heavy (m^*_{hh}) and light hole effective masses (m^*_{lh}) must be considered, since they are degenerate. This is calculated using Eq. 2.6.¹

$$m_{holes}^{*} = \left[m_{hh}^{\frac{3}{2}} + m_{lh}^{\frac{3}{2}} \right]^{\frac{3}{2}}$$
(2.6)

For lattice matched quantum well materials on the other hand, only the heavy hole effective mass has to be considered, since the heavy and light hole energy levels have been separated, with the heavy hole band maximum lying above the light hole maximum. Electron hole pair recombination will primarily occur between the conduction band and heavy hole band.

It should be pointed out that the values in table 2-6 are the density of states effective mass. For the X and L valleys however, these values are calculated based on its longitudinal effective mass (m_l) , and its transverse effective mass (m_l) . For example, although the density of states effective mass in the X-valley for GaP is 0.79, its longitudinal effective mass is 1.12, and its transverse effective mass is 0.22. These values correspond to the ellipsoidal constant energy surfaces within k-space (reciprocal space), as shown in Fig. 2-4, and can be combined to form a single value using Eq. 2.7,²¹

$$m^* = \left(V^2 m_l m_l^2\right)^{1/3} \tag{2.7}$$

where V represents the number of equivalent valleys.



Figure 2-4: Direct and Indirect k-space diagrams, with the ellipsoid constant energy surfaces. If the electrons are trapped within the Γ valley, the ellipsoidal constant energy surface will look like the diagram on the left, and will be a sphere. If they are trapped in the X-valleys, there will be six energy ellipsoids in the (100) directions, which can be described by m_l and m_b and will look similar to the diagram on the right.

2.1.4 Strain and Lattice Mismatch

In the past, semiconductor structures were limited to lattice matched materials, since a lattice mismatch would create strain, which created dislocations. However, for the thin layers used in QWs, it is possible to incorporate strain without dislocation formation, as long as the critical thickness is not exceeded.

There are two different ways to induce strain. These are externally and internally. Generally however, external strain is not applied to semiconductors, thus only internally induced strain is considered here. Internal strain is created when a material is grown on a substrate, where the substrate and epilayer have two naturally different lattice constants. This is referred to as a lattice mismatch, and results in either compressive or tensile strain.

Poisson's ratio (v) relates the strain in the horizontal / bi-axial plane (ε_x), with the strain in the vertical / uni-axial direction (ε_z), i.e., the direction of crystal growth. It is calculated using Eq. 2.8,³

$$v = \frac{C_{12}}{C_{11} + C_{12}} \tag{2.8}$$

where C_{11} and C_{12} are the elastic stiffness constants used to describe the material.

When a tensile stress is applied to a material in the vertical direction, causing an elongation, there will be a corresponding contraction in the horizontal plane within the material, which is compression. Materials behave this way to resist changes in their overall volume. This is demonstrated in Fig. 2-5. How well it resists changes to its volume is described by the Poisson ratio, which mathematically ranges from 0 to $\frac{1}{2}$. A

Poisson ratio of $\frac{1}{2}$ indicates that the volume stays constant under stress, whereas a Poisson ratio of 0 means there is no resistance to changes in volume. Typical semiconductor materials have Poisson ratios of about $\frac{1}{3}$.



*Figure 2-5: Materials under stress will exhibit both compressive and tensile strain in an effort to maintain their volume, based on the Poisson ratio.*²⁴

For growth of a QW heterostructure, a particular substrate is used as the foundation for the growth, and is chosen based on availability and lattice constant. If the lattice constant of the substrate and deposited epilayers match, there will be no strain. Alternatively, if the lattice mismatch is small (\sim 1%) and the thickness is small (\sim 5 nm), the epilayer will grow perfectly and match the substrate's lattice constant, but consequently strain will develop within the epilayer.



*Figure 2-6: When an epitaxial lattice mismatched layer is grown, the new growth will match the substrates lattice constant, and exhibit both compressive and tensile strain.*²

In the case where the epilayer's lattice constant is larger than the substrate's, a compressive strain is induced in the epilayer's bi-axial plane, as shown in Fig. 2-6. In the opposite scenario, a tensile strain is induced. As the thin strained layer is grown thicker, however, it will eventually become favorable for it to relax back to its natural lattice constant. This results in various dislocations within the system, typically seen as either 'edge' or 'screw' dislocations, as shown in Fig. 2-7.



*Figure 2-7: After the critical thickness has been surpassed, edge and screw dislocations are created.*²⁴

Edge dislocations disturb the crystal's periodicity with an extra row of atoms within the material, whereas screw dislocations are gradual shifts in atomic planes within the lattice. Unfortunately, dislocations form non-radiative recombination centers, which make them undesirable for optoelectronic devices, as carriers are needed for electron-hole pair recombination.

Therefore, knowledge of the critical thickness (h_c) is an important parameter to be considered in designing the device structure. The reader is referred to Ref [25] for an indepth discussion on this topic.

Fig. 2-8 demonstrates when it is energetically favorable for the material to relax due to strain. Below the critical thickness, it is energetically favorable for a strained layer to match the lattice constant of the substrate. Above it however, it is energetically favorable for the strained layer to relax and form dislocations.



Figure 2-8: Critical thickness vs. dislocations.²⁶

2.1.5 Energy Levels for Strained Materials

Once the energy bands of a material are determined under zero stress, its E-k diagram tends to appear similar to the first diagram in Fig. 2-9(a), which illustrates the conduction band and the valence heavy and light hole bands. Not included however, is the split off band.



*Figure 2-9: The bandgap decreases under a tensile strain, and increases for compressive strain. In both cases, the degeneracy between the heavy and light hole bands are lifted.*²

The magnitude of the energy band gap is influenced by the interatomic spacing within the crystal. As shown in Fig. 2-10, when the atoms get closer together, the bandgap increases, whereas if the atoms move farther apart, the bandgap decreases. Note that a strained layer parallels this observation. If the atoms are compressed closer together, its bandgap increases, as shown in Fig 2-9(b), whereas if they are forced apart (tensile strain), its bandgap decreases, as shown in Fig. 2-9(c). Also, the degeneracy between the heavy and light hole bands is lifted in a non-hydrostatic strained material, such as a QW, since the two bands no longer have the same energy at k=0, as shown in Fig. 2-9 (b,c).



*Figure 2-10: The bandgap changes as the interatomic spacings within a crystal change.*¹ *This is an example of silicon.*

To calculate the changes of the different valence band edges, the following 4×4 Hamiltonian is used,

$$\mathbf{H} = -\begin{bmatrix} P+Q & -S & R & 0\\ -S^{+} & P-Q & 0 & R\\ R^{+} & 0 & P-Q & S\\ 0 & R^{+} & S^{+} & P+Q \end{bmatrix} \begin{vmatrix} \frac{3}{2}, +\frac{3}{2} \\ \frac{3}{2}, +\frac{1}{2} \\ \frac{3}{2}, -\frac{1}{2} \\ \frac{3}{2}, -\frac{3}{2} \end{vmatrix}$$
(2.9)

where,

$$P = P_k + P_{\varepsilon}$$

$$P_k = \left(\frac{\hbar^2}{2m_o}\right) \gamma_1 (k_x^2 + k_y^2 + k_z^2)$$

$$P_{\varepsilon} = -a_v (\varepsilon_{xx} + \varepsilon_{yy} + \varepsilon_{zz})$$

$$S = S_k + S_{\varepsilon}$$

$$S_k = \left(\frac{\hbar^2}{2m_o}\right) 2\sqrt{3\gamma_3} (k_x + ik_y) k_z$$

$$S_{\varepsilon} = -d(\varepsilon_{zx} - i\varepsilon_{yz})$$

$$Q = Q_k + Q_{\varepsilon}$$

$$Q_k = \left(\frac{\hbar^2}{2m_o}\right) \gamma_2 (k_x^2 + k_y^2 - 2k_z^2)^{\dagger}$$

$$Q_{\varepsilon} = -\frac{b}{2} (\varepsilon_{xx} + \varepsilon_{yy} - 2\varepsilon_{zz})$$

$$R = R_{k} + R_{\varepsilon}$$

$$R_{k} = \left(\frac{\hbar^{2}}{2m_{o}}\right)\sqrt{3}\left[-\gamma_{2}\left(k_{x}^{2} - k_{y}^{2}\right) + 2i\gamma_{3}k_{x}k_{y}\right]$$

$$R_{\varepsilon} = \sqrt{3}/2 b(\varepsilon_{xx} - \varepsilon_{yy}) - id\varepsilon_{xy}$$

and where γ_1 , γ_2 , and γ_3 are the Luttinger parameters; and a_v , b, and d are the Bir-Pikus deformation potentials; ε_{ij} is the symmetric strain tensor; and the basis function $|j,m\rangle$ denotes the Bloch wave function at the zone center.²⁷ All are constants used to describe the material. In this scenario, the zero energy level is taken to be the top of the unstrained valence band.

The Hamiltonian is an operator that describes the heavy and light hole valence bands of the semiconductor for all cases of strain, with the split-off band being ignored due to large energy separation.²⁷ In the case of zero strain at k=0, the Hamiltonian is filled with zeros, indicating no change to the valence band energy levels. When strain is induced in the plane of growth however, at k=0, the following is observed,

$$\mathbf{H} = -\begin{bmatrix} P_{\varepsilon} + Q_{\varepsilon} & 0 & 0 & 0\\ 0 & P_{\varepsilon} - Q_{\varepsilon} & 0 & 0\\ 0 & 0 & P_{\varepsilon} - Q_{\varepsilon} & 0\\ 0 & 0 & 0 & P_{\varepsilon} + Q_{\varepsilon} \end{bmatrix} \begin{vmatrix} HH \uparrow \rangle \\ LH \uparrow \rangle \\ LH \downarrow \rangle$$

where,

$$\varepsilon_{xx} = \varepsilon_{yy} \neq \varepsilon_{zz}$$
 $\varepsilon_{xy} = \varepsilon_{yz} = \varepsilon_{zx} = 0$ $R_{\varepsilon} = S_{\varepsilon} = 0$

and where $HH\uparrow$, $HH\downarrow$, $LH\uparrow$ and $LH\downarrow$ represent the heavy hole and light hole spin-up and spin-down electron states. Since this is a diagonalized matrix, the eigenfunctions are easily recognized. Therefore, at k=0,

$$HH = -P_{\varepsilon} - Q_{\varepsilon} \qquad HH = a_{v}(\varepsilon_{xx} + \varepsilon_{yy} + \varepsilon_{zz}) + \frac{b}{2}(\varepsilon_{xx} + \varepsilon_{yy} - 2\varepsilon_{zz})$$
$$LH = -P_{\varepsilon} + Q_{\varepsilon} \qquad \text{or} \qquad LH = a_{v}(\varepsilon_{xx} + \varepsilon_{yy} + \varepsilon_{zz}) - \frac{b}{2}(\varepsilon_{xx} + \varepsilon_{yy} - 2\varepsilon_{zz})$$

where the strain induced through a lattice mismatch can be calculated using the following equations,

$$\varepsilon_{xx} = \varepsilon_{yy} = \frac{a_s - a}{a}$$
, and $\varepsilon_{zz} = -\frac{2C_{12}}{C_{11}}\varepsilon_{xx}$ (2.10)

where ' a_s ' is the lattice constant of the substrate, and 'a' is the natural atomic spacing of new growth being forced to change.²⁷

The change to the conduction band energy is calculated using the following equation,

$$E_{c}(\mathbf{k}=0) = E_{g} + a_{c}(\varepsilon_{xx} + \varepsilon_{yy} + \varepsilon_{zz})$$
(2.11)

where a_c is another Bir-Pikus deformation constant that depends on the material.

2.1.6 Effective Mass for Strained Materials

The effective mass within the heavy and light hole bands can change dramatically for cases of strain. For example, Fig. 2-11 demonstrates how strain can affect the valence band at different k values. Since the k_x and k_y directions are both in the plane of the surface and are equivalent, whereas the k_z direction is in the growth direction, the *E*-k diagrams show the k_x and k_y values on the left hand side of the diagram, whereas the k_z values are on the right. In the unstrained case, the *E*-k diagram takes on a parabolic shape near k=0, whereas for strained cases this symmetry disappears.



Figure 2-11: Strain changes the curvature of the heavy and light hole valence bands and removes the degeneracy. This is an example of a $Ga_xIn_{1-x}As$ material lattice matched to an InP substrate. The solid line represents the heavy hole, and the dotted line represents the light hole.²⁷

The equations of these energy bands are needed since effective mass is related to the band's curvature. As seen in Fig. 2-12, strain results in abrupt changes of the effective mass from the center of k-space to the outer edges.



Figure 2-12: Due to the curvature changes from strain, anisotropic behavior is seen for the effective mass in k-space. This is an example of a $Ga_xIn_{1-x}As$ material lattice matched to an InP substrate. The solid line represents the heavy hole, and the dotted line represents the light hole.²⁷

Although the split off bands have not been shown in these diagrams, when calculating the effective masses, accurate results for the light hole effective mass require that the split off bands be considered, due to spin orbit coupling.²⁷ In this scenario, a 6×6 Hamiltonian matrix can be used, which includes the split off band energy levels.²⁷

Conveniently however, electron-hole recombination within a compressively strained quantum well primarily takes place from the conduction band to what is called the heavy hole energy level, so for the purposes of this thesis, the spin-orbit coupling can be ignored. When considering the conduction band, an 8×8 Hamiltonian matrix is used.

The equations that describe the heavy and light hole bands are determined by finding the eigenfunctions of the Hamiltonian, which are found by diagonalizing the matrix. Once these functions are determined, the curvatures can be calculated. Generally however, determining the eigenfunctions of the Hamiltonian requires a great amount of calculation, thus prompting many researchers to use computer simulations to do the bulk of the calculations.

2.1.7 Energy Levels within a Quantum Well

After determining the effects of strain (if present) on the available energy states, quantum confinement is considered. In such a scenario, the following equation has to be solved,³

$$\sqrt{\frac{2m_b^*(V_o - E)}{\hbar^2}} = \frac{m_b^*}{m_w^*} \sqrt{\frac{2m_w^*E}{\hbar^2}} \tan\left(\sqrt{\frac{2m_w^*E}{\hbar^2}} \frac{L_w}{2}\right)$$
(2.12)

where m^*_b and m^*_w are the effective masses of the carriers in the well and barrier materials; L_w is the thickness of the quantum well; and V_o is the potential difference between the bulk materials used for the barriers and the quantum well. As this equation involves a tangent, there may be more than one solution, although the smallest value primarily only needs to be considered for electron-hole recombination. Please see appendix A for a detailed example.

2.1.8 Indices of Refraction for Bulk Materials

The index of refraction is a complex value used to describe light's apparent velocity within a medium, as compared to a vacuum. Consequently, the wavelength of the photon is also reduced within the medium, assuming n>1. These are based on the following equations,

$$n^* = n(\omega) + ik(\omega) \tag{2.13}$$

$$v = \frac{c}{n_{medium}}$$
(2.14)

$$\lambda_{medium} = \frac{\lambda_o}{n_{medium}} \tag{2.15}$$

where n^* is the refractive index, ω is the angular frequency, k is the extinction coefficient, v is the velocity, c is the speed of light, and λ_o is the free space wavelength. The imaginary component in Eq. 2.13 associated with the extinction coefficient is related to the amount of absorption the photons experience in the material. If a photon does not have enough energy to excite an electron from the valence band to the conduction band, there will be zero absorption, and thus the imaginary component will be zero. This is common for optoelectronic devices that use the barrier layers of a quantum well to act as the waveguide.

It is also important to point out that the index of refraction is a function of the photon's wavelength. For example, GaAs has a refractive index of 3.67 at a wavelength of 925 nm, and a refractive index of 3.58 at 1125 nm. Both have extinction coefficients of

zero. For a wavelength of 870 nm in GaAs however, absorption would occur and the imaginary component would not be zero.

The following references^{3,28} list the index of refraction for GaAs, InP, InAs, and GaP at various wavelengths over a large range. Trend lines were sketched to determine the index of refraction at any wavelength in the range of 925 to 1125 nm. The equations that describe those trend lines are:

$$\begin{split} n(\lambda)_{InAs} &= -9.43923 \times 10^{-10} \cdot \lambda^3 + 3.684314 \times 10^{-6} \cdot \lambda^2 - 5.02073 \times 10^{-3} \cdot \lambda + 5.90841 \\ n(\lambda)_{InP} &= -8.80194 \times 10^{-11} \cdot \lambda^4 + 3.54366 \times 10^{-7} \cdot \lambda^3 - 5.31575 \times 10^{-4} \cdot \lambda^2 + 0.351323 \cdot \lambda - 82.7751 \\ n(\lambda)_{GaAs} &= 2.9286 \times 10^{-11} \cdot \lambda^4 - 1.2864 \times 10^{-7} \cdot \lambda^3 + 2.1198 \times 10^{-4} \cdot \lambda^2 - 0.155707 \cdot \lambda + 46.5895 \\ n(\lambda)_{GaP} &= 1.02219 \times 10^{-11} \cdot \lambda^4 - 4.25838 \times 10^{-8} \cdot \lambda^3 + 6.65416 \times 10^{-5} \cdot \lambda^2 - 4.64294 \times 10^{-2} \cdot \lambda + 15.3685 \end{split}$$

The method commonly used to calculate the refractive index of any composition of GaInAsP is based on Vegard's law, as seen in Eq. 2.3. Unfortunately, Vegard's law is only an approximation, and a compilation of work from different researchers investigating the index of refraction for GaInAsP illustrates the inaccuracy between measured data and calculated data from Vegard's method.²⁹ For example, within the transparent region of a quaternary material, Vegard's law calculates a much higher refractive index than is actually measured, showing that it cannot be used for accuracy.

Refractive Indices of $Ga_xIn_{1-x}As_yP_{1-y}$ lattice matched to InP substrate: Measured data³⁰ and Adachi^{31,32}.

Since Vegard's interpolation method for the refractive index of GaInAsP is not accurate or precise, methods based on measured values are used. Figure 2-13 depicts refractive index data of various $Ga_xIn_{1-x}As_yP_{1-y}$ materials lattice matched to an InP substrate, determined for photon energies in the range of 0.5 to 2 eV.³⁰


Figure 2-13: Measured index of refraction data for $Ga_x In_{1-x} As_y P_{1-y}$ lattice matched to an InP substrate³⁰

Comparing the data at 1060 nm (1.17 eV) to the data acquired through Vegard's law reveals a significant discrepancy, as shown in Fig. 2-14.



Figure 2-14: Index of refraction comparison for $Ga_x In_{1-x}As_y P_{1-y}$; measured vs. Vegard's Law

A method of calculating the real part of the refractive index for $Ga_xIn_{1-x}As_yP_{1-y}$ in the transparent wavelength region, which agrees well with measured values, has been established by Adachi,^{31,32} and is written as,

$$n = \sqrt{A \left[f(x_o) + 0.5 \cdot \left(\frac{E_g}{E_g + \Delta_o} \right)^{1.5} \cdot f(x_{os}) \right] + B}$$
(2.16)

where

$$f(x_o) = x_o^{-2} \cdot \left(2 - \sqrt{1 + x_o} - \sqrt{1 - x_o}\right)$$
(2.17)

$$f(x_{os}) = x_{os}^{-2} \cdot \left(2 - \sqrt{1 + x_{os}} - \sqrt{1 - x_{os}}\right)$$
(2.18)

and

$$x_o = \frac{E_\lambda}{E_g}$$
, and $x_{os} = \frac{E_\lambda}{E_g + E_\lambda}$ (2.19)

where E_g is the bandgap energy; E_{λ} is the photon energy; and A, B and Δ are constants that describe the quaternary material, such that:

$$A_{GaInAsP(x,y)} = (1-x)yA_{oInAs}^{*} + (1-x)(1-y)A_{oInP}^{*} + xyA_{oGaAs}^{*} + x(1-y)A_{oGaP}^{*}$$
(2.20)

$$B_{GalnAsP(x,y)} = (1-x)yB^{*}_{InAs} + (1-x)(1-y)B^{*}_{InP} + xyB^{*}_{GaAs} + x(1-y)B^{*}_{GaP}$$
(2.21)

where A_{o}^{*} and B^{*} are the constants of the binary materials, as listed in Table 2-7.

Binary	A* _o	B*	$\Delta_{\rm o}$
InAs	5.14	10.15	0.40
InP	8.40	6.60	0.10
GaAs	6.30	9.40	0.34
GaP	14.71	4.38	0.10

Table 2–7: Optical Constants for Calculations of the Refractive Index³³

The split-off band energy Δ_o for a quaternary material lattice matched to InP does not vary linearly, but instead follows Eq. 2.22.³⁴

$$\Delta_{o} = 0.119 + 0.300 \cdot y - 0.107 \cdot y^{2} \quad \text{(lattice matched to InP)}$$
(2.22)

A comparison of the measured data with the expression given by Adachi is given in Fig. 2-15 and 2-16. Unfortunately, the measured data does not give uncertainties, so a quantitative comparison cannot be made. Adachi's equation produces the proper trend however, and produces much better results than Vegard's law. Adachi's equation only breaks down when the photon energy is close to E_g , at which point absorption plays a role, and the imaginary component is needed.



Figure 2-15: Refractive index comparison of Adachi; measured values and Vegard's Law at 1060 nm.



Figure 2-16: Refractive index comparison of Adachi and measured values at 1237.5 nm.

Refractive Indices of $Ga_xIn_{1-x}As_yP_{1-y}$ lattice matched to a GaAs substrate: Experimental Data³⁵

Although there is a large body of information for the refractive index of materials lattice matched to InP, *almost* no data is available for GaInAsP materials lattice matched to a GaAs substrate.³⁵ Adachi's equation did not agree with experimental values for a GaAs lattice match either, perhaps because an equation for the split-off band energy Δ_0 of GaInAsP (lattice matched to GaAs) could not be found, thus forcing a linear approximation to be made based on the binary values.

Some experimental data was obtained by Wallace *et al.* however.³⁵ Their work presents data on the index of refraction for various GaInAsP concentrations, lattice matched to GaAs at 808 nm, 850 nm, and 980 nm. The GaInAsP concentrations were presented in terms of the bandgap energy. Wallace *et al.* fitted two curves to the collected

data points, where one was a 2^{nd} order polynomial, and the other was a 3^{rd} order polynomial. These are reproduced below, and shown in Fig. 2-17, 2-18 and 2-19.

$$n_{i=2}(808) = 11.56 - 8.78E_g + 2.337E_g^2$$
(2.23)

$$n_{i=3}(808) = 30.77 - 42.06E_g + 21.52E_g^2 - 3.68E_g^3$$
(2.24)

$$n_{i=2}(850) = 10.714 - 7.906E_g + 2.102E_g^2$$
(2.25)

$$n_{i=3}(850) = 17.987 - 20.74E_g + 9.634E_g^2 - 1.469E_g^3$$
(2.26)

$$n_{i=2}(980) = 7.409 - 4.237E_g + 1.067E_g^2$$
(2.27)

$$n_{i=3}(980) = -6.904 + 20.95E_g - 14.828E_g^2 + 3.2E_g^3$$
(2.28)



*Figure 2-17: Index of refraction of GaInAsP, displayed as a function of material band gap, for 808 nm photons.*³⁵



Figure 2-18: Index of refraction of GaInAsP, displayed as a function of material band gap, for 850 nm photons.³⁵



Figure 2-19: Index of refraction of GaInAsP, displayed as a function of material band gap, for 980 nm photons.³⁵

Converting Eq. 2.27 and 2.28 to yield the refractive index as a function of the arsenic concentration (y) gives the following equations.

$$n_{i=2}(980) = 0.2467 y^2 + 0.0883 y + 3.2124$$
(2.29)

$$n_{i=3}(980) = -0.3119y^3 + 0.7147y^2 - 0.0898y + 3.2189$$
(2.30)

These are graphed in Fig. 2-20. For comparison's sake, the refractive indices determined using Vegard's Law and Adachi's equation are included. Both 2^{nd} order and 3^{rd} equations are included, since one is more appropriate than the other depending on the GaInAsP composition, as shown in Fig. 2-19. Therefore, Adachi's equation cannot be applied to GaInAsP compositions lattice matched to GaAs without an equation used to calculate the split-off band energy Δ_o . Instead, the measured values obtained from Wallace *et al.* must be used.



*Figure 2-20: Index of Refraction Comparison of Adachi and Vegard's equations, to experimental data from Wallace et al.*³⁵

2.2 Quantum Well Intermixing

Quantum Well Intermixing (QWI) is a material exchange process between a quantum well (QW) and the barrier layers, for the purpose of increasing the QW energy bandgap. This is a useful technique for changing (blue-shifting) the wavelength of the generated light output from laser diodes (LD), light emitting diodes (LED), and superluminescent diodes (SLD).

There are many different methods to achieve QWI. The method used for the work in this thesis was to use a phosphorus rich, low temperature grown epitaxial layer. Alternative methods however, are impurity induced disordering (IID), impurity free vacancy disordering (IFVD), laser induced disordering (LID), and photoabsorption induced disordering (PAID).³⁶ The basics of all of these methods is the introduction of a non-equilibrium concentration of point defects, which can be induced thermally to diffuse through the active region of the device causing intermixing of the QW and barrier layers.

QWI - Phosphorus Rich, Low Temperature Epitaxial Layers

The method used here to induce QWI is to cap the sample with a lattice matched low temperature epitaxially grown layer. This is grown at a temperature lower than is required for stoichiometry, producing a layer with excess group V atoms. Examples are a low temperature gallium indium phosphide (LT-GaInP) layer, lattice matched to a GaAs substrate;^{5,6} as well as low temperature indium phosphide (LT-InP) layer, lattice matched to a InP substrate.³⁷

These two types of materials are phosphorus rich, with the extra phosphorus existing within the material primarily as group V antisites.^{6,37,38} Upon a rapid thermal anneal, these P-antisites dissociate to become P-interstitials, leaving behind group III vacancies. Two possible QWI processes now exist. These are:

- The P-interstitials diffuse through the material replacing some arsenic atoms based on the P-As exchange process.⁵ The result is increased P in the QW and a broadening / smearing of the QW.³⁸
- The group III vacancies diffuse throughout the structure, producing a process for inter-diffusion between the QW and barrier layers.³⁸

Generally, both of these QWI scenarios can occur during a rapid thermal anneal (RTA). However, if there is no difference in the group III compositions of the quantum well and barriers layers, compositional intermixing occurs only for the group V sublattice. Alternatively, when there is no difference between the group V compositions in the QW and barriers, only the group III compositional intermixing occurs.

From previous work it was determined that the larger blue shift occurred when the QW and barriers had identical group III compositions. For the work of this thesis however, the LT-GaInP cap layer was further covered with a SiO_2 layer, in order to reduce surface dissociation of the GaInP during the anneal.³⁸

It was observed that the PL intensity produced by the quantum wells was initially increased after the RTA treatment, although there was a steady decrease in intensity as either the anneal temperature or time was further increased. Samples were annealed over a temperature range of 750 °C to 900 °C and for times of 30 s to 60 s.

2.3 Wave-Guide Design

Light that is created by electron-hole recombination within a quantum well must be guided out of the device, thus requiring good confinement from the material and structure.

Vertical confinement is created using materials with higher indices of refraction in the layers used to guide the light, as opposed to the adjacent cladding layers with lower refractive indices. This is required for total internal reflection (TIR). Since the thickness of a quantum well is too thin to guide a mode, the wave enters the barrier layer materials, which has sufficient total thickness.

Lateral confinement is created by the use of a ridge design for the device structure, as illustrated in Fig. 2-21. This is required since a lateral change in the refractive index cannot be achieved directly from the different layers within the heterostructure. When the ridge is employed however, the sides of the structure have a slightly lower effective index of refraction than the center, which is due to its close proximity to air. This allows for lateral total internal reflection within the central region. The barrier layers and QWs underneath the ridge are together defined as the core.



Figure 2-21: The ridge creates lateral confinement

Another factor to consider is the thickness of cladding material that creates TIR. Although the ray optics model suggests that all the light is completely reflected during TIR, in reality, an evanescent wave exists outside the core region, which must not reach the metal contacts where absorption losses will occur.

The reader is referred to the Refs [4,39,40] for detailed discussions on waveguide theory.

Modes of particular waveguide structures were investigated using RSoft's Beamprop, which is a computer simulations program that uses the finite difference method. Judgments were made based on the mode's confinement, which was defined as the amount of power within the waveguide core with respect to the power both within and outside the core. Simulations with varying ridge heights, varying 'slab heights away from the core', and different ridge widths were performed to optimize the device design with respect to the optical confinement.

For the simulations with varying ridge height, the slab height away from the core was fixed at 0.3 μ m, whereas the ridge height varied from 0 to 1.2 μ m, as illustrated in Fig. 2-22.

This simulated structure differs slightly from the actual structure grown for this thesis, which has top and bottom GaAs layers that are each 200 nm thick. Instead, the simulated structure was simplified by converting these GaAs layers to GaInP, in view of the fact that the simulations would not have included the top GaAs layer for any ridge height $\leq 1.0 \ \mu$ m. Since this top GaAs layer could not be included, the bottom GaAs layer was converted to GaInP for symmetry purposes.



Figure 2-22: Device structure with varying ridge height

For the simulations involving a varying 'slab height away from the core', the waveguide height was fixed at 3.22 μ m, and the 'slab height away from the core' varied from the top at the core (1.72 μ m) to the top of the waveguide (3.22 μ m). This gives a height range of 0 to 1.5 μ m, as illustrated in Fig. 2-23. (Note that these values were chosen based on the present device structure in use).



Figure 2-23: Device structure with a varying slab height away from the core.

The simulations of varying ridge height, presented in Fig. 2-24, show that any ridge height greater than 0.2 µm produced maximum power confinement.



Figure 2-24: The confinement factor is optimized for ridge heights greater than 0.2 μ m. Here the 'slab height away from the core' is fixed at 0.3 μ m.

The simulations of varying 'slab height away from the core', presented in Fig. 2-25, show that the best power confinement was achieved when this distance was $< 0.3 \mu m$ for a 3 μm width ridge, and $< 0.5 \mu m$ for a 6 μm width ridge. Although the results were slightly scattered, a pattern can clearly be seen.



Figure 2-25: The confinement factor is optimized when the slab height away from the core is less than 0.3 μ m for a 3 μ m width ridge, and 0.5 μ m for a 6 μ m width ridge. Here the ridge height is fixed at 1.2 μ m.

Both of these simulations suggest that the ridge width did not play a significant role in the confinement.

With this information, it was confirmed that our devices with a ridge height of 1.2 μ m and a 'slab height away from the main core' of 0.3 μ m, were ideally designed. Using these parameters, a simulation for 5 μ m width ridge was performed to view the mode. Fig. 2-26 qualitatively illustrates this using a coloured intensity scale, which is indicated from 0 to 1, whereas Fig. 2-27 and 2-28 quantitatively illustrate this using a vertical and horizontal intensity profile cut, both going through the center of the mode. This mode appeared to stabilize after traversing 300 μ m, but was left to traverse for 1000 μ m in the simulation.



Figure 2-26: The simulated single mode in a structure matching our waveguide design.



Figure 2-27: Vertical profile cut in the center of the mode, in figure 2-26.



Figure 2-28: Horizontal profile cut in the center of the mode, in figure 2-26.

This concludes the theory section. The next chapter discusses the processing and analysis techniques.

CHAPTER 3. Processing and Analysis

The first design step involves choosing the substrate that the device structure is to be grown on. GaAs was chosen, as it allows a target wavelength of 980 nm to be achieved. We grew each layer of the device by Molecular Beam Epitaxy.

3.1 Gas Source Molecular Beam Epitaxy (GSMBE)

The specific MBE system used for the growth described here is known as gas source molecular beam epitaxy (GSMBE). This system can grow semiconductor layers comprising the elements aluminum, gallium, indium, phosphorus, arsenic, antimony, and dope them n-type using silicon or p-type using beryllium. The layer materials used in the devices reported here were gallium and indium, supplied by standard effusion cells; as well as phosphorus and arsenic supplied by phosphine and arsine, which were thermally cracked to produce dimers of phosphorus (P₂) and arsenic (As₂). Smaller effusion cells supplied the dopant materials.

An inductively coupled plasma (ICP) source was used to de-oxidize the substrate. This is accomplished by directing reactive hydrogen atoms to the substrate, which then react with the oxide layer to produce water. These water molecules are then pumped out of the chamber, revealing a clean substrate surface.

The device structures grown for this work are shown schematically in Figs. 3-1 and 3-2, where compositions, thicknesses, dopant levels, and growth temperatures have been listed. All layers, except primarily the quantum well (QW) layers, had compositions that were lattice matched to the substrate. The exceptions to this were the barrier layers,

which were grown with a very small tension. The growth temperatures were measured with an optical pyrometer, except during the LT-GaInP growths, which were estimated from a thermocouple placed behind the substrate.

~100nm			300°C
100nm			250°C
200nm	1x10 ¹⁹ cm ⁻³ Be Doped		540°C
1000nm	1x10 ¹⁸ cm ⁻³ Be Doped		540°C
5nm	1x10 ¹⁸ cm ⁻³ Be Doped	'Etch Stop'	540°C
300nm	1x10 ¹⁸ cm ⁻³ Be Doped		540°C
100nm		'Barrier Layer'	540°C
5nm		'Strained Quantum Well'	540°C
10nm		'Barrier Layer'	540°C
5nm		'Strained Quantum Well'	540°C
100nm		'Barrier Layer'	540°C
1300nm	1x10 ¹⁸ cm ⁻³ Si Doped		540°C
200nm	1x10 ¹⁸ cm ⁻³ Si Doped		570°C
	1x10 ¹⁸ cm ⁻³ Si Doped		~
	~100nm 100nm 200nm 1000nm 5nm 100nm 5nm 10nm 5nm 100nm 1300nm 200nm	$\begin{array}{c c c c c c c c c c c c c c c c c c c $	$\begin{array}{c c c c c c c c c c c c c c c c c c c $

Figure 3-1: Structure #1; Two Strained Quantum Wells, each 5 nm thick.

SiO ₂	~100nm			300°C
LT-Ga _{0.515} In _{0.485} P	100nm			250°C
GaAs	200nm	1x10 ¹⁹ cm ⁻³ Be Doped		540°C
Ga _{0.515} In _{0.485} P	1000nm	1x10 ¹⁸ cm ⁻³ Be Doped		540°C
GaAs	5nm	1x10 ¹⁸ cm ⁻³ Be Doped	'Etch Stop'	540°C
Ga _{0.515} In _{0.485} P	300nm	1x10 ¹⁸ cm ⁻³ Be Doped		540°C
Ga _{0.75} In _{0.25} As _{0.49} P _{0.51}	100nm		'Barrier Layer'	540°C
Ga _{0.75} In _{0.25} As	8nm		'Strained Quantum Well'	540°C
Ga _{0.75} In _{0.25} As _{0.49} P _{0.51}	100nm		'Barrier Layer'	540°C
Ga _{0.515} In _{0.485} P	1300nm	1x10 ¹⁸ cm ⁻³ Si Doped		540°C
GaAs	200nm	1x10 ¹⁸ cm ⁻³ Si Doped		570°C
GaAs Substrate (100)		1x10 ¹⁸ cm ⁻³ Si Doped	,	~

Figure 3-2: Structure #2; One Strained Quantum Well, 8 nm thick.

After the growth, the sample was removed from the chamber and the SiO_2 layer was grown over the top surface using Plasma Enhanced Chemical Vapor Deposition (PECVD).

3.2 Plasma Enhanced Chemical Vapor Deposition

Plasma enhanced chemical vapor deposition (PECVD) was used for the deposition of silicon-dioxide (SiO₂). Silane (SiH₄) and nitrous oxide (N₂O) gases were sent into the chamber at set flow rates, at 90 sccm and 70 sccm. The chamber pressure was 650 mTorr. Using an applied power of 50 W, a growth rate of approximately 0.92 nm/s was observed for the following reaction.⁴¹

$$SiH_4 + 2N_2O \xrightarrow{50Watts/300Celsius} SiO_2 + H_4 + 2N_2$$

A substrate temperature of 300 $^{\circ}$ C was used producing a SiO₂ layer with a smooth surface. The reader is referred to Ref [42] for an in depth discussion of CVD technology.

3.3 Rapid Thermal Anneal

For the purpose of quantum well intermixing (QWI), the device structure is given a rapid thermal anneal (RTA) within flowing nitrogen, with temperatures ranging from 800 °C to 825 °C, and times ranging from 30 to 60 s.

The sample was sandwiched between silicon wafers to minimize surface dissociation, and then placed inside a 'Carbon Boat' with a lid. The boat is connected to a thermocouple that monitors the temperature of the sample, which is then placed inside the RTA furnace. Beginning at room temperature, the RTA furnace is ramped at the rate of 50 °C/s until it reaches 500 °C, at which point the temperature is held steady for 30 s. After this brief pause, the temperature is increased at the same rate until it reaches the desired temperature (800-825 °C), and is held steady for the desired time (30-60 s). When the furnace is turned off, the sample cools quickly via the flowing nitrogen gas.

For comparison purposes, samples with and without the LT-GaInP layer were annealed together. Fig. 3-3 shows an example of a recorded RTA temperature trace showing the rapid increase from room temperature to 800 °C, and held for 30 s.



Figure 3-3: Typical RTA plot

3.4 Photoluminescence

Photoluminescence (PL) is used to determine the QW emission wavelengths of variously annealed samples. In order to maximize the PL intensity, all layers are removed by chemical etching down to the etch stop layer (see Figs. 3-1 and 3-2).

The SiO₂ layer was removed by placing the sample into hydrofluoric acid (HF) for a time period depending on its concentration. With an HF concentration of 47%, the etch rate is reported to be ~20 nm/s, whereas at 10%, the etch rate is ~1 nm/s.⁴³ The 'as grown' LT-GaInP and GaInP layers were removed by placing the sample into a 1HCl:3H₃PO₄ solution,⁴⁴ which was measured to etch 1 nm/s.⁴⁵ However, due to the layer intermixing after the anneal, the formation of GaInAsP at the LT-GaInP/GaAs interface caused the rate to significantly drop, since it took up to 20 mins to remove the entire LT-GaInP layer. The 'as grown' GaAs layer was removed by placing it into a 1H₂SO₄:8H₂-O₂:80H₂O solution,⁴⁴ which is reported to have an etch rate of 9 nm/s,⁴⁶ but which also took significantly longer after the anneal. Typically, it was the material around the interfaces that took the majority of time to etch completely.

The PL system uses a helium neon (HeNe) laser (λ =632.8 nm) as the excitation source. The emitted light from the sample has a range in energies centered around the bandgap energy. The spectral output is broadened by fluctuations in the QW thickness; lateral composition modulation (LCM) within quantum well and/or barrier materials,⁴⁷ potential variations in quantum well intermixing, and a non-zero temperature. Also, its thickness may vary by ±2 monolayers.

To collect the spectrum, the measured intensity at each wavelength is required. This is accomplished by sending the light to a grating, where it is reflected at an angle dependant on the wavelength, its angle of incidence, and the density of grooves on the grating. In this case, the grooves are fixed at 600 lines/mm, so by rotating the grating, the angle of incidence changes, and a small range of different wavelengths are directed into the detector at different angles, as shown in Fig. 3-4. The range of wavelengths allowed through the slit was 3 nm.

There are other components to the PL system. These are: a pin hole used for alignment purposes; two lenses used to focus and collect the light; a beam splitter and a mirror used to split and direct the light; a HeNe pass filter which only allows light from the HeNe laser to pass through it; a chopper; and, a lock-in-amplifier. This is shown schematically in Fig. 3-5.



Figure 3-4: The Grating system reflects different wavelengths into the detector by rotating the grating itself.



Figure 3-5: The Photoluminescence setup

The 'Chopper' is a device that rotates, letting light through at 210 Hz, and is used to isolate the signal from ambient light using the lock-in-amplifier.

A silicon detector was used, which has a cutoff wavelength at approximately 1060 nm. An upper limit exists as well, since high energy photons are more quickly absorbed at the surface of the detector. Fig. 3-6 shows the responsivity (*R*) curves for silicon, InGaAs and germanium photodetectors, as well as the quantum efficiencies (η), which are defined as:

$$R = \frac{I_p}{P_o} = \frac{\eta q \lambda}{hc}, \quad \text{and} \quad \eta = \frac{number \cdot of \cdot electron \cdot hole \cdot pairs \cdot generated}{number \cdot of \cdot incident \cdot photons}$$
(3.1)

where P_o is the optical power incident on the photodetector, I_p is the photocurrent, q is the charge of an electron, λ is the freespace wavelength, c is the speed of light, and h is Planck's constant.



Figure 3-6: Responsivity of Silicon, GaInAs and Germanium detectors⁴

The PL spectrum measured will be a convolution of the emitted spectrum with the instrument responsivities. Figure 3-7 is a typical measured spectrum seen from the photoluminescent setup.



Figure 3-7: Example PL spectrum

3.5 Photolithography

The devices were defined and fabricated using standard photolithography techniques. The final device geometry is shown in figure 3-8.



Figure 3-8: Final device geometry with physical isolation between the two sections.

Since each device is physically separated (by 15 μ m) into two different sections, one is called the blue section, which was capped with LT-GaInP during RTA; and the other is called the red section, which was not capped. Although they share the same waveguide, they are electrically separate.

As demonstrated in Fig. 3-9, the devices are fabricated on a 7° angle. Note that the red section is labeled with the 'R', whereas the adjacent blue sides are not labeled, but instead are numbered corresponding to the widths of the ridge. These will either be 3, 4, 5 or $6 \mu m$.



Figure 3-9: The devices are fabricated on a seven-degree angle.

3.6 Optical Spectrum Analyzer (OSA)

Each device is evaluated based on its spectral output with reference to power and bandwidth. With the aid of a microscope, both the 'red' and 'blue' sections are electrically connected in a forward bias configuration, and the currents adjusted to vary the output spectrum.

A tapered optical fiber is placed at the facet of the device, where the emitted light enters the fiber and is directed to the spectrum analyzer. The model being used was a Hewlett Packard 86140A OSA. This has a scanning wavelength range of 600 to 1700 nm, and operates on the same principles as the photoluminescence system. With built in detector responsivities, the OSA compensates for differing amplitude sensitivities.⁴⁸

3.7 Free Space Optical Power Detection

A germanium pin photodetector was used to measure the total free-space power. It has a detection wavelength range of 800 nm to 1600 nm. Instead of separating each wavelength with a grating, as done with the OSA and PL systems, all of the light from the SLD was directed into the detector. This gives a measurement of the overall total power.

The detector produces a photocurrent, and then converts this into power based on Eq. 3.1. When converting the photocurrent to power, a known responsivity value is used. This is based on one wavelength value however. Since the SLD spectrum has a range of wavelengths, this creates some uncertainty in the final value. This is estimated to be within 1%.

This uncertainty was estimated by first making a linear approximation of the responsivity curve for germanium between 900 and 1100 nm. The equation was then applied to a simulated Gaussian curve that represented the spectrum, (as well as actual measured spectra from an OSA), but then re-adjusted based on the responsivity of a single chosen mean wavelength. This produced a spectrum that was close to the original, but slightly different. The total power of two spectra were then calculated and compared to determine the difference. Example spectra taken from the OSA had close-to-Gaussian shapes; and the chosen wavelength was always within 10 nm of the true mean wavelength. Under these conditions, the calculated power difference was less than 1%.

CHAPTER 4. Results

4.1 As-Grown wafers

Photoluminescence measurements were performed on the as-grown wafer to determine its peak wavelength, FWHM, and relative power. The wafer for structure #1, which involved two 5 nm quantum wells, as seen in Fig. 3.1, was examined at both the center and the edge of the wafer using pieces cleaved to approximately 2 mm × 4 mm. Samples taken from near the edge of the wafer produced a slightly broader spectrum than that seen from a sample taken near the center. This is believed to be due to a slightly hotter MBE growth temperature at the outside of the wafer. The average peak wavelength was 1007 nm, with a FWHM of 42 nm and an intensity of 188 μ V.

The standard deviations (defined with a 68.3% confidence level; taken from four samples) were 1 nm for the wavelength; 15% for the FWHM; and 7% for the intensity. Due to a limited amount of data however, these uncertainty values are applied to all subsequent PL data.



Figure 4-1: Photoluminescent signals from Structure #1 reveal a peak wavelength of 1007 nm with a FWHM of 42 nm.

The PL signal of the material grown for structure #2, which contains one 8 nm quantum well, as seen in Fig. 3.2, is shown in Fig. 4-2. Its peak wavelength is 1042 ± 1 nm, with a FWHM of 47 ± 6 nm, and a PL signal of $182 \pm 12 \mu$ V. The origin of the other PL signal at 859 nm is probably from the GaAs layers.



Figure 4-2: Photoluminescent signal from Structure #2 reveals an approximate peak wavelength of 1042 nm and a FWHM of 47 nm.

4.2 Quantum Well Intermixing

Small pieces from the wafers of structure #1 and structure #2 were annealed at various temperatures and for different times (as defined in section 3.3), to determine the suitable conditions for satisfying the device design criteria. The requirement is a broad spectral output from a two-section device with modified active regions that emit at two distinct peak wavelengths. This is achieved by QWI with different capping layers on the two regions to give different blue shifts. The two peak wavelengths are restricted from separating too far apart however, (i.e. < the average FWHM of each separated peak) since the goal is to obtain a broad Gaussian-like shaped optical spectrum centered about the desired wavelength, as opposed to a spectrum with two separated peaks.

Fig. 4-3 illustrates the results from three different RTA conditions for structure #1 with different cappings. The anneal conditions were a) 800 °C for 30 s; b) 800 °C for 60 s; and c) 825 °C for 60 s. For the first RTA, two pieces were annealed, one of which had a 100 nm LT-GaInP capping layer, and one that did not. Both were covered with an additional 100 nm of SiO₂. The wavelength difference between the two peaks with and without the LT-GaInP indicates the wavelength difference expected between the two sections of the device. The spectra parameters are summarized in table 4-1. Identical samples were also annealed under different anneal conditions, and included were samples capped without SiO₂. The results are summarized in table 4-2 and 4-3. To reduce uncertainty, all specimens were annealed simultaneously for each anneal condition.

Structure #1 RTA 800 °C / 30 s	Peak Wavelength (nm)	PL Intensity (µV)	FWHM (nm)
As-Grown (no anneal)	1007 ± 1	197 ± 30	46 ± 3
No LT-GaInP + SiO2 Cap	994 ± 1	362 ± 54	36 ± 3
LT-GaInP + SiO2 Cap	967 ± 1	414 ± 62	35 ± 2

Table 4-1: Date	from the RTA	test at 800 °C	for 30 s, as seen in Fig	g. 4-3 (a	I)
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Structure #1 RTA 800 °C / 60 s	Peak Wavelength (nm)	PL Intensity (µV)	FWHM (nm)
As-Grown (no anneal)	1007 ± 1	197 ± 30	46 ± 3
No LT-GaInP + SiO2 Cap	989 ± 1	243 ± 36	52 ± 4
No LT-GaInP & No SiO2 Cap	978 ± 1	134 ± 20	51 ± 4
LT-GaInP + SiO2 Cap	959 ± 1	347 ± 52	32 ± 2
		<pre></pre>	

Table 4-2: Data from the RTA test at 800 °C for 60 s, as seen in Fig. 4-3 (b)

Structure #1 RTA 825 °C / 60 s	Peak Wavelength (nm)	PL Intensity (µV)	FWHM (nm)
As-Grown (no anneal)	1006 ± 1	189 ± 28	46 ± 3
No LT-GaInP + SiO2 Cap	975 ± 1	115 ± 17	40 ± 3
No LT-GaInP & No SiO2 Cap	985 ± 1	13 ± 2	60 ± 4
LT-GaInP + SiO2 Cap	931 ± 1	119 ± 18	33 ± 2

Table 4-3: Data from the RTA test at 825 °C for 60 s, as seen in Fig. 4-3 (c)







Figure 4-3: a) RTA results with Structure #1 for800 °C for 30 s; b) 800 °C for 60 s; and c) 825 °C for 60 s.

As can be seen in Fig. 4-3 (a), the PL intensity increased with the anneal at 800 °C for 30 s. However, Fig. 4-3 (b) and 4-3 (c) show that when the anneal time is prolonged to 60 s and the temperature is increased to 825 °C, the PL intensity is significantly reduced. Although a decrease in intensity is undesirable, larger blue shifts between peaks can only be achieved with longer or hotter RTAs. For example, the blue shift between the LT-GaInP and non-LT-GaInP specimens was 27 ± 2 nm for the 800 °C / 30 s RTA; 31 ± 2 nm for the 800 °C / 60 s RTA; and 44 ± 2 nm for the 825 °C / 60 s RTA. Therefore, RTA decisions must consider both the power output and the blue shift between peaks.

As observed in Fig. 4-3 (b,c), the SiO_2 cap layer significantly helped the QWI process for samples without LT-GaInP. For example, its blue shift was reduced (relative to samples without the SiO_2 cap), and a higher PL intensity resulted. As seen in Fig. 4-3 (c), without the SiO_2 capping layer, the PL intensity became negligible.

The peak wavelength shifts seen in Fig 4-3 (a,b,c) and tables 4-1, 4-2 and 4-2 (for the data with SiO₂), are summarized in Fig. 4-4.





For structure #2, three different RTA temperature/time combinations were applied at 825 °C for 30 s, 45 s and 60 s. This temperature was chosen based on the results from structure #1. Comparisons were again made between pieces with and without LT-GaInP, and all were covered with a layer of SiO₂. The results are all presented in a single graph in Fig. 4-5, with the as-grown curve included for comparison. Table 4-4 summarizes the data.

The amount of relative blue shifting between the specimens with LT-GaInP and without LT-GaInP for structure #2 is not as large as it was with structure #1. This is due to its thicker quantum well, which was 8 nm, as opposed to 5 nm. As can be determined from Table 4-4, the relative blue shifts were 26 ± 2 nm, 28 ± 2 nm, and 36 ± 2 nm for the anneals of 825 °C for 30, 45 and 60 s respectively. A steady degradation in intensity can be clearly seen with increasing times.



Figure 4-5: RTA results for structure #2 at 825°C for 30, 45 and 60 s

Structure #2	RTA	Peak Wavelength (nm)	PL Intensity (µV)	FWHM (nm)
As-Grown (no anneal)	- *	1043 ± 1	159 ± 24	50 ± 4
No LT-GaInP + SiO2 cap	825°C / 30 s	1031 ± 1	230 ± 35	36 ± 3
No LT-GaInP + SiO2 cap	825°C / 45 s	1027 ± 1	245 ± 37	40 ± 3
No LT-GaInP + SiO2 cap	825°C / 60 s	1026 ± 1	204 ± 31	41 ± 3
LT-GaInP + SiO2 cap	825°C / 30 s	1005 ± 1	522 ± 78	40 ± 3
LT-GaInP + SiO2 cap	825°C / 45 s	999 ± 1	371 ± 56	42 ± 3
LT-GalnP + SiO2 cap	825°C / 60 s	990 ± 1	134 ± 20	45 ± 3

Table 4-4: Data from Fig. 4-5

Fig 4-6 summarizes the results seen in Fig 4-5 (a,b,c) and table 4-4.



Figure 4-6: Peak Wavelength Shift from Structure #2 after RTA

Fig. 4-7 reveals the importance of SiO_2 on the PL output for specimens with LT-GaInP. It is believed that the SiO_2 layer prevents surface dissociation from the LT-GaInP, which causes the PL intensity to increase. The results for this figure are summarized in Table 4-5.



Figure 4-7: An additional SiO₂ capping layer helps the QWI for both scenarios with and without LT-GaInP.

Structure #2: RTA 825C/30s	Peak Wavelength (nm)	PL Intensity (µV)	FWHM (nm)
As-Grown (no anneal)	1043 ± 1	159 ± 24	50 ± 4
No LT-GaInP + No SiO2 cap	1025 ± 1	160 ± 24	38 ± 3
No LT-GaInP + SiO2 cap	1031 ± 1	231 ± 35	36 ± 3
LT-GaInP + No SiO2 cap	1005 ± 1	372 ± 56	42 ± 3
LT-GaInP + SiO2 cap	1005 ± 1	522 ± 78	40 ± 3

Table 4-5: Data from Fig. 4-5

4.3 Processing

Three different sets of devices were created with the two different structures (as seen in Fig. 3-1 and 3-2), with an anneal using: LT-GaInP and SiO₂ covering the regions on the wafer that will comprise the section with the shorter emission wavelength; and SiO₂ over the regions that will determine the emission for the longer wavelength. The first set of

devices were created with an RTA of 800°C for 60 s using structure #1; the second were created with an RTA at 825°C for 60 s also using structure #1; and the third were created with an RTA at 825°C for 30 s using structure #2. The completed wafer is shown in Fig. 4-8.



Figure 4-8: A close-up of the completed devices after photolithography.

Four devices are shown in Fig. 4-9 (a), which demonstrates the seven-degree angle. Note that these devices must be cleaved on the cleavage planes of the crystal structure, and therefore appear like the diagram to the right in Fig. 4-9 (b), where the cleavage lines are set to line up with the end of the ridge between sections.



Figure 4-9: a) On the left are four devices showing both the LT-GaInP and non LT-GaInP sections, as well as the seven degree angle. b) the diagram on the right shows how the devices were cleaved, where the ends of the ridges line up with the cleavage plane between sections.

A high magnification microscope view of the isolation region between sections is shown in Fig. 4-10. The yellow regions are gold, and the dark blue regions are SiO_2 . Although the metallization is separated by 15 µm, the ridges of each section are separated by 5 µm. Note that in this image there is some debris to the left side of the waveguide, however, it is believed that this will have a minimal effect.



Figure 4-10: The different sections are isolated physically and electrically.
The following SEM pictures, seen in Fig. 4-11, were taken to examine the ridges formed in structure #1. The undercutting of the ridge is due to the orientation that the ridges were fabricated on with respect to the crystal axis; [110].^{49,50}



Figure 4-11: The devices made from structure #1 had undercut ridges.

The substrate in structure #1 was of European / Japanese flat definition, whilst structure #2 was grown on a U.S. substrate. This was unknown at the time. Consequently, the devices made from structure #2 were fabricated on the $[\overline{1} \ 10]$ orientation instead of the [110] direction, causing the ridges to etch with an outward slope. This is seen in the SEM images shown in Fig. 4-12.

Although these devices still work under such a scenario, the current density will not be as high as they would be with undercut ridges. To compensate, higher pumping currents are required for satisfactory results.



Figure 4-12: The ridges for the devices made from structure #2 were outward sloping.

4.4 Device Analysis

After mounting the devices to copper carriers using an epoxy, both sections of the device were contacted with electrical probes, and the temperature was controlled and set to 20 °C

via a thermoelectric cooler. The high power emitted from these devices made it easy to monitor the beam shape with an IR card. In the majority of cases, it appeared to be single spatial mode.

The section of the device covered in LT-GaInP during RTA, which exhibits the largest blue shift in the PL, is denoted as the blue section. The section without LT-GaInP during RTA is denoted as the red section.

4.4.1 Spectral Width

Spectral widths of 60 ± 2 nm and 55 ± 1 nm were seen from both structures after the selected RTA conditions. The outputs of all devices were measured coupled to a tapered fiber at the blue section facet.

Initially, an RTA at 800 °C for 60 s was applied to structure #1. Although these devices emitted high output power and the PL peaks were separated by 31 nm, low bandwidth resulted. Fig. 4-13 and 4-14 demonstrate two typical spectra seen from these devices with this particular RTA. A spectral width of 22 ± 1 nm, with mean wavelength of 981 ± 2 nm and maximum spectral density of $129 \pm 13 \mu$ W/nm, was obtained for devices with 750 µm blue and red sections, using currents of 100 mA in the blue section and 150 mA in the red section. A spectral width of 36 ± 3 nm, with mean wavelength of 974 ± 1 nm, and maximum spectral density of $63 \pm 6 \mu$ W/nm, was obtained for devices with 300 µm blue and 500 µm red sections, using currents of 100 mA in the blue section and 100 mA in the red section. These currents were chosen to maximize the spectral width.



Figure 4-13: Output spectral density from Structure #1 with an RTA at 800 °C for 60 s with a 750 µm red section and 750 µm blue section.



Figure 4-14: Output spectral density from Structure #1 with an RTA at 800 °C for 60 s with a 500 µm red section and 300 µm blue section.

A second set of devices was made from structure #1, using an RTA at 825 °C for 60 s. The highest output power and largest bandwidth came from devices made with 750 μ m red and blue sections. As seen in Fig. 4-15 (a) and 4-16 (b), the peaks from each section appeared to be distinct.

In Fig. 4-15, the current in the blue section was fixed at 50 mA and the current in the red section was increased from 30 to 50 mA. With 30 mA, the red section doesn't

contribute to the FWHM, but it becomes significant when biased at 40 mA and 50 mA. The largest bandwidth for this device, with a ridge width of 5 μ m and 40 mA applied to the red section, was 60 ± 2 nm, as seen in Fig. 4-15 (b). Its mean wavelength was not in the center of the spectrum until the current in the red section was increased to 50 mA, which shifted the mean wavelength to 953 ± 1 nm, and increased its power by a factor of two. Its spectral width decreased to 57 nm ± 3 nm however. These results are summarized in Table 4-6.

Fig. 4-16 (a,b,c) presents the same information for a ridge 4 μ m wide, but with currents ranging from 20 to 40 mA in the red section, while the blue section remained at 50 mA. The mean wavelength is 951 ± 1 nm, with a FWHM of 62 ± 2 nm. The data from Fig. 4-16 is summarized in Table 4-7.

As a consequence of increasing the contribution from the red section, the mean wavelength is seen to red shift. Multiple peaks were also sometimes seen in these spectra, and although the exact cause of this is unknown, it could be due to small amounts of feedback within the structure.

Blue Section Current (mA)	Red Section Current (mA)	Mean Wavelength (nm)	FWHM (nm)	Max. Spectral Density (µW/nm)
50	30	937 ± 1	24 ± 2	22 ± 1
50	40	947 ± 1	60 ± 2	22 ± 1
50	50	953 ± 1	57 ± 3	38 ± 3
	TT 11 / /	D (

Table 4-6: Data	from Figure	4-13(a,b,c)
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Blue Section Current (mA)	Red Section Current (mA)	Mean Wavelength (nm)	FWHM (nm)	Max. Spectral Density (µW)
50	20	929 ± 1	25 ± 2	30 ± 2
50	30	939 ± 1	31 ± 2	32 ± 2
50	40	951 ± 1	62 ± 2	36 ± 2

Table 4-7: Data from Figure 4-14 (a,b,c)



Figure 4-15: Output spectral density for constant current in the blue section of structure #1 set to 50 mA, and an increasing current in the red section ranging from 30 to 50 mA. The above graphs are for a 5 μ m width ridge device.



Figure 4-16: Output spectral density for constant current in the blue section of structure #1 set to 50 mA, and an increasing current in the red section ranging from 20 to 40 mA.. The above graphs are for a 4 μ m width ridge device.

Fig. 4-17 demonstrates that light from the blue section optically pumps the red section. In this case, 250 mA of current was applied to the blue section, and only 27 mA in the red section. This resulted in a large spectral width, measured at 60 ± 1 nm, with a mean wavelength of 946 ± 1 nm and a maximum spectral density of $62 \pm 2 \mu$ W/nm.



Figure 4-17: Optical pumping of the red section with the power generated in the blue section is shown. In this example, a 6 µm ridge, 750 µm red and 750 µm blue section device was used with 250 mA in the blue section and 27 mA in the red section.

The devices made from structure #2 were given an anneal of 825 °C for 30 s. Although the two different PL peaks were only separated by 26 ± 2 nm, a spectral width of approximately 55 ± 1 nm was produced, as seen in Fig. 4-18.

In contrast to the results from structure #1 with RTA 825 °C for 60 s, the best spectral width seen from in structure #2 was not achieved with devices having 750 μ m red and blue sections. Instead, this was achieved using devices with shorter blue sections, which reduced the amount of absorption of light created in the red section. A shorter blue section was needed due to the lack of separation between the two PL peaks seen in Fig. 4-5 and 4-6.

Fig. 4-18 shows that a structure with a 300 μ m blue section and a 700 μ m red section, with a 3 μ m wide ridge, produced a maximum spectral width of 55 ± 1 nm. The current in the red section was fixed at 50 mA, whereas the current in the blue section was gradually increased from 0 to 60 mA, (although the results for currents of 50 and 60 mA are not graphed, since they overlap the I=40 mA curve), and the peak was centered at 1015 ± 1 nm at the higher blue section currents. This is summarized in Table 4-8. The devices with a 400 μ m blue section and a 600 μ m red section produced similar results.



Figure 4-18: Output spectral density for devices made from structure #2.

Blue Section Current (mA)	Peak Wavelength (nm)	FWHM (nm)	Max. Spectral Density (nW/nm)
0	1042 ± 1	25 ± 3	97 ± 1
5	1028 ± 1	40 ± 2	166 ± 1
10	1019 ± 1	46 ± 2	310 ± 1
20	1015 ± 1	49 ± 2	507 ± 1
30	1013 ± 1	51 ± 2	591 ± 1
40	1015 ± 1	54 ± 1	610 ± 1
50	1015 ± 1	55 ± 1	596 ± 1
60	1017 ± 1	56 ± 1	560 ± 1

Table 4-8:Data from figure 4-16, plus the data for the currents of 50 and 60 mA.

4.4.2 Optical Power

A detector was set up to measure the free-space power of these devices, with the current in the red section fixed at 50 mA, and the current in the blue section ranging from 0 mA to a high current appropriate to the section-length. For the devices made from structure #1 with an RTA of 825 °C for 60 s, with 750 μ m red and blue sections, the blue current was increased from 0 to 198 mA. Fig. 4-19 demonstrates that under these circumstances, the optical power ranged from 0 to approximately 38 mW. The optical power using high currents was similar for the different ridge widths, however, at lower currents the power differed by a factor of 2. For example, the optical power with 50 mA in both sections gives an optical power of 7.00 \pm 0.07 mW in a 3 micron ridge device, but only 3.49 \pm 0.03 mW in a 6-micron ridge device. This is presumably due to the factor of two in current density produced in the smaller ridges.



Figure 4-19: Optical power of devices made from Structure #1.

Table 4-9 summarizes the data in Fig. 4-19.

Ridge\B-Current	50 mA	100 mA	150 mA	198 mA
3 µm	7.00 ± 0.07 mW	19.4 ± 0.2 mW	30.9 ± 0.3 mW	38.4 ± 0.4 mW
4 µm	5.87 ± 0.06 mW	17.2 ± 0.2 mW	$28.6 \pm 0.3 \text{ mW}$	$37.3 \pm 0.4 \text{ mW}$
5 µm	4.15 ± 0.04 mW	14.8 ± 0.1 mW	$26.7 \pm 0.3 \text{ mW}$	$36.5 \pm 0.4 \text{ mW}$
6 µm	3.49 ± 0.03 mW	13.6 ± 0.1 mW	25.9 ± 0.3 mW	36.8 ± 0.4 mW
T_{α}	bla 1 0. Optical	Dowow up Car	want us Didaa	Width

Table 4-9: Optical Power vs. Current vs. Ridge Width

Presented in Fig. 4-20 is the additional contribution of power per incremental increase in current from Fig. 4-19, i.e. the efficiency for different ridge widths (dL/dI). In general, the behavior for all the devices is an initial increase in the efficiency at low currents, which then drops with higher currents. At low currents (< 100 mA in Fig. 4-20), the 3 µm wide ridge devices show the largest efficiency, which decreases as the ridge width increases. At high currents (> 100 mA in Fig. 4-20), the 6 µm wide ridge devices show the largest efficiency, which decreases as the ridge width increases. At high currents (> 100 mA in Fig. 4-20), the 6 µm wide ridge devices show the largest efficiency is due to a balance between high current density, (which raises the efficiency), and high amounts of heat, (which lowers the efficiency). It is believed the factor of two for power at low currents (between the ridge widths of 3 and 6 microns), disappears at high currents for this reason.



Figure 4-20: Ridge width efficiency.

Fig. 4-21 presents the spectra for two devices both having 750 μ m red and blue sections, with one having a 4 μ m ridge and the other having a 5 μ m ridge. Although both have currents of 50 mA in the blue section and 40 mA in the red section, the effect of the thinner ridge is clearly seen to produce a spectrum with higher power, due to higher current density. For example, at 50 mA, the current density in the blue section for the 4 μ m ridge is 1.7 kA/cm², whereas it is 1.3 kA/cm² for the 5 μ m ridge.

It was also observed that the red section produced more power than the blue section when using the thinner ridge. Although the explanation for this is unknown, this could be due to the blue section becoming more transparent to the red section light when pumping with a higher current density.



Figure 4-21: Spectra for samples with two different ridge widths.

Fig. 4-22 presents the voltage data for the same scenarios, demonstrating that higher voltages are needed for the thinner ridged devices. For example, when 50 mA is applied to both sections, the 3 μ m ridge device with 750 μ m in both sections had an

applied voltage of 2.17 volts, whereas the 6 μ m ridge device had an applied voltage of 1.99 volts.



Figure 4-22: I-V curves for structure #1 with RTA 825 °C / 60 s.

By converting the blue section current in Fig. 4-22 to current density however, it is apparent that the different ridge width devices all behave the same. The only exception is with the 3 μ m wide device, which has a voltage difference of 4%.



Figure 4-23: J-V curves for structure #1 RTA 825 °C / 60 s.

The optical power from the devices made from structure #2 was expected to be low due to its outward sloping ridges, which resulted in lower current densities and lower optical confinement. Adding to this was the restriction of using a smaller blue section to reduce attenuation.



Figure 4-24: Optical power of Structure #2.

Fig. 4-24 presents the optical power for the devices made from structure #2 with a 700 μ m red section and a 300 μ m blue section. The current in the red section was again fixed at 50 mA, and the current in the blue section was only ranged from 0 to 75 mA, due to its shorter length, to prevent device failure. As seen, there is a slight inconsistency (perhaps due to unknown damage to the device) as the 3 μ m device did not produce the highest amount of power at the lower currents. However, the rest of the data is consistent with the trends suggested from Fig. 4-19. For example, at low currents, the 4 μ m ridge produced a higher amount of optical power than the 5 μ m ridge, which in turn produced more power than the 6 μ m ridge. Also, at the higher currents the 6 μ m ridge became the

most efficient ridge, followed by the 5 μ m, 4 μ m and then the 3 μ m wide ridge. Figs. 4-25 and 4-26 presents the I-V and J-V curves for these devices, which is consistent with Figs. 4-22 and 4-23.



Figure 4-25: I-V curves for structure #2 RTA 825 °C / 30 s.



Figure 4-26: J-V curves for structure #2 RTA 825 °C / 30 s.

4.4.3 Device Failure

Devices made from both structures were seen to irreversibly fail after hitting a critical voltage, which was either due to damage to the device structure, or due to very high currents. This is seen in Fig. 4-25. Although the voltage was seen to decrease in this scenario, it was also seen to increase in some occasions as well. Data was recorded from five failing devices made from structure #2, with the average voltage failure occurring at 5.3 ± 0.5 V.

Also, at high currents and before device failure, sudden small changes in the voltage were sometimes seen, potentially indicating non-ideal electrical contact, or device degradation.



Figure 4-25: Device failure

4.4.4 Leakage Resistance

Leakage resistances between the two different sections were investigated for four devices with different ridge widths, both having 750 μ m red and blue sections. The results are presented in Table 4-10.

This was accomplished by applying currents to each section until their voltages were equal, noting the two currents, and then turning one of the currents off (for example, in the blue section). The current in the red section would then be raised until the voltage in the blue section had its initial voltage again, which in turn raised the voltage in red section, but indicated the flow of current due to leakage. The difference in voltage between the two sections, divided by this leakage current, would indicate the leakage resistance.

As seen in this case, the 3 μ m device had the highest resistance between the two different sections at 1157 \pm 10 Ω , whereas the leakage resistance for the 6 μ m ridge device was only 366 \pm 4 Ω . This suggests that the devices with smaller ridge widths are better at separating the individual currents from each section.

Ridge Width	R-Leakage
3µm	$1157\pm10~\Omega$
4µm	$677\ \pm 6\ \Omega$
5µm	$511\pm5~\Omega$
6um	$366 \pm 4 \Omega$

Table 4-10: Leakage Resistance between the red and blue sections for devices with different ridge thicknesses.

Chapter 5. Conclusions and Future Work

5.1 Conclusions

Superluminescent diodes, structured with two sections, and use of quantum well intermixing (QWI), were fabricated on a GaAs substrate to produce a target wavelength of \sim 1 µm. The goal was to produce large spectral width and high power. This was accomplished by applying a thin layer of GaInP grown at low temperature (LT-GaInP) with an excess of P atoms, to one section of the device and annealing it. The differences of QWI between the two sections created different QWs, which produced a broad spectral width.

The following is a summary of all the bandgap blue shifts seen between the material with and without LT-GaInP capping layers (with SiO₂), for different anneals.

Structure	RTA	Blue Shift ($\Delta\lambda$)
1	800 °C / 30 s	27 ± 2 nm
1	800 °C / 60 s	31 ± 2 nm
1	825 °C / 60 s	44 ± 2 nm
2	825 °C / 30 s	26 ± 2 nm
2	825 °C / 45 s	28 ± 2 nm
2	825 °C / 60 s	36 ± 2 nm

Table 5-1: Summary of Blue Shifts between section with and without LT-GaInP

As shown in Table 5-1, the PL peaks from the two section created using structure #1 (Fig. 3-1) with RTA 825 °C / 60 s were separated by 44 ± 2 nm. This enabled the use of the longest blue section with minimal absorption of generated light from the red section, which resulted in larger output power and broader spectral width.

The use of LT-GaInP and SiO_2 capping layers showed significant power improvements after an RTA. Therefore, diodes employing the use of only one section could also benefit from the use of quantum well intermixing with these two capping layers, depending on its growth method and temperature.

Also, although the temperature was held constant at 20 °C, power improvements could be seen at lower temperatures.

In conclusion, structure #1 produced the best results. Its ridges had some undercutting due to its [110] orientation, which produced higher current densities and better optical confinement than the outward sloping ridges fabricated in structure #2, which were orientated on the $[\overline{1} \, 10]$ direction. Also, due to a 44 ± 2 nm separation between the two PL peaks, the structure with a 750 µm blue sections could be used, enabling high power and a broad spectral width of 60 ± 2 nm. It was seen that the narrowest ridge devices gave the best performance. When comparing the SLDs of this thesis to recently reported SLDs, as well as current commercially available SLDs, in the 980 nm regime (tables 1-1 and 1-2), a significant improvement in both power and spectral width is seen with the devices fabricated from structure #1. For example, although the other SLDs vary in both power and spectral width, generally the power has improved, and the spectral width has doubled.

5.2 Future Work

Structure #2 was grown with a thicker quantum well in an effort to produce a longer wavelength. Consequently, a thicker quantum well is less sensitive to quantum well

intermixing, making it harder to produce larger relative blue shifts between the two section-peaks. Instead, an alternative option would be to grow structure #1 with its quantum wells closer together. This would induce coupling and produce the desired red shift, but keep its higher sensitivity to QWI.

During photolithography, the boundary layers for the sections with LT-GaInP were very challenging to etch after a rapid thermal anneal. This created the concern that the etch stop layer would be completely etched through in the red sections. Instead, a reactive ion etch (RIE) might be more appropriate. This would avoid the problem of dealing with different etch rates for different sections on the wafer.

Absorption measurements of the red-section light for different blue-section lengths are needed. This should be measured at the blue section facet, with varying currents in both sections. It would also need to be done for devices fabricated with different QWI/RTAs.

Additionally, an anti-reflective coating should be applied to the devices to determine if there would be a power improvement, as well as to determine if the multiple peaks seen within the spectrum are due to a feedback mechanism.

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APPENDIX A: Quantum Well Energy Level Calculations

Scenario:

 $Ga_{0.47}In_{0.53}As$ quantum well, 5nm thick, surrounded by InP barriers, lattice matched to an InP substrate.

$$\sqrt{\frac{2m_b^*(V_o - E)}{\hbar^2}} = \frac{m_b^*}{m_w^*} \sqrt{\frac{2m_w^*E}{\hbar^2}} \tan\left(\sqrt{\frac{2m_w^*E}{\hbar^2}} \frac{L_w}{2}\right)$$

To determine the lowest bound energy states within the QW, the above equation needs to be solved. Therefore, data on the height of the potential well energy barriers (V_o), as well as the effective masses, need to be acquired. The energy values should also be converted into Joules so that the units within the tangent function can cancel each other out, noting and using the following conversion: $1 \text{ Joule} = 1 \text{ kg} \cdot m^2/s^2$.

Potential Barrier (V_o) Calculations

Referring to M. Levinshtein,^{20,21} the following values are given in Table A-1:

Material	Valence Band Edge	Conduction Band Edge
InP	-5.724 eV	-4.380 eV
Ga0.47In0.53As	-5.240 eV	-4.500 eV

Table A-1: Energy levels measured from the vacuum level

The Ga_{0.47}In_{0.53}As quantum well has bulk conduction and valence energy band edges at -4.500 eV and -5.240 eV. The InP barriers have the bulk conduction and valence energy band edges at -4.380 eV and -5.724 eV. Therefore, the energy bands look like the following diagram in Fig. A-1, where the potential barrier (V_o) equals to 0.120 eV in the conduction band, and 0.484 eV in the valence band.

Figure A-1: Energy Band Diagram 1

Effective Mass (m^{*})

Referring to M. Levinshtein,^{20,21} the following effective masses are given in Table A-2.

Material	Effective Electron Mass	Effective Heavy Hole Mass	Effective Light Hole Mass
InP	0.08	0.6	0.089
Ga0.47In0.53As	0.041	0.45	0.052

Table A-2: Effective Masses

Solution for the Conduction Band

$$\sqrt{\frac{2m_b^*(V_o - E)}{\hbar^2}} = \frac{m_b^*}{m_w^*} \sqrt{\frac{2m_w^*E}{\hbar^2}} \tan\left(\sqrt{\frac{2m_w^*E}{\hbar^2}} \frac{L_w}{2}\right)$$

Left Side of the Equation

$$\sqrt{\frac{2 \times 0.08 \times 9.109 \times 10^{-31} kg \cdot (0.12 eV - E) \times 1.602 \times 10^{-19} J / eV}{(1.055 \times 10^{-34} J \cdot s)^2}}$$

Right Side of the Equation

$$\frac{0.08}{0.041} \times \sqrt{\frac{2 \times 0.041 \times 9.109 \times 10^{-31} kg \times E \times 1.602 \times 10^{-19} J/eV}{(1.055 \times 10^{-34} J \cdot s)^2}} \times \tan\left(\sqrt{\frac{2 \times 0.041 \times 9.109 \times 10^{-31} kg \times E \times 1.602 \times 10^{-19} J/eV}{(1.055 \times 10^{-34} J \cdot s)^2}} \cdot \frac{5nm}{2}\right)$$

Under the following scenario, 'E' equals 0.059 eV, which places the first energy band at -4.500 eV + 0.059 eV = -4.441 eV.

Solution for Valence Band

Because the heavy and light hole bands have different effective masses, their energy levels within the quantum well exist in different positions. Therefore, they are treated separately.

The effective mass for the heavy and light hole bands within lattice matched barrier material exist together at k=0, and therefore must be combined using $m^* = (m_{hh}^{3/2} + m_{lh}^{3/2})^{2/3}$. This equals 0.623.

The heavy hole energy level is determined using the same method with the conduction band, but replacing the effective mass with 0.45, the barrier effective mass with 0.623, and the potential barrier V_o with 0.484 eV. Under such conditions, the lowest bound energy level appears at 0.023 eV.

For the light hole energy level, the effective mass in the well is 0.052, and 0.623 in the barriers. The potential barrier V_o is 0.484 eV. This places the lowest bound energy level at 0.055 eV.

Among the heavy and light hole energy levels within the QW, the lowest is from the heavy hole. This places the lowest bound energy level in the quantum well's valence band at -5.240 eV - 0.023 eV = -5.263 eV.

Quantum Well Emission



Figure A-2: Energy Band Diagram 2

Therefore, the effective bandgap in the quantum well is 0.822 eV, which produces 1508.0 nm photons.

$$\lambda = \frac{hc}{E} = \frac{6.626 \times 10^{-34} \, J \cdot s \times 3 \times 10^8 \, m/s^2}{0.822 eV \times 1.602 \times 10^{-19} \, J/eV} = 1508 nm$$

To see another example, please refer to "Physics of Optoelectronic Devices" by S. L. Chuang, Page 95-97.

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