Optimisation of 1.3 $\mu$m strained-layer semiconductor lasers.

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I would like to dedicate this thesis to my family and friends, who have all shown great patience in waiting for its completion.
Abstract.

The objectives of the research undertaken have been to investigate the properties of semiconductor lasers operating at around 1.3 µm. The aim of the investigation is to suggest modifications which give rise to improved operating characteristics especially in the high temperature (approaching 85 °C) range.

The investigation can be divided into 2 sections: a theoretical approach and an experimental section. The theoretical study examined the performance of compressively strained InGaAsP/InP multiple quantum-well lasers emitting at 1.3 µm in order to investigate the important factors and trends in the threshold current density and differential gain with strain, well width and well number. Structures with a fixed compressive strain of 1 % but variable well width, and also with a fixed well width but variable strain from 0 % to 1.4 % have been considered. It has been found that there is little benefit to having compressive strains greater than 1 %. For structures with a fixed 1 % compressive strain and unstrained barriers, an optimum structure for lowest threshold current density and a high differential gain has been found to consist of six 35 Å quantum-wells. In addition, compensated strain (CS) structures with compressive wells and tensile barriers have been examined. It is shown that the conduction band offset can be significantly increased and the valence band offset reduced in such structures, to give band-offset ratios comparable with aluminium based 1.3 µm devices. The gain calculations performed suggest that there is little degradation in the threshold carrier density or differential gain due to these alterations in the band offsets; and hence a better laser performance is expected due to a reduction in thermal leakage currents due to the improved electron confinement.
The experimental study concentrates on looking at certain key design parameters to investigate their effect on the laser performance. These design parameters range from the number of quantum-wells to the device length. The experimental study confirms the conclusions drawn in the theoretical investigation that the optimum structure for a 1.3 μm InGaAsP laser for low threshold current, high efficiency and high characteristic temperature operation consists of six 1% compressively strained 50 Å quantum-wells in a device of medium length (approx. 450 μm). The inclusion of a high reflection coating on one facet provides further improvement in the device performance, but increases the production cost dramatically.

Also investigated in the experimental section is the effect of changing the device material from InGaAsP to InGaAlAs. The results discussed do not offer firm evidence of any improvement in the device characteristics in switching from a P-based to an Al-based structure. This is mainly due to the added complication of switching to a RWG structure from a BH structure.

Another explanation for the relatively poor performance of InGaAsP 1.3 μm lasers has been examined. That is leakage of the carriers out of the well region. Evidence of a leakage current has been seen primarily in devices with a low number of quantum-wells. A novel measurement technique has been demonstrated, which should prove useful for obtaining a numerical value for the leakage current in semiconductor lasers. The results presented suggest that leakage current is not significant for a 9 well device until operating at temperatures above around 373 K. This is supported by evidence supplied by the spontaneous emission spectra.
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Contents.

Abstract. ii

Acknowledgements. iv

1 Introduction. 1

2 Basic Semiconductor Laser Theory. 7
   2.1 Introduction. .................................................................7
   2.2 Electronic Transitions. ....................................................7
   2.3 Density of States. ..........................................................9
   2.4 Threshold Carrier Density. .............................................11
   2.5 Threshold Current. ........................................................12
      2.5.1 Non-Radiative Auger Current. ...............................13
   2.6 Temperature Dependence of the Threshold Current. .....16
   2.7 Efficiency. .................................................................19

3 Theoretical study of 1.3 μm InGaAsP compressively strained quantum-well lasers. 21
   3.1 Introduction. ........................................................................21
   3.2 Strained InGaAsP quaternary material parameters. ..........22
   3.3 Laser Modelling. ................................................................26
   3.4 Optimum structures and laser parameter trends. ..........28
   3.5 Discussion and Results. ....................................................29
      3.5.1 Fixed strain, variable well width. ..............................29
      3.5.2 Fixed well width, variable strain lasers. .................37
      3.5.3 Zero-net-strain structures. .......................................39
      3.5.4 Compensated strain. ..............................................42
   3.6 Conclusion. ......................................................................44
4 Experimental study of strained InGaAsP semiconductor lasers. 45
   4.1 Introduction ........................................................................................................ 45
   4.2 The effect of well number on device characteristics ....................................... 46
       4.2.1 Light-Current measurements ................................................................ 46
       4.2.2 Spontaneous emission measurements ..................................................... 51
   4.3 Cavity length dependence of device characteristics ....................................... 61
   4.4 Using facet coatings to change the mirror losses ............................................ 66
       4.4.1 Verification of the mirror losses ............................................................. 67
   4.5 Conclusions ....................................................................................................... 76

5 Comparison of InGaAsP and InGaAlAs semiconductor lasers. 78
   5.1 Introduction ....................................................................................................... 78
   5.2 Light-Current Measurements ........................................................................... 79
   5.3 Spontaneous emission measurements ............................................................. 83
   5.4 Conclusions ....................................................................................................... 88

6 Investigation of the leakage current in 1.3 µm semiconductor lasers. 91
   6.1 Introduction ....................................................................................................... 91
   6.2 Evidence of a "leakage" current .................................................................... 92
   6.3 Novel measurement technique .................................................................... 97
   6.4 Conclusions ..................................................................................................... 103

7 Thesis Summary .................................................................................................... 105
Chapter 1.

Introduction.

Strained-layer semiconductor structures are commercially produced in vast numbers creating a multi-million pound annual turnover. They find application principally in the semiconductor laser, which is used in the communications industry and in optical data storage. The vast expansion in the semiconductor laser industry occurred during the late seventies and eighties; long after the first semiconductor lasers were produced by three different groups in 1962. In the early days there was a major problem with the reliability of the devices. Lasers could be produced that worked well at low temperatures, but when these devices were operated at room temperature their lifetimes were too short for commercial exploitation. The first useful devices followed the introduction of the heterostructure in 1969.

Consequent development with latticed matched GaAs/AlGaAs heterostructures resulted in commercial devices in 1971. The reduction in the active layer thickness, due to continued advances in growth techniques, of a semiconductor laser led to the introduction of the quantum-well laser, first observed in 1975 [1.1], which showed improved performance over conventional double heterostructure lasers. The quantum-well laser structures were restricted, however, because it was thought that the quantum-well and barrier compositions had to have lattice constants very close to that of their InP or GaAs substrates. Vast numbers of these lattice matched devices were designed and implemented until improved fabrication techniques allowed the introduction of strain.
By the early eighties, crystal growers could produce high quality interfaces between incoherent materials; a result of efforts to increase the range of materials available to device designers. This, together with the realisation, by Adams [1.2] and Yablonovitch and Kane [1.3], that strain may advantageously alter the electronic and optical properties of materials, resulted in the appearance of strained-layer lasers. To date, development has concentrated on strained layers. Meanwhile, work to improve their efficiency, reliability, power, temperature stability, etc. is continuing.

In this thesis, theoretical and experimental studies are performed to determine the effects of a variety of the important design parameters on the performance of semiconductor lasers operating at wavelengths of around 1.3 \( \mu \text{m} \). These studies explore the important factors and trends seen in the operating characteristics of these devices. The following sections give a brief overview of the work described in this thesis.

**Chapter 2: Basic Semiconductor Laser Theory.**

In chapter 2, a brief introduction to qualitative semiconductor laser theory is presented. This covers the basic concepts necessarily assumed throughout the remainder of this thesis. The ideas of optical absorption, spontaneous and stimulated emission and the density of states are covered. The Bernard-Duraffourg condition is explained and related to the transparency carrier density, which is then extended to the net stimulated emission rate, optical gain and the threshold gain condition for a Fabry-Perot type laser device. The theory of the threshold current is explained and developed to include the radiative and non-radiative contributions important in lasers operating with a wavelength of around 1.3 \( \mu \text{m} \). The classification of the temperature dependence of the threshold current including its radiative and non-radiative components is introduced. Finally, the external quantum differential efficiency is briefly discussed and related to the optical losses.
Chapter 3: Theoretical study of 1.3 μm InGaAsP compressively strained quantum-well lasers.

In this chapter, a theoretical study of compressively strained InGaAsP quantum-well lasers emitting at wavelengths of 1.3 μm is presented. This study examines the important factors and trends in the threshold current density and the differential gain seen by changing the important design parameters of quantum-well width, number of wells and the strain grown into the well. The results obtained in this 1.3 μm system are compared with the more extensively studied InGaAsP quantum-well lasers emitting at 1.55 μm, emphasising the similarities and differences between these two technologically important wavelength ranges.

This chapter examines structures with a fixed 1% well strain (close to the optimum), but with variable well width, and then with a fixed well width of 50 Å, but variable well strain (from 0 to 1.4 %), all with unstrained barriers. Also considered are structures incorporating zero-net-strain (ZNS) and compensated strain (CS) structures with compressive wells and tensile barriers.

It is shown that theoretically there is little benefit to having compressive strains greater than 1 %. For structures with a fixed 1 % compressive strain and unstrained barriers it is shown, in this chapter, that the optimum structure for lowest threshold current density and a high differential gain consists of six 35 Å quantum-wells. This chapter demonstrates that with the incorporation of tensile-strained barriers, between the compressively strained quantum-wells, the conduction band offset can be significantly increased and the valence band offset reduced to give band offset ratios comparable with aluminium-based 1.3 μm devices.

Chapter 4: Experimental study of strained InGaAsP semiconductor lasers.

This chapter presents an experimental analysis of compressively strained 1.3 μm InGaAsP quantum-well lasers. The study concentrates on certain important design criteria with the aim of establishing trends that can be employed to predict optimum structures for
device applications. The design criteria examined are number of quantum-wells, cavity length and facet coating (i.e. the mirror losses). Comparisons are made between certain sets of devices, which vary only slightly in structure, enabling the key properties of the lasers to be identified. Wherever possible, connections are made to the theoretical study presented in chapter 3.

The lasers being studied are intended for application in optical fibre communication systems. The basic requirements for lasers used in these systems are low threshold current densities (more specifically low threshold currents); high differential efficiencies and thermal stability. It is on these properties that this chapter concentrates.

The analysis employs a variety of experimental techniques to investigate the laser characteristics and observed trends. These techniques include the measurement of the light-current characteristics as a function of temperature for the different structures. Also measured are the spontaneous emission spectra for these devices. By combining the results of these measurements the properties of the lasers are explained.

The ideal number of wells for low threshold current density operation is shown to be 6 wells and this agrees with the theoretical predictions made in the chapter 3. Based on the theory presented in chapter 3 and the experimental results presented in this chapter, the optimum 1.3 μm InGaAsP laser for low threshold current, high efficiency and high $T_0$ operation is predicted to consist of six 1% compressively strained 50 Å quantum-wells in a device of medium length (approx. 450 μm) with a high reflection coating on one facet. This basic design can be "tuned" for the exact application using the trends seen in this chapter.

**Chapter 5: Comparison of InGaAsP and InGaAlAs semiconductor lasers.**

An important consideration of device structure not covered in chapter 4 is that of the material composition. There are primarily two material compositions used for lasers operating at wavelengths around 1.3 μm, these are InGaAsP and InGaAlAs devices. The
majority of this thesis has concentrated with the InGaAsP structures, however it has been suggested that a better temperature performance be obtained by employing InGaAlAs devices. This improvement is attributed to a reduced carrier (electron) leakage into the barrier and surrounding regions, brought about by the increased conduction band offset between the well and barrier. This chapter presents an examination on these aluminium-based lasers to investigate what improvements using this composition can make.

The results presented do not give any firm evidence of improvement in the device characteristics in switching from a P-based to an Al-based structure. This is assigned to the added complication of switching to a RWG structure from a BH structure.

Switching to a ridge waveguide structure gave rise to a slight increase in the room temperature threshold current density. This increase may have appeared to be artificially large due to current spreading. More importantly, for telecommunication purposes, this appeared as a large increase in threshold current. However, as discussed in chapter 4, there are more factors to be considered than just the threshold current. Switching to a RWG structure increased the temperature stability of the threshold current (i.e. T₀). This improvement in T₀ is accounted for by the incorporation of a parallel current path that is not as temperature sensitive. This follows as the improvement is seen both in the Al-based and the P-based RWG structures.

Although, it is stated that no firm evidence of improved device characteristics is seen due to the incorporation of aluminium into the device structure, there is no sign of emission from the barrier region in these devices. This would support the prediction that incorporating Al increases the conduction band well to barrier offset and thus reduces the thermal excitation of electrons into the barrier region.

Chapter 6: Investigation of the leakage current in 1.3 μm semiconductor lasers.
Employing the proposed alterations, suggested in the previous chapters, on the device structure, the lasing characteristics still fall short of the required specifications. In order to
assess what further improvements can be made to the device structure, another explanation for the poor device performance is investigated in this chapter - carrier leakage.

In the structures studied carriers are thought to spillover out of the wells. These carriers can recombine in the barrier and separate-confinement-heterostructure (SCH) regions or can be thermally excited into the InP cladding region. Both of these carrier paths are unproductive to the lasing process and can be combined into a term called "leakage current". In this chapter evidence of this leakage is observed and a novel method of measuring this leakage current is presented.

The results presented indicate that the leakage current is not significant for a 9 well device until operating at elevated temperatures. This is supported by evidence supplied by the spontaneous emission spectra.
Chapter 2.

Basic Semiconductor Laser Theory.

2.1 Introduction.

This chapter introduces the fundamental theory that will be required to provide an adequate description of semiconductor lasers relevant to the work discussed later in this thesis. A more detailed description of semiconductor laser theory can be found in a variety of texts including Agrawal and Dutta [2.1], Suematsu and Adams [2.2], Casey and Panish [2.3], and Thompson [2.4].

2.2 Electronic Transitions.

Although, the electronic band structure in a semiconductor is complicated the electronic transitions can be described in terms of the interaction between a pair of electronic states in a two level laser system. In both systems there are three basic interactions between
photons and electrons. These processes, spontaneous emission, optical absorption and stimulated emission are shown schematically below.

In an undoped, direct bandgap semiconductor laser in thermal equilibrium there are usually only a few filled states in the conduction band and conversely only a few empty states in the valence band. The small number of electrons in the conduction band will tend to recombine with the holes in the valence band emitting a photon via spontaneous emission.

![Schematic Diagram of Transitions](image)

Fig. 2.1. The three basic transitions in a semiconductor laser. Electrons are represented by the filled circles and holes by the empty circles.

If a photon of suitable energy, $h\nu$, (greater than that of the bandgap) passes through the material it has a high probability of being absorbed by exciting an electron from the valence band into the conduction band.

The third process, stimulated emission, occurs when a photon of suitable energy interacts with an electron in the conduction band stimulating the electron to recombine with a hole in the valence band and emitting another photon. This second photon matches the stimulating photon in phase and frequency. This process is highly improbable in thermal equilibrium because the population of electrons in the valence band is much greater than that in the conduction band, meaning most photons would interact via optical absorption. In order to increase the probability of stimulated emission the population of electrons in the conduction band and holes in the valence band have to be increased. This population
inversion is usually achieved by electrical injection. As the number of electrons in the conduction band increases, a point is reached when a passing photon has the same probability of interacting via stimulated emission as it does of being absorbed, at this point the semiconductor is optically transparent. The condition for net stimulated emission is that first stated by Bernard and Duraffourg [2.5]:

\[ E_{fc} - E_{fv} > h\nu > E_g \]  

Eq. 2.2.1

where \( E_{fc} \) and \( E_{fv} \) are the quasi-Fermi levels in the conduction and valence bands, respectively and \( E_g \) is the band-gap energy. The quasi-Fermi levels describe the probability distributions of electrons in the conduction and valence bands. Hence there is net stimulated emission, or optical gain, for photons with a range of energies, \( E = h\nu \), between the band-gap energy, \( E_g \), and \( E_{fc} - E_{fv} \). Thus, there is a certain number of injected carriers per unit volume, or carrier density, above which the semiconductor will undergo net stimulated emission. This is known as the transparency carrier density, the transparency condition being defined as:

\[ E_{fc} - E_{fv} = E_g \]  

Eq. 2.2.2

2.3 Density of States.

The carrier density at which transparency occurs depends largely on the density of states (DOS) in the conduction and valence bands. The density of states of a bulk 3-dimensional semiconductor is shown in Fig. 2.2a, along with the carrier occupancy (shaded region). It can be seen that the density of states and carrier occupancy become increasingly small near the band-edge. The majority of direct radiative transitions in a laser take place via carriers in states close to the conduction and valence band-edges. Thus the 3-dimensional
structure is inefficient since there are very few carriers in these regions to take part in radiative recombination.

Contrast this with the 2-dimensional quantum-well density of states and carrier occupancy, shown in Fig. 2.2b. Here, the DOS has a step-like shape with a finite value at the band-edge; therefore carrier occupancy is higher at lower energies. A strained layer quantum-well semiconductor also has a 2-dimensional DOS but here the carrier density required to achieve the Bernard and Duraffourg condition is reduced due to the reduction in the valence band effective mass. This is illustrated by the idealised DOS shown in Fig. 2.2c.

![Density of States (DOS) and Carrier Occupancy](image)

(a) Bulk, $m_v = 5m_e$  
(b) Quantum-well, $m_v = 5m_e$  
(c) Strained QW, $m_v = m_e$

Fig. 2.2. The density of states (DOS) and carrier occupancy (shaded area) for (a) bulk; (b) quantum-well; and (c) idealised strained quantum-well.
2.4 Threshold Carrier Density.

Although net stimulated emission occurs as soon as the carrier density exceeds the transparency point, the laser does not lase until the number of carriers is increased up to a certain critical value known as the threshold carrier density, $n_{th}$. This value corresponds to the point where the net stimulated emission, or optical gain, equals the sum of all the various losses in the laser. This requires that there is optical feedback. For the devices used in this work this is achieved by the cleaved facets of the semiconductor laser forming a Fabry-Perot cavity. The cleaved facets provide about 30% optical intensity reflection due to the differences between the refractive indices of the semiconductor and air. The amount of reflection can be easily altered by applying anti- or high-reflection coatings on the cleaved facets. The net round trip gain, $g_{fp}$, of a Fabry-Perot cavity of length L, and facet reflection coefficients $R_1$ and $R_2$ is given by:

$$g_{fp} = R_1R_2 \exp[2L(G - \alpha_i)]$$

where $G$ is the modal optical gain and $\alpha_i$ is the internal optical loss. In a semiconductor laser, the width of the propagating optical field profile is typically larger than the thickness of the gain region. Consequently, the optical field only partly overlaps with the gain region and this overlap is expressed by the optical confinement factor, $\Gamma$. Thus, the modal gain, $G$, is related to the material gain, $g$, through $\Gamma$, by:

$$G = \Gamma g$$

At threshold, the round trip gain, $g_{fp} = 1$, giving:

$$\Gamma g_{th} = \alpha_i + \frac{1}{2L} \ln \left[ \frac{1}{R_1R_2} \right]$$

Quantum-well devices have a logarithmic dependence of gain with carrier density:
\[ g = g_0 \ln \left[ \frac{n}{n_t} \right] \quad \text{Eq. 2.4.4} \]

where \( n_t \) is the 2-D transparency carrier density and \( g_0 \) is a parameter related to the differential gain, \( \frac{dg}{dn} \) (but with the same units as \( g \)). Therefore the threshold carrier density, \( n_{th} \), can be related to the threshold gain, \( g_{th} \), as:

\[ n_{th} = n_t \exp \left[ \frac{g_{th}}{g_0} \right] \quad \text{Eq. 2.4.5.} \]

**2.5 Threshold Current.**

Injection of carriers into the laser is achieved by applying a voltage across the device. The carriers can recombine radiatively and non-radiatively to produce a current through the laser and an associated threshold current density, \( J_{th} \), where for long wavelength lasers we assume:

\[ J_{th} = e \left( A n_{th} + B n_{th}^2 + C n_{th}^3 \right) \quad \text{Eq. 2.5.1} \]

where \( e \) is the electronic charge, \( A n_{th} \) and \( C n_{th}^3 \) are the contributions to the current from non-radiative recombination. The \( A n_{th} \) term is due to recombination via defects in the material. This process can be thought of as a one-carrier mechanism but can be considered negligible in the devices studied in this thesis due to the high quality growth techniques and materials used. The \( C n_{th}^3 \) term is caused by Auger recombination, which involves three carriers (see below) hence the \( n^3 \) nature. The \( B n_{th}^2 \) term is the radiative recombination current density caused by recombination via spontaneous emission – a two carrier process. The relative proportions of the different contributions to the total
threshold current is heavily dependent on both the optoelectronic properties of the active region material and the engineered laser design.

2.5.1 Non-Radiative Auger Current.

Non-radiative recombination mechanisms include recombination at defects, surface recombination, Auger recombination and current leakage effects. It is thought that the most important contribution to the non-radiative current in 1.3 μm semiconductor lasers is Auger recombination, of which there are two main mechanisms: band-to-band [2.6-2.9] and phonon-assisted [2.10] Auger recombination. Although Auger recombination is thought to be the most significant component of the non-radiative current, current leakage effects have been observed and these will be investigated in Chapter 6.

Band-to-Band Auger.

A schematic of the band-to-band Auger recombination process is shown in Fig. 2.3. An electron (1) and a hole (1’) recombine across the band-gap, exciting a third carrier to higher energy, due to a Coulombic interaction between the carriers. There are two dominant processes involving excitation of an electron (2) to a higher lying conduction state (2’) (CHCC) or an electron (2) from the spin-split-off band into an empty heavy-hole state (2’) (CHSH), as shown in Fig. 2.3.
Band-to-band processes involve three carriers and have a rate that may be approximated (using Boltzmann statistics) [2.1] for the direct process by:

\[
R_u = C n^3 \exp \left[ -\frac{\Delta E_u}{k_b T} \right]
\]

where \( C \) is the Auger recombination coefficient determined primarily by the band-structure and optical matrix elements, \( n \) is the carrier density, \( k_b \) is Boltzmann’s constant, \( \Delta E_u \) is the activation energy for the process and \( T \) is the temperature.

The relative strengths of these processes are heavily dependent on the temperature and band-gap of the semiconductor because the laws of conservation of energy and momentum must be observed for the four particles \((1,2,1',2')\). These processes can therefore give rise to a strongly temperature sensitive threshold current variation in devices where this loss mechanism is present.

Assuming parabolic conduction, valence and spin-orbit bands, and Boltzmann statistics the minimum activation energy for the CHCC and CHSH processes are given by:
\[ \Delta E_a \,(CHCC) = \frac{m_c}{m_c + m_h} E_g \]  

Eq.2.5.3

where \( m_c \) and \( m_h \) are the conduction and valence band masses respectively, and \( E_g \) is the band-gap energy, and;

\[ \Delta E_a \,(CHSH) = m_s \frac{E_g - E_{so}}{(2m_h + m_c - m_s)} \]  

Eq. 2.5.4

where \( m_s \) is the mass of the spin-split-off band and \( E_{so} \) is the spin-split-off energy.

It can be seen from these equations that the activation energy is proportional to the band-gap, \( E_g \), and inversely proportional to the valence band effective mass, \( m_h \). Thus, it was predicted by Adams[2.11] that a reduction in \( m_h \) due to the incorporation of compressive strain into a laser device would reduce the Auger recombination rate due to an increasing activation energy, \( \Delta E_a \).

**Phonon-Assisted Auger.**

The phonon-assisted processes [2.10, 2.12] are similar to those of Fig. 2.3 except that the final state \((1')\) is reached by interaction with a phonon from an intermediate state \((1'')\), as shown in Fig.2.4.
It has been shown that band-to-band Auger recombination is the dominant loss mechanism in long wavelength bulk laser devices [2.13]. Recent experimental evidence indicates this is also the dominant loss process both in lattice-matched and strained quantum-well structures [2.14].

2.6 Temperature Dependence of the Threshold Current.

As stated earlier (Eq. 2.5.1) the threshold current density can be written as:

\[ J_{th} = e\left(AN_{th} + BN_{th}^2 + CN_{th}^3\right) \quad \text{Eq. 2.5.1} \]

In order to classify the temperature dependence of the lasers a characteristic temperature, \( T_0 \), is defined as:
To $1dJ$,

\[ T_o = \left[ \frac{1}{J_{th}} \frac{dJ_{th}}{dT} \right]^{-1} \] \hspace{1cm} Eq. 2.6.1

which can solved if $T_0$ is independent of temperature as:

\[ J_{th} = J_o \exp \left[ \frac{T}{T_o} \right] \] \hspace{1cm} Eq. 2.6.2

where $T$ is the temperature at which $J_{th}$ is measured and $J_o$ is the threshold current extrapolated to absolute zero. A high value of $T_0$ would therefore indicate a low sensitivity to temperature and is desired for telecommunication uses.

With the high quality growth techniques and materials used in the devices studied in this thesis the $A_{nth}$ term can be considered negligible, reducing Eq. 2.5.1 to:

\[ J_{th} \sim e^{B(T) + C_{nth}} \] \hspace{1cm} Eq. 2.6.3

This suggests that the temperature dependence of the threshold current is determined by the temperature dependences of the radiative recombination current density and the Auger recombination current. The radiative current at threshold can be written as:

\[ J_{rad} (T) \sim B(T) \left[ n_{th} (T) \right]^2 \] \hspace{1cm} Eq. 2.6.4

We can assume the temperature dependence of the individual components of the radiative current; for the radiative current density coefficient:

\[ B(T) \sim T^{-1} \] \hspace{1cm} Eq. 2.6.5

and for the carrier density:

\[ n_{th} (T) \sim T^{1+x} \] \hspace{1cm} Eq. 2.6.6
where $x=0$ for an ideal quantum well [2.15] and the value of $x$ therefore represents a deviation from the ideal case. Combining Eqs. 2.6.1 and 2.6.3 a characteristic temperature for the radiative current can be calculated to be:

$$T_0^{(Rad)} = \left[ \frac{1}{J_{Rad}} \frac{dJ_{Rad}}{dT} \right]^{-1} = \frac{T}{2x+1} \quad \text{Eq. 2.6.7}$$

This indicates that a device dominated by radiative recombination can have a characteristic temperature as high as the measurement temperature (i.e. ~300K at room temperature).

The Auger recombination current at threshold can be written as:

$$J_{Aug}(T) \propto C(T)[n_{th}(T)]^2.$$ \quad \text{Eq. 2.6.8}

We assume the temperature dependence of the Auger recombination coefficient to be:

$$C(T) = C_0 \exp\left[ -\frac{\Delta E_a}{k_bT} \right]. \quad \text{Eq. 2.6.9}$$

Combining Eqs. 2.6.1, 2.6.6, 2.6.8 and 2.6.9 a characteristic temperature for the Auger recombination current can be calculated to be:

$$T_{0}\text{(Aug)} = \left[ \frac{1}{J_{Aug}} \frac{dJ_{Aug}}{dT} \right]^{-1} = \frac{T}{3 + 3x + \frac{\Delta E_a}{k_bT}} \quad \text{Eq. 2.6.10}$$
This result asserts that even an ideal device (with $x = 0$ and a negligible Auger activation energy) dominated by Auger recombination cannot have a characteristic temperature higher than one third of the measurement temperature (i.e. $\sim$100K at room temperature).

### 2.7 Efficiency.

![Fig. 2.5. Typical plot of the light output against the applied current for a semiconductor laser.](image)

Fig. 2.5 shows the light output from the facet of a typical semiconductor laser as a function of drive current through the laser, known as an L-I plot. Below the laser threshold the current mainly consists of spontaneous and non-radiative recombination current. When the current is increased past threshold stimulated emission begins to dominate. As can be seen, immediately past threshold the light increases dramatically in a linear fashion with current, for an ideal device. The slope of the linear region is the
external quantum differential efficiency, $\eta_d$, of the laser. This is a measure of the efficiency with which the laser converts current into photons by stimulated emission, and is proportional to the ratio of the photon escape rate to the photon generation rate, given by:

$$\eta_d = \eta_i \left( \frac{1}{2L} \ln \left( \frac{1}{R_1 R_2} \right) \right)$$

where $\eta_i$ is the internal efficiency, which is the ratio of the radiative to the total recombination rates. Above threshold stimulated emission dominates and ideally, $\eta_i = 1$. So, the external efficiency is then simply related to the ratio of the optical loss through the facets to the total optical losses in the active region.
Chapter 3.

Theoretical study of 1.3 μm InGaAsP compressively strained quantum-well lasers.

3.1 Introduction.

In this chapter a theoretical study of compressively strained InGaAsP quantum-well lasers emitting at 1.3 μm is presented. Comparisons are made between the results obtained in this 1.3 μm system and the more extensively studied InGaAsP quantum-well lasers emitting at 1.55 μm, emphasising the similarities and differences between these two technologically important wavelength ranges.

In order to illustrate the important trends involved in these devices, results are presented on structures with a fixed 1% well strain (close to the optimum), but with variable well width, and then with a fixed well width of 50 Å, but variable well strain, all with unstrained barriers. The gain is calculated as a function of carrier density, and then estimates of the threshold current density and differential gain (dg/dn) are made as a function of well number in each case.

Also considered are structures incorporating zero-net-strain (ZNS) and strain compensated (CS) structures with compressive wells and tensile barriers.
The theoretical study is carried out using a set of computer programs developed by Silver et al. [3.1]. These programs calculate the material parameters, quantum-well bandstructure, linear gain and carrier and current densities. An outline of how and what information is generated by these programs is included in this chapter.

### 3.2 Strained InGaAsP quaternary material parameters.

The material parameters used to model strained InGaAsP quantum well lasers are summarised in Table (3.1) taken from [3.2].

<table>
<thead>
<tr>
<th>Material</th>
<th>InAs</th>
<th>GaAs</th>
<th>GaP</th>
<th>InP</th>
</tr>
</thead>
<tbody>
<tr>
<td>a (Å)</td>
<td>6.058</td>
<td>5.653</td>
<td>5.451</td>
<td>5.869</td>
</tr>
<tr>
<td>E_g (meV)</td>
<td>360</td>
<td>1420</td>
<td>2740</td>
<td>1350</td>
</tr>
<tr>
<td>Δ0 (meV)</td>
<td>380</td>
<td>340</td>
<td>80</td>
<td>114</td>
</tr>
<tr>
<td>m_e (m_0)</td>
<td>0.0223</td>
<td>0.0665</td>
<td>0.17</td>
<td>0.079</td>
</tr>
<tr>
<td>m_{hh} (m_0)</td>
<td>0.342</td>
<td>0.382</td>
<td>0.79</td>
<td>0.56</td>
</tr>
<tr>
<td>m_{hh} (m_0)</td>
<td>0.0255</td>
<td>0.080</td>
<td>0.14</td>
<td>0.12</td>
</tr>
<tr>
<td>E_{v,as} (eV)</td>
<td>-6.68</td>
<td>-6.84</td>
<td>-7.06</td>
<td>-7.04</td>
</tr>
<tr>
<td>a_v (eV)</td>
<td>1.0</td>
<td>1.16</td>
<td>1.7</td>
<td>1.27</td>
</tr>
<tr>
<td>a_c (eV)</td>
<td>-5.88</td>
<td>-8.06</td>
<td>-9.45</td>
<td>-6.18</td>
</tr>
<tr>
<td>b (eV)</td>
<td>-1.8</td>
<td>-1.7</td>
<td>-1.5</td>
<td>-1.5</td>
</tr>
<tr>
<td>Bandgap bowing (meV)</td>
<td>370 (InGaAs)</td>
<td>790 (InGaP)</td>
<td>280 (InAsP)</td>
<td>210 (GaAsP)</td>
</tr>
</tbody>
</table>

Table 3.1. Binary material parameters used to calculate the strained quaternary InGaAsP material parameters.

Ternary and quaternary material parameters for In_{1-x}Ga_xAs_yP_{1-y} are interpolated from the four binary components of InP, InAs, GaP and GaAs (given in Table 3.1), using the following expressions:
\begin{equation}
Q(x, y) = \frac{x(1-x)[yT_{GaAs}(x) + (1-y)T_{GaP}(x)]}{x(1-x) + y(1-y)} + \frac{y(1-y)[xT_{GaP}(y) + (1-x)T_{InAsP}(y)]}{x(1-x) + y(1-y)}
\end{equation}

where

\begin{equation}
T_{ABC}(x) = xB_{AC} + (1-x)B_{BC} + C_{ABC}x(1-x)
\end{equation}

and \(B_{AC}, B_{BC}\) are the binary parameters, \(C_{ABC}\) is the ternary bowing parameter, and \(x\) is the fractional composition of \(A\) in \(A_xB_{1-x}C\).

The room temperature parameters shown in Table (3.1) are defined as:- \(a\) is the lattice constant; \(E_g\) is the band-gap energy; \(\Delta_0\) is the spin-orbit splitting energy; \(m_c, m_{hh},\) and \(m_{lh}\) are the effective masses for the conduction, heavy-hole and light-hole bands respectively; \(E_{v,as}\) is the valence band averages; \(a_v\) and \(a_c\) are the hydrostatic deformation potentials; and \(b\) is the shear deformation potential.

The band line-ups between the well and the barrier materials in the quantum-wells are calculated using model solid theory [3.3, 3.4].

Fig. (3.1) shows the composition dependence of the room temperature band-gap for strained quaternary \(In_{1-x}Ga_xAs_yP_{1-y}\) grown on InP. Energy contours are shown every 50 meV. The solid line originating in the bottom left hand corner shows alloy compositions lattice matched to InP, while the dashed lines above and below are for 1% tensile and compressive strain respectively. Using strained quaternary material allows a wide scope for possible laser structures, including the possibility of independent variation of the strain and well width for a given emission wavelength.
Fig. 3.1. Strained band-gap (in meV) for \( \text{In}_{1-x}\text{Ga}_x\text{As}_y\text{P}_{1-y} \) quaternary material.

For emission at 1.3 \( \mu \text{m} \), the strained band-gap of the well must be less than 954 meV, in reality lower still allowing for quantum confinement effects to be taken into account. The band-gap of the barrier must be chosen to give sufficient carrier confinement within the well region, whilst also allowing confinement of the optical field. Typical barrier band-gaps therefore vary from about 1000 meV (1.2 \( \mu \text{m} \)) and 1250 meV (1.0 \( \mu \text{m} \)).
It is possible to grow zero-net-strain (ZNS) and compensated strain (CS) structures operating at a wavelength of 1.3 \( \mu \text{m} \). These structures use oppositely strained well and barrier materials to balance out the strain over the entire structure. Devices using this arrangement of strain increase the number of quantum-well-barrier repeats that can be grown before plastic relaxation becomes a problem. So long as the strain in each layer does not exceed a critical value [3.6], it is in principle possible to grow-zero-net strain (ZNS) structures \textit{ad infinitum}, or compensated strain (CS) structures, where the maximum number of quantum-wells is increased compared to the case for lattice matched barriers. The permissible growth combinations are compressive wells with unstrained and tensile barriers or tensile wells with unstrained and compressive barriers. In addition, structures can be grown which contain both compressive and tensile wells with unstrained...
barriers, although these structures are more suitable for polarisation-insensitive amplifiers than for lasers [3.7].

The range of InGaAsP compositions that can be used in ZNS, CS or unstrained barrier structures emitting at 1.3 μm, subject to the above constraints, is shown in fig. (3.2). The diagonal lines with labels on the right hand vertical axis indicate the degree of lattice mismatch while the two curved contours indicate material with constant band-gap of 950 meV and 1250 meV. In this chapter, the focus will be on compressive wells with unstrained or tensile barriers although it can be seen that there is still a wide range of material compositions available. It can also be noted that there is larger scope for using tensile wells with unstrained/compressive barriers than for 1.55 μm emitting InGaAs(P) devices [3.2].

3.3 Laser Modelling.

As discussed in chapter 2, the threshold current density, \( J_{th} \), of 1.3 μm lasers is assumed to be determined by radiative recombination, \( J_{rad} \), and non-radiative recombination, \( J_{NR} \), via Auger recombination. Experimental work has shown this to be valid for 1.3 μm devices [3.8, 3.9]. As a result the threshold current density can be expressed as:

\[
J_{th} = J_{rad} = eB_{2D}n_{2D}^2 + J_{NR} = eC_{2D}n_{2D}^3,
\]

where \( e \) is the electronic charge, \( B_{2D} \) is the radiative recombination coefficient, and \( C_{2D} \) is the Auger recombination coefficient. Experimental and theoretical work suggests that Auger recombination contributes around 60% of the total threshold current at room temperature in lasers operating at 1.3 μm [3.9, 3.10]. It is my feeling that the Auger contribution is more important than this figure suggests. As a result this chapter concentrates on this recombination, by assuming the variation of threshold current with
well composition can be estimated by working with 2D threshold carrier densities ($n_{2D}$) and by reducing equation (3.3.1) to the form:

$$J_{\text{th}} = N\epsilon C_{2D} n_{2D}^3,$$

Eq. 3.3.2

where $N$ is the number of quantum-wells and with $C_{2D} = 1.3 \times 10^{-16} \text{cm}^4 \text{s}^{-1}$ [3.10, 3.11], extrapolated from measurements of $C_{2D}$ under high pressure and experimental data at 1.55 $\mu$m. The recombination coefficient is assumed to be constant as a function of composition, strain and 2D carrier density.

Gain as a function of carrier density is calculated using the quantum well valence band structure generated from a 2-band k.p Hamiltonian, including the heavy-hole (HH) and light-hole (LH) bands [3.12]. The interaction of these bands with the spin-split-off band has been neglected because we are only interested in compressively strained wells. Both the valence and conduction bandstructure are calculated by solving Poisson’s and Schrodinger’s equations self-consistently [3.1], using a 5-point difference method [3.13] which can take account of carrier spillover into the barrier region. These bandstructures are then used to calculate gain spectra for single quantum-wells using the density matrix formulation [3.14] including Lorenztian type broadening [3.15]. In order to determine the threshold condition for multiple quantum-well lasers the optical confinement factor ($\Gamma$) is calculated [3.16] followed by the threshold gain required to overcome the mirror and internal losses. We consider structures with 80 $\AA$ barriers and 160 $\AA$ quaternary waveguide regions, each with a 1200 meV band-gap (equivalent to a wavelength of 1.05 $\mu$m). All the devices were modelled to be 750 $\mu$m in length and the internal losses, $\alpha$, were set equal to $6 \text{cm}^{-1}$ [3.17, 3.18, 3.19].
3.4 Optimum structures and laser parameter trends.

The search for optimum structures is performed by focusing on key parameters in quantum-well design such as well width and strain. This allows the important trends to be established which can then be applied to other combinations of material composition not covered in this thesis. The laser characteristics of 1.3 μm devices are governed by a number of interacting and competing effects:

Valence band density of states (DOS).

The incorporation of strain into a quantum-well splits the degeneracy of the light- and heavy-hole states at the valence band maximum [3.12] which leads to a reduced in-plane hole effective mass, and consequently a reduced density of states (DOS) [3.20] as discussed briefly in section 2.3. This decreases the carrier density required for population inversion and hence reduces transparency and threshold current densities over comparable unstrained devices [3.21, 3.22]. The valence band DOS will be minimised in thin, highly strained wells, where the sub-band separation is maximised [3.12] and hence would lead to the lowest threshold values.

Optical transition strengths.

Above transparency, the peak gain as a function of carrier density is strongly influenced by the optical transition strength as well as by the density of states. The optical transition strength depends directly on the degree of overlap between the electron and hole envelope functions. As the electron envelope function tends for narrow wells to penetrate more strongly into the barrier compared to the hole envelope function, the transition strength increases with increasing well width in conflict with the density of states which is optimised for narrow wells.

Optical confinement factor.

In laser structures there is a further consideration of coupling the quantum-well active region to the optical field. The optical confinement factor, Γ, is governed by both the well width and the number of quantum-wells, in addition to the detailed structure of the
separate confinement heterostructure (SCH) used as the light waveguiding region. The effect of the well width dependence of $T$ is cancelled out by the reciprocal well width dependence of the optical peak material gain (via the density of states) [3.14] and hence does not play a part in determining lasing trends. Furthermore, the SCH region is assumed identical in all structures studied here, to ensure a similar influence in all cases. However, the dependence of $T$ on well number still remains, as the waveguide thickness increases with the number of wells, and will be shown to influence the balance between the competing effects discussed above.

The interplay of these fundamental laser parameters on the threshold current density and differential gain at threshold is investigated by focusing on two structure types. First to be considered are multiple-quantum-well (MQW) structures with fixed 1% compressive strain in the wells and variable well width; with the emission wavelength maintained at 1.3 $\mu$m by varying the well composition. Then, by studying the variation of laser characteristics with strain, keeping the well width fixed at 50 Å, the effects on the lasing properties whilst keeping an effectively constant optical confinement factor and optical transition strength can be seen.

### 3.5 Discussion and Results.

#### 3.5.1 Fixed strain, variable well width.

**Threshold current density.**

Fig. (3.3) shows the threshold current density, calculated from Eq. 3.3.2, as a function of well width for 1% compressively strained multiple quantum-well structures emitting at 1.3 $\mu$m.
Fig. 3.3. Estimated threshold current density for multiple quantum-well structures of 1% compressive InGaAsP at a fixed emission wavelength and varying well width.

The well width varies from a minimum of 25 Å (below which well width fluctuations become a problem) to a maximum of 100 Å (where quantum-well devices begin to exhibit an almost 3-dimensional density of states). For up to eight wells, the predicted threshold current density initially decreases as well width is increased and reaches a minimum between 30 and 60 Å, depending on the number of wells. Beyond the minimum value the threshold current density increases, and for the widest wells, exceeds the value initially obtained for the 25 Å wells. For lasers with more than eight wells, where the optical confinement factor, $\Gamma$, is large there is no minimum in the threshold current density in the range considered, and the lowest threshold values are found for those devices with the narrowest wells.
Fig. 3.4. (i) Valence band-structure, and (ii) density of states (DOS), for 1% compressive InGaAsP 1.3 μm lasers for (a) 25 Å, (b) 40 Å and (c) 100 Å well widths.

The results of these calculations follow a very similar trend to that obtained in 1.55 μm devices [3.2] and which arises from competition between the valence band DOS and optical transition strength effects. The DOS increases with increasing well width promoting an increase in the threshold current density, whereas the optical transition strength encourages a reduction in threshold current due to an increased weighting with increasing well width. This is illustrated by comparing Fig. (3.4) where we observe (i) the valence subband structure and, (ii) the density of states for (a) a 25 Å, (b) a 40 Å and (c) a 100 Å quaternary quantum-well, and Fig. (3.5) where the zone centre TE (E1-HH1) transition strength is plotted as a function of well width.
The competing effects produce modal gain ($\Gamma \times$ material gain) versus 2-D carrier density (per well) curves as shown in Fig. (3.6) for the three well widths: (i) 25 Å, (ii) 40 Å and (iii) 100 Å. The threshold modal gain is estimated to be 22.5 cm$^{-1}$ for a 750 µm device with an internal loss of 6 cm$^{-1}$, as indicated on the graphs by the horizontal dot-dashed line. The two plots are for (a) 4QW and (b) 12QW laser devices and are almost identical to those obtained in the work by Silver and O’Reilly [3.2].

For a four quantum well device (Fig. (3.6a)) the competition between the DOS and optical transition strength causes the 40 Å curve to produce the lowest threshold carrier density at threshold modal gain. For the 12 quantum well case (Fig. (3.6b)) the modal gain at a given carrier density is much increased since $\Gamma$ increases. However, since the threshold modal gain required for lasing is the same for all lasers of equal length and facet reflectivity, we are effectively looking for a threshold material gain which is closer to transparency for structures with a large number of wells. The transparency carrier density (i.e. the carrier density where material gain = 0) is primarily determined by population inversion and therefore dominated by DOS effects. The steady deterioration in
the DOS as well width increases (see Fig. (3.4)) therefore gives the lowest threshold carrier density in the 25 Å case for the 12QW device.

As with the 1.55 μm devices we find that the behaviour of the threshold current density as a function of well width is characterised by competition between the valence band density of states and the optical transition strength. The relative importance of the two effects is determined by the optical confinement factor and hence by the position of the threshold gain on the material gain versus carrier density curve.

We see also for each well width a minimum in the threshold current density as a function of well number. This time the competition is between the magnitude of the optical confinement factor and the number of wells that need to be pumped. We know that the

---

**Fig. 3.6.** Modal gain versus 2D carrier density curves for 1%, 1.3 μm lasers with (i) 25 Å, (ii) 40 Å and (iii) 100 Å well widths. Graph (a) is for a 4QW and (b) for a 12QW device.
optical confinement factor increases with well number, reducing the threshold current density per well. However, this improvement is eventually counteracted by the larger number of wells in the structure each of which has to be pumped.

The differences in the trends seen on Fig. (3.3) between 1.3 and 1.55 μm devices are only subtle ones. In the 1.55 μm case the threshold current density with well widths greater than ~70 Å is lower for four wells than eight wells, but in the 1.3 μm case the eight-well device always has the lower threshold current density. This is due to a greater importance of the optical confinement factor compared to the number of wells being pumped for the 1.3 μm case. This is also evident for very thin wells where the eight-well device has a lower threshold current density than the six-well sample.

Fig. (3.3) allows us to estimate that the threshold current density at room temperature should be minimised with six, 35 Å quantum-wells. There is quite a broad “window” (between 30 and 60 Å) where the threshold current density is relatively constant. For more than eight wells the threshold current is minimised using the thinnest possible wells.

This conclusion seems to be supported by experiments which show minimum threshold current densities for devices using two, 0.85 % [3.19], five, 1 % [3.23] and five, 1.4 % [3.24] compressively strained 55-60 Å wells. The well widths used are inside the predicted “window”, however we note that width fluctuations are an important consideration in device growth for devices with well widths less than 40 Å. This may, in practice, raise the lower limit of the “window” from 30 Å to 40 Å. The threshold current densities for the devices mentioned above are 190, 250 and 450 Acm^{-2} with cavity lengths of 3000, 1500 and 350 μm respectively, implying mirror loss values of 4.2, 8.3 and 35.6 cm^{-1}. Threshold current values of 100, 140 and 250 Acm^{-2} predicted by our calculations for these devices follow the same trend as that observed by experiment. The calculated values are low compared with the experimental values since we have not allowed for the added radiative current contribution to the threshold current. This contribution is not negligible and could be of the order of 10 Acm^{-2} per well and would
therefore raise the calculated values closer to those seen by experiment. These values would become 120, 190 and 300 Acm\(^{-2}\) respectively. If we also include a leakage current which could be as much as 20% of the total injected current [3.25] these values would then be as high as 150, 240 and 380 Acm\(^{-2}\) which compare well with the experimental values.

\textit{Differential gain.}

As with the threshold current density the differential gain, \(\frac{dg}{dn}\), for devices emitting at 1.3 \(\mu\)m also follows a similar trend as that seen at 1.55 \(\mu\)m. Fig. (3.7) shows the differential gain (expressed in the conventional 3D units) as a function of well width for different numbers of wells (4 to 16) and at transparency (denoted as an infinite number of quantum-wells, or inf. QW, on Fig. (3.7)). For a given number of wells there is a maximum in \(\frac{dg}{dn}\) decreasing from 45 Å for four wells to 35 Å for an infinite number; a similar region to the minima seen in the threshold current density of Fig. (3.3). The magnitude of \(\frac{dg}{dn}\) increases as the number of wells increases, but eventually begins to saturate after 12 wells.
Again we can use the same explanation as discussed in reference [3.2] to account for the trend observed: that is, an interplay between the density of states and the optical transition strengths. In this case, though, the competition effects the differential gain regardless of the value of the optical confinement factor, resulting in a maximum value for all numbers of wells. The optical confinement factor proves important when considering the value of differential gain. The larger values of differential gain occur close to transparency i.e. devices with small threshold material gains (large numbers of wells). However, as the threshold gain approaches transparency, the improvement in differential gain is reduced and begins to saturate as observed after 12 wells and, if enough well numbers were plotted, $\frac{dg}{dn}$ would converge on the inf. QW line.

Again, the differences between the differential gain plots for 1.3 and 1.55 µm are only small. The plot for 1.3 µm devices shows a maximum in $\frac{dg}{dn}$ for narrower wells. Also $\frac{dg}{dn}$ does not level out as the well width is increased as the 1.55 µm plot shows, but instead follows an almost constant decrease. This suggests that the valence band DOS has
a greater importance for $\frac{dg}{dn}$ in the 1.3 µm case than it does compared to 1.55 µm lasers.

We conclude from Fig. (3.3) that the optimum 1 % compressive strained structure for lowest room temperature threshold current density consists of six 35 Å quaternary wells, although a range of well widths and numbers of wells can be used to provide threshold current density values very close to this value. Our calculations also show that for a given number of wells the differential gain can be significantly improved by choosing a well width close to that of the optimum composition for lowest threshold current. These conclusions are akin to those determined in the 1.55 µm work [3.2].

3.5.2 Fixed well width, variable strain lasers.

In this section we calculate the threshold current density and differential gain at threshold for 50 Å MQW structures emitting at 1.3 µm with strain varying from 0 % to 1.4 %. The results of our calculations are summarised in Fig. (3.8). As strain increases there is a rapid decrease in the threshold current density, as shown in Fig. (3.8a). Unfortunately, the rapid improvement levels out, with only marginal further reduction for compressive strains greater than about 1 %. The differential gain shown in Fig. (3.8b), displays a similar behaviour, increasing by about 65 % between 0 and 1 % strain, beyond which it also starts to level out, as previously reported for 1.55 µm devices [3.2, 3.26].
Fig. 3.8. Estimated (a) threshold current density, and (b) differential gain, as a function of strain for MQW structures emitting at 1.3 μm with a fixed 50 Å well width.

The similarity in trends between 1.3 and 1.55 μm can again be explained by the similar nature in which the lasing parameters change. The important factor here is the thermal distribution of carriers within the valence band, which can be assessed from the position of the quasi-Fermi level for holes (E\text{Fv}). Fig. (3.9) shows the hole quasi-Fermi level at transparency and at a fixed material gain of 870 cm\(^{-1}\) as a function of strain – equivalent to the threshold material gain required for a 6QW device. The separation between E\text{Fv} and the valence band edge eventually saturates with increasing strain, both at transparency and threshold. This indicates that the improved valence band dispersion at higher strains does not significantly benefit the hole distribution and does not produce further improvements in the lasing characteristics.
Considering the additional growth problems associated with higher compressive strains, such as critical thickness effects, we conclude that the incorporation of 1% strain is probably the optimum in compressively strained 1.3 μm devices. This appears to be an accurate estimate when considering the experimental devices with the minimum threshold current densities [3.19, 3.23, 3.24]. In these cases the devices use compressive strains of 0.85 %, 1 % and 1.4 % respectively. Also we show agreement with experiment in the improvement going from unstrained to 1% compressive wells, that is a factor of two decrease in threshold current density [3.19].

![Graph](image)

**Fig. 3.9.** Variation of valence band quasi-Fermi level as a function of well compressive strain between 0% and 1.4%.

### 3.5.3 Zero-net-strain structures.

We now consider the effects of introducing tensile strain into the barriers to achieve compensated strain or even zero-net-strain structures. Zero-net-strain structures consist of wells and barriers of opposite strain such that:
\[ \varepsilon_\perp(\text{well})L_\text{well} + \varepsilon_\perp(\text{barrier})L_\text{barrier} = 0 \quad \text{Eq. 3.5.1} \]

where \( L_\text{well} \) and \( L_\text{barrier} \) are the total well and barrier widths, with strains (perpendicular to the growth direction) of \( \varepsilon_\perp(\text{well}) \) and \( \varepsilon_\perp(\text{barrier}) \) respectively. Such ZNS structures cannot overcome the limitations of critical thickness in a single layer, but they do, in principle, allow an infinite number of well/barrier repeats to be grown. We concentrate here on ZNS structures emitting at 1.3 \( \mu \text{m} \) with 50 Å, 1 % compressive wells and with variable tensile strain in the fixed band-gap barrier material. The chief effect that the barrier strain has on the band structure is to modify the conduction and valence band offsets. Fig. (3.10) shows the calculated variation of relevant conduction and valence band energies for quantum-wells with barrier regions with fixed band gap (equivalent to a wavelength of 1.05 \( \mu \text{m} \)) and variable tensile strain.

Fig. 3.10. Variation of band offset, confinement energy and energy required to escape out of the well for (a) electrons and (b) heavy-holes for zero-net-strain material as a function of barrier tension.
Fig. (3.10a) shows the variation in the conduction band offset ($\Delta E_c$), the electron confinement energy for the lowest electron state ($E_{\text{conf}}$) and the energy an electron requires to escape from the quasi-Fermi level, at transparency, for electrons, $E_{\text{fc}}$, into the barrier ($E_{\text{esc}}$). The splitting of the barrier valence band edges due to the incorporation of tensile strain and the variation in well bulk bandgap required to keep a fixed emission wavelength leads to an increase in the conduction band offset. This increase in $\Delta E_c$ along with only a very small rise in the electron quantum confinement as the well bandgap is altered results in an increase in the energy required to escape from the lowest confined state out of the quantum well and into the barrier of about 50 meV from 0 to 1 % barrier tensile strain. Since the electron population in the barriers is determined predominantly by the Fermi level to barrier energy separation, an increase in this energy, $E_{\text{esc}}$, will reduce the electron density in the barrier region. We see that $E_{\text{esc}}$ does indeed increase by 50 meV over 0-1 % tension.

Fig. (3.10b) shows corresponding curves for the valence band. In this case we note that although the valence band maximum in the well is determined by the heavy-hole band edge, the thermal emission of holes from the well is determined by the offset between heavy holes in the well and light holes in the barrier region, which decreases with increasing tensile strain [3.27]. Here we have calculated the valence band offset between the heavy hole state in the well and the light hole state in the barrier ($\Delta E_{\text{hhw-lhb}}$), the heavy hole confinement energy for the lowest state in the well ($E_{\text{conf}}$) and the energy required for a hole to escape from the quasi-Fermi level, at transparency, for holes into the light hole state in the barrier ($E_{\text{esc}}$). The bandgap of the barrier material remains constant with strain and hence the increase in the conduction band is reflected by a similar decrease in the valence band offset. This will increase the escape probability of the holes. However, this increase in escape probability in the valence band is not as significant as the predicted decrease in escape probability in the conduction band due to the much greater effective mass of the holes compared to electrons.
From Fig. (3.10) we see that it is possible to alter the band offset ratios to give values comparable with those of aluminium-based alloy structures, which have been suggested to reduce the thermionic emission of electrons into the barrier [3.28, 3.29].

3.5.4 Compensated strain.

Fig. (3.11) shows the modal gain curves near threshold for a series of compensated strain structures with 50 Å, 1% compressive wells and 1.05 μm, 80 Å barriers with varying degrees of tensile strain, with (a) 4 and (b) 12 quantum-wells. Also shown is the threshold modal gain required for a 750 μm long device (the dash-dot line). All devices emit at 1.3 μm and the well bandgap energy varies from 870 to 855 meV for 0 to 1.2% tensile strain. It can be seen that, as the barrier tension is increased, the carrier density at the gain required for threshold initially decreases and then increases after 0.25% strain. However, the change is very small (note the carrier densities seen in Fig. (3.11)) and there is no appreciable variation in threshold carrier density or differential gain with barrier tension. This does not seem to agree with experiment [3.5], where it has been shown that strain compensated lasers exhibit lower threshold currents and higher differential efficiencies compared with equivalent lasers with unstrained barriers.
Fig. 3.11. Modal gain versus 2D carrier density curves for 1%, 1.3 μm lasers with variable compensated strain (barrier tension). Graph (a) is for a 4QW and (b) is for a 12QW device.

The improvement with compensated strain seen in the experimental results could be due to several reasons, which our model does not take into account. One of the factors that has not been calculated is the thermal leakage of electrons into the InP cladding region. We have argued above, that the inclusion of tensile strain in the barrier would result in better confined electrons and therefore it follows that with this improvement in electron confinement the leakage current would be reduced. Similarly, we would expect that recombination in the barrier region would be reduced as the depth of the electron well increases. Another possibility is that the larger escape probability of holes with tensile barriers will improve the distribution of holes in the MQW structure, and hence distribute more evenly the carriers throughout the structure. A final point to consider is that of
improved device quality with the inclusion of barrier strain due to the elimination of critical thickness problems, which again our calculations cannot take into account.

3.6 Conclusion.

We have estimated theoretically the threshold current density and the differential gain at threshold for 1.3 μm InGaAsP compressively strained quaternary lasers. In our survey we showed that for structures with 1% compressive wells and unstrained barriers the room temperature threshold current density is minimized, in a structure consisting of six ≈35 Å quantum-wells, although this minimum is quite wide (30Å < L_z < 60Å). The differential gain per well is maximized for large numbers of wells, with a well width in the range of minimum threshold current. Finally, for structures with fixed well width and variable strain we find little benefit for either threshold current density or differential gain in having compressive well strains of greater than ≈1%. These predictions agree with experimental results and also equate with the trends obtained for 1.55 μm devices [3.2].

We also examined zero-net-strain and compensated strain structures with compressive wells and tensile barriers. We showed how these could be used to modify the conduction and valence band offset to give values similar to those found in structures based on aluminium alloys. It appears from our calculations that there is little change in intrinsic lasing characteristics seen in these structures, but from experiment there seems to be some benefit in going to tensile barriers.
Chapter 4.

Experimental study of strained InGaAsP semiconductor lasers.

4.1 Introduction.

Using modern growth techniques there is a large range of device structures that can be realised. The devices can be varied to such a large extent it would be impossible to look at all possible combinations of variables. In this chapter important design criteria are considered with the aim of establishing trends which can be employed to predict optimum structures for device applications.

This chapter presents an experimental analysis of compressively strained 1.3 μm InGaAsP quantum-well lasers. These lasers are intended for application in optical fibre communication systems. Comparisons are made between certain sets of devices which vary only slightly in structure, enabling the key properties of the lasers to be identified. Wherever possible, connections are made to the theoretical study presented in chapter three.

The analysis employs a variety of experimental techniques to investigate the laser characteristics and observed trends. These techniques include the measurement of the light-current characteristics as a function of temperature for the different structures. Also
measured are the spontaneous emission spectra for these devices. Using the results of these measurements the properties of the lasers are explained.

As mentioned earlier, devices such as these are intended for commercial telecommunication applications. The basic requirements for lasers used in optical communication systems are low threshold current densities (more specifically low threshold currents), high differential efficiencies and that they be thermally stable. It is on these properties that this chapter concentrates.

4.2 The effect of well number on device characteristics.

The properties of a set of buried heterostructure devices with the same structure except for the number of quantum-wells were measured. The structure of these lasers is a number of 50Å, 1% compressively strained quantum-wells with partially compensated barriers (of 0.2% tensile strain). The band-gaps of the well and barrier materials are 1.4 and 1.05 μm respectively. The devices are 350 μm long and emit at a wavelength close to 1.3 μm. The buried heterostructure widths were 1 μm.

4.2.1 Light-Current measurements.

Simple light-current (L-I) characteristics were measured for these devices at temperatures of 25, 40, 55, 70 and 85 °C. These temperatures were measured using a chromel-alumel thermocouple with the reference junction in an ice-water mix and the measuring junction placed in the device heat-sink within 1 cm of the device. The validity of the measurements was checked by measuring the temperature in this manner and comparing it with that measured with a similar thermocouple with the junction in the place of the device. This verification suggested that our temperature measurement was accurate to within 2°.
The measurements were made pulsed to avoid heating effects. The pulses used were 1 \( \mu \text{s} \) wide with a pulse period of 1 ms. The current was measured using an induction probe and an oscilloscope. The current pulsed was displayed on the oscilloscope and the voltage produced at the top of the pulse translated into the drive current using the relation of 1 mV to 1 mA.

Characteristic temperatures \( (T_0) \) were calculated from the measurements by plotting the logarithm of the measured threshold currents against temperature (examples are shown in figs 5.2 and 5.5(a)). These plots produced very good straight lines, whose gradient was the reciprocal of the \( T_0 \) values.

Fig. 4.1 shows the threshold current density as a function of the number of wells. It can be seen that the lowest threshold current density occurs with the six well sample as predicted by theory for a 50 Å well. The general trend is also very similar to that predicted theoretically (see Fig. 3.3). There is a large improvement in going from 4 to 6 wells and then a gradual increase in the threshold current density as the number of wells increases. This is due to the improvement due to an increased optical confinement factor with increasing well number being counteracted by the number of wells which have to be pumped as the well number is increased past 6.

![Figure 4.1](image-url)  

Fig. 4.1. Threshold current density as a function of well number at 298 K. Also shown is the theoretical trend for a 350 \( \mu \text{m} \) long device, adjusted to appear on the same scale.
It does appear that the 7 well sample does not fit this trend accurately. The threshold current density is almost the same as the 9 well sample and is not somewhere between the 6 and 9 well values. This is possibly because the 7 well sample is of a lower growth quality than the other samples. This can also be seen in Fig. 4.2a which shows the characteristic temperature ($T_0$) as a function of well number. Considering only the 4, 5, 6 and 9 well samples it can be seen that there is a steady improvement in $T_0$ as the well number increases. This could be explained by considering the gain spectra of these devices. The larger values of $T_0$ occur as the threshold material gain is decreased [4.1, 4.2] which is achieved by increasing the optical confinement factor, in this case by increasing the number of quantum-wells. The 7 well sample does not follow this trend, it behaves more like a 5 well sample suggesting that the expected improvements in going from a 5 well to a 7 well device have been counteracted by some growth irregularities. Further evidence suggesting that the 7 well devices tested in this section are of a lower quality can be seen in the later section 4.4 where 7 well devices with similar structures are tested. These devices show reduced threshold current densities (approximately 1350 Acm$^{-2}$ at 25 °C) and improved $T_0$ s (approx. 52 K). These values would fit better with the trends observed here.

There is a noticeable difference between the experimentally observed and theoretically predicted threshold current density values. Using the theoretical model employed in previous chapter, a non-radiative threshold current density can be calculated for this 6 well device, at room temperature, using the correct values for device length (350 µm) and internal losses (13 cm$^{-1}$). This calculation produces a non-radiative threshold current density of 370 Acm$^{-2}$. This is still significantly lower than the 1500 Acm$^{-2}$ measured experimentally. However, there has been no account taken of the radiative current component, which has recently been shown to be approximately equal to the non-radiative current component for 1.3 µm lasers at room temperature [4.3]. Incorporating this radiative current component an overall current density of 740 Acm$^{-2}$ is obtained.
Including a leakage current which could be as much as 20% of the total injected current [4.4] this value would then be 890 A cm\(^{-2}\) which is approaching the measured value.

![Fig 4.2. (a) Temperature characteristic versus well number and (b) Threshold current density versus well number at a range of temperatures.](image)

Fig. 4.2b shows how the threshold current density (J\(_{th}\)) varies with the number of wells at different temperatures up to 358 K. This behaves as expected when the room temperature J\(_{th}\) plot is combined with the T\(_0\) plot. In this plot it is easier to see that the 7 well device does not seem to follow the same trends as the other samples. It can also be noticed that at higher temperatures the minimum threshold current no longer occurs for a 6 well sample but for the 9 well device. This is due to the improved temperature characteristic of the 9 well device.

The external differential efficiency of these devices is shown in Fig. 4.3a as a function of well number at room temperature. The efficiency is about 10 % higher for the 4 well device compared to the other devices which are approximately equal. As stated in chapter 2, the external efficiency can be written as
\[ \eta_d = \eta \left( \frac{\alpha_m}{\alpha_m + \alpha_i} \right) \]

where \( \alpha_m \) are the mirror losses and \( \alpha_i \) are the internal losses. The internal losses are a function of well number, the more wells the higher the internal losses [4.5]. So we would expect the 4 well device to have the higher efficiency. However, we would expect from this reasoning to see the efficiency of the other devices continue to fall as the well number increased which is not the case. For an ideal laser the internal efficiency above threshold should be 1, i.e. all extra carriers are turned into photons. In order for us to explain the observed trend, via Equation 4.2.1, the internal efficiency must improve as the number of wells is increased. This is not unexpected since devices with more wells lase nearer transparency, meaning that less carriers are required to achieve lasing. With this lower carrier density there is a lower probability of non-radiative recombination and therefore a higher probability that a carrier will go on to produce a useful photon. However, there is an alternative explanation, the major loss in these devices could simply occur in the cladding region and the number of wells makes little difference. This reasoning would imply the 4 well result is anomalously high.

![Fig. 4.3. (a) External efficiency as a function of well number at 298 K and (b) External efficiency versus temperature for differing well numbers.](image)
The effect of temperature on the external differential efficiency for each well number is shown in Fig. 4.3b. This behaves much like the threshold current density with temperature. The devices with the worst temperature characteristics have the efficiency fall off the most as the temperature is increased. This is as expected since there is a link between the temperature characteristics of the differential quantum efficiency and the threshold current density \[4.6\].

In the previous chapter we assumed that the threshold current density was dominated by non-radiative recombination, via Auger recombination. This was supported by recent experimental work \[4.6, 4.7\]. This assumption can be checked in these using the spontaneous emission spectra.

4.2.2 Spontaneous emission measurements.

The spontaneous emission spectra of these devices were measured by placing an optical fibre close to the side the device. The laser is driven pulsed and some of the light emitted from the side of the device is collected by the multimode fibre and transmitted into an optical spectrum analyser, OSA. Measurements were made as a function of current and as a function of temperature. At each temperature the fibre was positioned to give the maximum light input to the OSA. This was done since as the temperature changed the heat sink and laser mountings expanded changing the collection factor of the experiment, it was thought that by optimising for the light collected a near constant collection factor could be achieved. The set up is shown in the schematic below.

![Schematic of experimental set up for spontaneous emission measurements.](image)

Fig. 4.4. Schematic of experimental set up for spontaneous emission measurements.
Fig. 4.5. The measured spontaneous emission spectra obtained using a optical fibre to collect the light emitted from the side of a device. Measurements were made at (a) 298 and (b) 358 K. Spectra are shown for at $\frac{1}{4}I_{th}$, $\frac{1}{2}I_{th}$, $\frac{3}{4}I_{th}$, $I_{th}$, $3/2I_{th}$, $2I_{th}$ and $3I_{th}$.

Fig. 4.5 shows an example of the spectra obtained at 298 and 358K. These spectra clearly show the the carrier density pins above threshold. Also evident is a small peak at a wavelength of 1075 nm, this peak corresponds to the barrier bandgap energy and is evidence of recombination in the barrier region. This peak can be taken as confirmation that there is leakage of carrier out of the well and into the barrier and SCH regions. This will be looked at in more detail in Chapter 6 of this thesis.
Fig. 4.6. The measured spontaneous emission spectra for a 4 well device at (a) 298 and (b) 358 K. Spectra are shown for current values of $\frac{1}{4} I_{th}$, $\frac{1}{2} I_{th}$, $\frac{3}{4} I_{th}$, $I_{th}$ and just above $I_{th}$.

The spontaneous emission spectra were measured both above and below threshold. Fig. 4.6 shows the measured spectra as a function of current for a 4 well device at (a) 298 K and (b) 358 K.
The spontaneous emission spectra at room temperature are as expected. When the temperature is raised to 358 K a secondary emission peak is observed at around 1075 nm. This can be attributed to emission from the barrier region. Emission from the barrier in this device fits with its poorer characteristic temperature compared to devices with more wells. The carriers escaping into the barrier produce a current contribution which has a detrimental effect on the device characteristics, increasing the threshold current. We can compare this directly with a 9 well device. Fig. 4.7 shows the spontaneous emission spectra for a 9 well device at (a) 298 K and (b) 358 K. In this case we see no emission from the barrier region at the elevated temperature, corroborating the better temperature characteristic. It can be seen from Fig. 4.8 that the 6 well device has a spontaneous emission spectrum which appears to be better than that of the 4 well device but with more
barrier emission than that of the 9 well device. This is as expected due to the threshold current temperature characteristics measured.

![SPS figure](image)

Fig. 4.8. The measured spontaneous emission spectra for a 6 well device at (a) 298 and (b) 358 K. Spectra are shown for current values of \(\frac{1}{4}I_{th}, \frac{1}{2}I_{th}, \frac{3}{4}I_{th}, I_{th}\) and just above \(I_{th}\).

It is possible to obtain a characteristic temperature associated with the radiative current using the integrated spontaneous emission. At threshold the carrier density pins. The result of this should be that every injected carrier produces a useful photon. Since the carrier density pins at threshold the spontaneous emission must also pin due to the direct relationship \(L = Bn^2\). Using the definition of a characteristic temperature, \(T_0\), as

\[
T_0 = \left[ \frac{1}{J} \frac{dJ}{dT} \right]^{-1}
\]

Eq. 4.2.2
where \( J \) is the current density, a characteristic temperature for the radiative current \( T_0(I_{rad}) \) can also be defined (as discussed in chapter 2):

\[
T_0(I_{rad}) = \frac{T}{2x + 1} \quad \text{Eq. 4.2.3}
\]

where \( x=0 \) for an ideal quantum-well [4.9] and the value of \( x \) represents a deviation from the ideal case. It has already been shown that the characteristic temperature for an Auger dominated system can be written as

\[
T_0(Aug) = \frac{T}{3 + 3x + \frac{\Delta E_a}{k_b T}} \quad \text{Eq. 4.2.4}
\]

where \( k_b \) is Boltzmann's constant and \( \Delta E_a \) is the activation energy for the recombination process.

Information about the temperature characteristics of the device can be obtained using this \( T_0 \) for the radiative current. Using the radiative \( T_0 \) an idea of how much the device varies from the ideal case can be acquired (\( x \) in Eq. 4.2.3). This value can be used in Eq. 4.2.4 to calculate an activation energy for the Auger process.

In order for the results to be meaningful there has to be some manipulation of the obtained spectra. As discussed earlier these spectra show emission from the barrier region. Later spectra also show a lasing lines. In order to get a true determination of the total light from a spontaneous spectrum these extra emission regions need to be removed. This was done on all spectra in this thesis by performing a visual smoothing on the spectra.
Fig. 4.9. Integrated spontaneous emission versus current for (a) 4, (b) 6 and (c) 9 well devices. Results are plotted at 298 K (filled circles) and 358 K (open diamonds).

The characteristic temperatures estimated from Fig. 4.9 are given in the table below: Also shown (in italics) are modified results for the 4 well device, assuming a similar deviation from the ideal case.

<table>
<thead>
<tr>
<th>No. of wells</th>
<th>$T_0(I_{rad})$</th>
<th>$T_0(I_{th})$</th>
<th>$x$</th>
<th>$\frac{T}{3+3x}$</th>
<th>$\Delta E_a/k_bT$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>101</td>
<td>39</td>
<td>0.99</td>
<td>50</td>
<td>1.7</td>
</tr>
<tr>
<td>4</td>
<td>167</td>
<td>39</td>
<td>0.40</td>
<td>71</td>
<td>3.5</td>
</tr>
<tr>
<td>6</td>
<td>173</td>
<td>45</td>
<td>0.37</td>
<td>73</td>
<td>2.6</td>
</tr>
<tr>
<td>9</td>
<td>175</td>
<td>60</td>
<td>0.35</td>
<td>74</td>
<td>0.9</td>
</tr>
</tbody>
</table>

Applying the equations above gives $x$ values of 0.99, 0.37, and 0.35 for the 4, 6 and 9 well samples. This implies that the threshold carrier density temperature dependence is
different in the case of the 4 well sample to that of the 6 and 9 well samples. This does not seem to be logical and raises a doubt over these experimental results which will be considered in more detail below. The threshold carrier density temperature dependence is expected to be approximately constant for this set of devices which differ only in the number of quantum-wells. For this reason a modified set of results have been shown in the above table (in italics) assuming a deviation from the ideal case \((x)\) of 0.40. The Auger activation energies vary as 3.5, 2.6 and 0.9 \(k_bT\) for well numbers of 4 (modified), 6 and 9 respectively. These results would suggest that the Auger activation energy varies almost linearly with the number of wells and that as the number of wells was increased up to 11 the Auger activation energy would reach zero, before going negative for more wells. This does not make sense and throws more doubt on to the results achieved.

These results show the method of how values for the deviation from the ideal case \((x)\) and the Auger activation energy \((\Delta E_a)\) can be obtained, the actual results presented suggest that there are some errors in these measurements. Possibly the easiest way for an error to occur is a variation in the collection factor. The method employed here to maintain a constant collection factor was a continual optimisation of the fibre position to ensure that the maximum light was collected. This method is easy to implement in practice, but obviously there is some doubt over the reliability of the results produced. More recently an alternative approach to make these measurements involving a more intrusive examination [4.10] has been developed. This method involves masking part of the substrate and etching a “window” in the InP substrate. This “window” can be placed directly above an optical fibre bonded into a heatsink and spontaneous emission can be collected in this manner with a constant collection factor. This method has been used in a later chapter in order to look at the spontaneous emission from Ridge Waveguide devices.

In order to determine whether these devices are dominated by Auger recombination the spontaneous emission must be examined. It has already been stated (Chapter 2) that there is a relationship between current and carrier density.
where each power of carrier density, $n^z$, indicates a different recombination mechanism. $z=1$ would indicate recombination via defects in the material, $z=2$ suggests recombination through spontaneous emission and $z=3$ would imply Auger recombination.

The $Bn^2$ term is the contribution due to spontaneous emission. This means that the total light under the spontaneous emission plot (Fig. 4.6) or the integrated spontaneous emission, $L$ is proportional to $Bn^2$:

$$L \propto n^2 \quad \text{Eq. 4.2.6}$$

hence

$$n \propto L^{1/2} \quad \text{Eq. 4.2.7}$$

a plot of $\ln(I)$ against $\ln(L^{1/2})$ should yield a straight line for currents below threshold. The slope of this straight line region is the $z$ value referred to above and enables the dominant recombination mechanism to be determined.
Fig. 4.10. Plots showing the carrier dependence of the recombination mechanism just below threshold. Results are plotted for (a) 4, (b) 6 and (c) 9 well devices at 298 and 358 K.

The z values for these devices as calculated from Fig. 4.10 are given in table 4.2, below.

<table>
<thead>
<tr>
<th>No. of wells</th>
<th>z @ 298K</th>
<th>z @ 358K</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>2.6</td>
<td>3.5</td>
</tr>
<tr>
<td>6</td>
<td>2.8</td>
<td>2.5</td>
</tr>
<tr>
<td>9</td>
<td>2.6</td>
<td>2.7</td>
</tr>
</tbody>
</table>

These values are close to 3, suggesting that the devices are dominated by Auger recombination. This substantiates the assumptions made in chapter 3 about the dominant recombination process. However, as we have seen already with the values obtained for x, these results are not entirely reliable and since these figures are based on the same
measurements the results here are also questionable and therefore we cannot attribute too much significance to the z values over 3.

In order to decide on an optimised structure is must be established which is the most important property for the required application. A six well structure would result in a device with the lowest room temperature threshold current density whilst also providing a good external efficiency, in comparison with the other well numbers tested. If better performance were required at higher temperatures the inclusion of more wells would facilitate this. However, with more wells would come a higher room temperature threshold current density and an expected decrease in the external efficiency. For a high room temperature external efficiency fewer number of wells should be used.

4.3 Cavity length dependence of device characteristics.

The cavity length of a device is an important design criterion. Increasing the cavity length reduces the mirror loss, which is the facet loss per unit length. This leads to a reduction in threshold gain per unit length and threshold carrier density. With a reduction in threshold carrier density, a reduction in the threshold current density would be expected. Conversely since the external efficiency is related to the internal efficiency by the ratio of the mirror losses to total losses a reduction in the external efficiency would be anticipated with an increased cavity length and hence a reduced mirror loss.
Fig. 4.11. (a) Threshold current density and (b) external efficiency against temperature for 4 well and 9 well devices of 350 and 450 µm length at both 298 and 358 K.

To analyse the relative importance of these competing effects, measurements were made on devices of different cavity lengths. The device structures were the same as those used in the previous section. The available cavity lengths were 350 and 450 µm for the 4 and 9 well samples. Fig. 4.11 show the variation of (a) threshold current density and (b) external efficiency with temperature for 4 and 9 well devices at the two different cavity lengths available. These plots show that the general trends obtained follow the predictions made above.
By making measurements of the spontaneous emission spectra as function of current and temperature it can be established that the intrinsic properties of these lasers are not changing as the length of the devices are altered. Comparing the spectra at 298 and 358 K for the 4 well device at 350 µm Fig. 4.6 with that at 450 µm Fig. 4.12 and for the 9 well device at 350 µm Fig. 4.7 with that at 450 µm Fig. 4.13 there is one appreciable difference, the amount of light collected in the longer devices is greater. This can be explained by the fact the measurements were made using slightly different set-ups, most notably a different optical fibre. There is the appearance of other small differences such as the non-pinning of the longer devices at 358 K, however these devices were driven further past threshold than the corresponding 350 µm devices. It should also be noted that the longer devices have the spectra measured for a larger wavelength range.
Figs. 4.9 and 4.14 show that there is very little difference in the temperature characteristics between the different length devices. This is true for both the radiative current and the threshold current. This is perhaps a bit surprising as a longer device has a reduced threshold material gain which has been seen to give rise to a higher temperature characteristic, $T_0$. The difference in the length between the two sets of devices is not large, the change in mirror loss between the two cavity lengths studied is just 8 cm$^{-1}$ (from 35 cm$^{-1}$ at 350 μm to 27 cm$^{-1}$ at 450 μm). Any improvement in the $T_0$ would therefore only be small and may not be seen due to experimental scatter.

Changing the cavity length of a device can have a dramatic effect on its properties. In this section only a small change in the cavity length was considered. This change resulted in no appreciable difference in the temperature characteristics but exhibited a variance in
both threshold current density and external efficiency. The threshold current density was reduced by increasing the cavity length. The external efficiency is, as expected, also reduced with increasing cavity length. It must be pointed out though that although the threshold current density is reduced by using a longer device the actual threshold current is increased. This suggests that for room temperature operation a shorter device would demonstrate the preferable characteristics for application in an optical fibre communication system, ignoring power and gain saturation.

![Graph](image_url)

**Fig. 4.14.** Integrated spontaneous emission versus current for (a) 4 and (c) 9 well devices. Results are plotted at 298 K (filled circles) and 358 K (open diamonds).
4.4 Using facet coatings to change the mirror losses.

In the previous section the effect of cavity length on the lasing characteristics was examined. The differences noticed were due to the change in the facet loss per unit length or the mirror loss which effected the amount of gain required to achieve lasing. The availability of different length devices was very limited but there is another way to alter the mirror losses. The mirror loss, $\alpha_m$, is given by

$$\alpha_m = \frac{1}{2L} \ln \left( \frac{1}{R_1 R_2} \right)$$

Eq. 4.4.1

where $L$ is the cavity length and $R_1$ and $R_2$ are the two facet reflection coefficients. Thus the mirror loss can be changed by altering the facet reflectivities, which can be done by applying coatings of different refractive indices to the facets.

Measurements were made to determine their lasing characteristics of a set of devices with the same structure but with different mirror losses. These devices are composed of seven 60 Å, 0.8% compressively strained quantum-wells with 100Å unstrained barriers. The band-gaps of the wells and barriers are 1.4 and 1.1 μm respectively. The devices emit at a wavelength of around 1.3 μm. The mirror losses were varied both using facet coatings and different cavity lengths. Below is a summary of the cavity lengths and facet coatings (as quoted) to give the various mirror losses.

<table>
<thead>
<tr>
<th>chip type</th>
<th>cavity length (µm)</th>
<th>facet 1</th>
<th>facet 2</th>
<th>$\alpha_m$ (cm$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>un</td>
<td>350</td>
<td>0.30</td>
<td>0.30</td>
<td>34.4</td>
</tr>
<tr>
<td>-5</td>
<td>350</td>
<td>0.03</td>
<td>0.88</td>
<td>51.9</td>
</tr>
<tr>
<td>c3</td>
<td>280</td>
<td>0.03</td>
<td>0.88</td>
<td>64.9</td>
</tr>
<tr>
<td>c2</td>
<td>350</td>
<td>0.03</td>
<td>0.30</td>
<td>67.3</td>
</tr>
</tbody>
</table>

Fig. 4.15 shows the threshold current density plotted against the mirror loss at 298 and 358 K. This plot is not as expected. The threshold current density would be predicted to
increase as the mirror loss was increased due to a decreasing threshold gain requirement. This is not the case as it appears that the device with a mirror loss of 51.9 cm\(^{-1}\) has a significantly lower than expected threshold current density. In order to explain this a check on the mirror losses was made. The device with a mirror loss of 65 cm\(^{-1}\) has also deviated from the expected trend. This deviation is much smaller than that seen for the 51.9 cm\(^{-1}\) device and is probably due to experimental scatter.

![Graph showing threshold current versus mirror loss at 298 and 358 K.](image)

4.4.1 Verification of the mirror losses.

There are two factors which control the facet loss per unit length or mirror loss. These are the cavity length and the facet reflection coefficients. The cavity length could be checked using a calibrated microscope and was found to be in agreement with the lengths stated. A more involved method was employed to check the facet reflection coefficients.

The external efficiency of the devices was measured out of both facets. The ratio of the efficiencies out of the two ends of the device can be predicted by theoretical analysis (below) and compared with the experimentally obtained values to confirm the facet reflection coefficients.
Considering a device (schematic shown below) of length L, with gain per unit length g and facet reflection coefficients of $R_1$ and $R_2$ for the right and left hand facets respectively, with incident and reflected waves whose intensities are $A$, $B$, $C$, and $D$ at the facets it can be shown that

\[ B = A \exp(gL) \]

therefore

\[ C = R_1 B = R_1 A \exp(gL) \]

and thus

\[ D = C \exp(gL) = R_1 A \exp(2gL) = A/R_2 \]

![Schematic showing relative intensities of incident and reflected waves at the facets of a device.](image)

Fig. 4.16. Schematic showing relative intensities of incident and reflected waves at the facets of a device.

The lasing condition states that the round trip gain must equal unity, giving

\[ 1 = R_1 R_2 \exp(2gL) \]

giving

\[ \exp(gL) = \left[ \frac{1}{R_1 R_2} \right]^{1/2} \]

This means that the light transmitted out of the two facets is
RH end = (1 - R₁)A exp(gL)  \quad LH end = (1 - R₂)R₁A exp(2gL)

\[ \frac{RH}{LH} = \left( \frac{1 - R₁}{R₁R₂} \right) \left( \frac{1 - R₂}{R₁} \right)^{\frac{1}{2}} \]  
Eq. 4.4.2

The table below shows the values of the ratio of the output efficiencies of the two facets; (a) measured experimentally and (b) calculated from the above expression using the quoted facet reflectivities.

<table>
<thead>
<tr>
<th>chip type</th>
<th>facet 1</th>
<th>facet 2</th>
<th>(a) measured ratio</th>
<th>(b) calculated ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>un</td>
<td>0.30</td>
<td>0.30</td>
<td>1.0</td>
<td>1</td>
</tr>
<tr>
<td>-5</td>
<td>0.03</td>
<td>0.88</td>
<td>2.1</td>
<td>43.8</td>
</tr>
<tr>
<td>c3</td>
<td>0.03</td>
<td>0.88</td>
<td>45.7</td>
<td>43.8</td>
</tr>
<tr>
<td>c2</td>
<td>0.03</td>
<td>0.30</td>
<td>4.2</td>
<td>4.4</td>
</tr>
</tbody>
</table>

There is good agreement between the calculated and experimentally obtained ratios for the devices with the exception of the -5 lasers. This was the device which did not appear to fit the expected threshold current trend. Having established that the facet reflection coefficients are not as stated, the real values have to be ascertained. In order to achieve the ratio measured the facet coatings needed would have to be (assuming that one of the coatings was either of 3 % or 88 % or the device had one facet uncoated, a reflectivity of 30 %).
Considering the mirror loss value, it is clear that a mirror loss of 25 cm⁻¹ would provide the best fit to the threshold current density trend on the previous plot; the facet coatings of this device has been assumed to be 30%/55%. These values will be used throughout the rest of this chapter.

Fig. 4.17 shows the threshold current density as a function of the modified mirror loss at 298 and 358 K. This plot follows the expected trend in that as the mirror loss is increased the threshold current also increases. The slight deviation of the 64.9 cm⁻¹ device the observed in the threshold current density plot can be attributed to experimental scatter.

![Fig. 4.17. Threshold current density as a function of mirror loss at 298 and 358K.](image)

The threshold current density increases rapidly with temperature for the devices with the higher mirror losses. This is reflected in the characteristic temperatures of the devices changing from approx. 50 K for the devices with α_m less than 35 cm⁻¹ to around 40 K as the mirror loss is increased.
Fig. 4.18. External efficiency versus mirror loss. Plot (a) show the efficiencies from both the front and rear facets at 298 K, together with experiment and theoretical averages. Plot (b) shows how the efficiency varies with temperature.

Fig. 4.18(a) shows a plot of the external differential efficiency as a function of the modified mirror loss for both facets ($R_1$ and $R_2$). Also shown is the average external efficiency for the two facets and a theoretical line showing how the external efficiency would vary if both facets had identical coatings, i.e. $R_1=R_2$ (an internal loss of 6 cm$^{-1}$ is assumed and the line normalised to the uncoated device). The efficiency measured from the facet with the lower reflection coefficient, $R_1$, appears to vary in a random fashion, since $R_1/R_2$ varies in a random fashion. This is almost a mirror of the efficiency measured from the facet with the higher reflection coefficient, $R_2$. In fact the efficiency of the $R_2$ facet should be a reflection of the $R_1$ efficiency in the $R_1=R_2$ line, since at threshold the total round trip gain must equal 1 for all the devices. A check on the symmetry of the relative efficiencies measured from the two facets can be achieved by verifying that the average of the two facets follows the theoretical line, $R_1=R_2$. The experimentally obtained points are in reasonable agreement with the theoretical line.
The external efficiency is plotted for the lower reflective facet, $R_1$, at 298 and 358 K in Fig 4.18(b). The efficiency imitates the threshold current density at high temperatures by degrading more rapidly when the mirror loss is highest. This is not unexpected since there is a link between the temperature characteristics of the differential quantum efficiency and the threshold current density [4.6].

Fig. 4.19. The measured spontaneous emission spectra for (i) an uncoated and (ii) an assumed 30%/55% facet coated 350 μm device at (a) 298 and (b) 358 K. Spectra are shown for current values of $\frac{1}{4}I_{th}$, $\frac{1}{2}I_{th}$, $\frac{3}{4}I_{th}$, $I_{th}$, $\frac{3}{2}I_{th}$ and $2I_{th}$.

Figs 4.19 and 4.20 show the measured spontaneous emission spectra for these devices at 298 and 358 K. There are distinct differences between the spectra for the devices with high and low mirror losses. There is a reasonable amount of pinning for the devices with the lower facet losses, whereas there is a considerable increase in the spontaneous emission detected at currents above threshold for the c2 and c3 devices. This can also be
seen in Figs 4.21(a-d) which shows the integrated spontaneous emission as a function of current for the 4 device types at 298 and 358 K. This compares with the spectra obtained for the 4 and 9 well 450 \, \mu m long devices where the 9 well device pinned better than the 4 well sample. In both cases the devices with a higher threshold gain exhibit the largest amount of non-pinning. This non-pinning can probably be attributed to a non-linear gain coefficient [4.11] and this would explain its prominence in the devices with the higher threshold gains.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig420.png}
\caption{The measured spontaneous emission spectra for (i) an 3\%/88\% facet coated 280 \, \mu m and (ii) a 3\%/30\% facet coated 350 \, \mu m device at (a) 298 and (b) 358 K. Spectra are shown for current values of \( \frac{1}{4}I_{th} \), \( \frac{1}{2}I_{th} \), \( \frac{3}{4}I_{th} \), \( I_{th} \), \( 3/2I_{th} \) and \( 2I_{th} \).}
\end{figure}

From Figs. 4.14 and 4.21 and Equations 4.2.5 and 4.2.6 it is possible to calculate deviations form the ideal case, \( x \), using the radiative temperature characteristics. These values are given in the table below:
### Table

<table>
<thead>
<tr>
<th>No. of Wells</th>
<th>Mirror Loss</th>
<th>$T_0(I_{rad})$</th>
<th>$T_0(I_{th})$</th>
<th>$x$</th>
<th>$\Delta E_f/k_B T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>26.8</td>
<td>106</td>
<td>38</td>
<td>0.9</td>
<td>2.2</td>
</tr>
<tr>
<td>9</td>
<td>26.8</td>
<td>206</td>
<td>57</td>
<td>0.2</td>
<td>1.6</td>
</tr>
<tr>
<td>7</td>
<td>25.7</td>
<td>190</td>
<td>46</td>
<td>0.3</td>
<td>2.6</td>
</tr>
<tr>
<td>7</td>
<td>34.4</td>
<td>195</td>
<td>52</td>
<td>0.3</td>
<td>2.0</td>
</tr>
<tr>
<td>7</td>
<td>64.9</td>
<td>125</td>
<td>40</td>
<td>0.7</td>
<td>2.4</td>
</tr>
<tr>
<td>7</td>
<td>67.3</td>
<td>112</td>
<td>39</td>
<td>0.8</td>
<td>2.2</td>
</tr>
</tbody>
</table>

Fig. 4.21. Integrated spontaneous emission versus current for (a) uncoated 350 µm, (b) an assumed 30%/55% 350 µm, (c) 3%/88% 280 µm and (d) 3%/30% facet coated 350 µm devices. Results are plotted at 298 K (filled circles) and 358 K (open diamonds).

This suggests that as the threshold gain approaches transparency the temperature dependence of the carrier density tends to the temperature. These results also implies that
for these devices the activation energy for Auger recombination is about $2k_B T$. Auger being the dominant recombination method as verified by the slope of the straight line for currents just below threshold in the plots of $\ln(I)$ against $\ln(L^{1/2})$ shown in Fig. 4.22. Although as discussed earlier the values obtained for $x$ are dubious due to the measurement technique and so there is an uncertainty in the activation energy for the Auger recombination.

![Graphs showing carrier dependence](image)

Fig 4.22. Plots showing the carrier dependence of the recombination mechanism just below threshold. Results are plotted for (a) uncoated 350 \( \mu \text{m} \), (b) an assumed 30%/55% 350 \( \mu \text{m} \), (c) 3%/88% 280 \( \mu \text{m} \) and (d) 3%/30% facet coated 350 \( \mu \text{m} \) devices at 298 K (filled circles) and 358 K (open diamonds).

Again these calculations produce $z$ values for some of these devices which are greater than 3. Again throwing doubt on the validity of these results.
Changing the mirror loss with the use of facet coatings enables the characteristics of the laser to be modified to satisfy the required application. The threshold current density can be improved by applying a high reflection coating to one facet. This would also result in a higher external differential efficiency from the uncoated facet. Due to the reduced threshold gain of this laser the expected temperature characteristic would also be improved. A laser such as this would be favourable for use in optical fibre communication systems. The facet coatings can be selected in this manner to match a range of applications.

4.5 Conclusions.

Important design parameters have been considered in this chapter in order to establish their effects on the crucial laser characteristics. These were the number of quantum-wells, the cavity length and the facet reflectivities. The ideal number of wells for low threshold current density operation is 6 wells and corresponds with the theoretical predictions made in the previous chapter.

Based on the theory presented in chapter 3 and the experimental results presented in this chapter the optimum 1.3 μm InGaAsP laser for low threshold current, high efficiency and high T₀ operation would consist of six 1% compressively strained 50 Å quantum-wells in a device of medium length (approx. 450 μm) with a high reflection coating on one facet. The basic structure following the theoretical predictions presented in the previous chapter, combined with the appropriate choice of length and facet coatings from the trends seen in this chapter.

An important consideration not yet mentioned is that of the device production cost. The device characteristics have to be played off to some point with the manufacturing cost. This has its largest effect on the recommended design because applying a facet coating is an expensive process. Ideally, from a production perspective, the need for a facet coating
would be eliminated. In order to comply with this and still maintain a high level of device performance the cavity length should be selected to satisfy the most important characteristic for the required application. If the device has to operate with a low threshold current and high efficiency a shorter device should be used. Although this increases the threshold current density, the more important threshold current would be reduced and the external efficiency increased. The most significant decline in this laser's performance would be to increase the temperature sensitivity of the laser. A longer device would give a better temperature performance.
Chapter 5.

Comparison of InGaAsP and InGaAlAs semiconductor lasers.

5.1 Introduction.

As mentioned in Chapter 4 there are several permutations of device structure available to realise specific device requirements. An important consideration not covered in the previous chapter is that of the material composition. For lasers operating at wavelengths around 1.3 μm there are primarily two material compositions used. These are InGaAsP and InGaAlAs devices. The majority of this thesis has been concerned with the InGaAsP structures, however it has been suggested that InGaAlAs devices exhibit a better temperature performance [5.1, 5.2]. These improvements are suspected to be due to reduced carrier (electron) leakage into the barrier and surrounding regions. This reduced leakage is thought to be brought about by the increased conduction band offset between the well and barrier. It is therefore logical to carry out an examination on these lasers to investigate what improvements can be made by using this composition.

The analysis employs the same experimental techniques used in the previous chapter to investigate the laser characteristics. Again the laser properties scrutinised are those relevant to telecommunication applications, i.e. threshold current density, differential efficiency and temperature characteristics.
5.2 Light-Current Measurements.

Measurements were made on a set of Ridge Waveguide InGaAlAs devices. The structure of these devices is five, 50 Å, 1% compressively strained quantum-wells between unstrained barriers. The band-gaps of the well and barrier materials are 1.4 and 1.08 μm respectively. The devices are either 250 or 350 μm long and emit at a wavelength close to 1.3 μm. The ridge width is 3 μm.

Simple light-current (L-I) characteristics were measured using a pulsed current source operating with a pulse width of 1 μs and a pulse period of 1 ms. The measurements were made at various temperatures up to 85 °C. The results of these measurements are summarised in Figs. 5.1-5.3, which show the threshold current density ($J_{th}$), ln($J_{th}$) and external differential efficiency as a function of temperature for the two device lengths. Also plotted are the corresponding results for a five well InGaAsP buried heterostructure (BH) as studied in section 4.2.1 of this thesis.

![Graph showing threshold current density versus temperature for differing length Al-based devices.](image)

Fig 5.1. Threshold current density versus temperature for differing length Al-based devices. Also shown is the result obtained earlier for a 5 well InGaAsP BH device.
Fig 5.2. $\ln(J_{th})$ versus temperature for differing length Al-based devices. Also shown is the result obtain earlier for a 5 well InGaAsP BH device.

Fig 5.3. External differential efficiency versus temperature for differing length Al-based devices. Also shown is the result obtain earlier for a 5 well InGaAsP BH device.

Comparison between the 5 well BH device and the InGaAlAs (Al-based) devices measured show that little change is observed in the room temperature threshold current density in going from an InGaAsP (P-based) system to an Al-based system. Although, it must be noted that the actual change in the threshold current is quite considerable, going from $\sim$8 mA to $\sim$25 mA. This increase in threshold current could imply that the threshold current density in the Al-based system should really be lower than it appears as a result of current spreading.
There is an improvement observed in the characteristic temperature, $T_0$, of the Al-based system. This can be seen by looking at the $T_0$ values given in Fig. 5.2. There is also a similar improvement in the observed external differential efficiency. However, these improvements in the temperature characteristic and efficiency could be due to either switching to the Al-based system or because the laser is a ridge waveguide device and not a buried heterostructure device. In order to decide which of these is the dominant factor, some P-based ridge waveguide devices were examined.

The P-based lasers consist of seven, 60 Å, 0.8% compressively strained quantum-wells, with 100 Å unstrained barriers. The band-gaps of the well and barrier materials are 1.4 and 1.1 µm respectively. The devices are 350 µm long and emit at a wavelength close to 1.3 µm. Measurements were again made using a pulsed current source operating with a period of 1 ms and a pulse width of 1 µs. The ridge width is 3 µm.

![Graph showing threshold current density versus temperature for P-based and Al-based RWG devices.](image)

Fig 5.4. Threshold current density versus temperature comparing P-based (square) and Al-based (triangles) RWG devices.
Fig. 5.5(a). In(Jth) versus temperature and (b) External differential efficiency versus temperature comparing P-based (square) and Al-based (triangles) RWG devices.

Fig. 5.4 shows the average threshold current density as a function of temperature for three P-based devices compared to the results obtained earlier for the Al-based devices. The threshold current density (Jth) values are similar to those seen for the 350 μm long Al-based devices for all temperatures. This is also true for the threshold current. The similarity in temperature performance can be seen clearly in Fig. 5.5(a) by comparing the characteristic temperature values given. This suggests that the improvement seen in the T₀ values in going from the P-based BH structure to the Al-based RWG structure is more to do with the change in the current confinement system than the materials used in the active region. This is probably due to the introduction of a parallel current path, with the ridge structure, that is not as temperature sensitive.

There is also an improvement in the external differential efficiency seen by switching to an Al-based RWG device. This improvement is also seen by employing a ridge waveguide P-based system, Fig. 5.5(b). This again seems to be due to the switch from a BH to a RWG structure but is hard to explain as an improvement in the efficiency would be expected by changing from a RWG to a BH structure and not the other way around.
5.3 Spontaneous emission measurements.

Making spontaneous emission measurements on RWG devices is more complicated than BH devices. In RWG devices the layer containing the active region continues with the same material to the edge of the device. If the optical fibre was positioned at the side of the device (as in the method described earlier for BH devices) no spontaneous emission would be observed as the material surrounding the active region would absorb the photons emitted in a stimulated absorption process. In order to collect enough spontaneous light to be detected and analysed a new method has to be employed. This method involves masking part of the substrate and etching a "window" in the InP substrate. The "window" was 50 μm wide and 100 μm long. By butting an optical fibre up to this window spontaneous emission can be collected and spectra obtained. Fig. 5.6 shows a schematic of the experimental set up required to measure the spontaneous emission from a RWG device.

![Diagram](image)

Fig. 5.6. Schematic showing the set up required to measure spontaneous emission from a RWG device.
Fig. 5.7. The measured spontaneous emission spectra for an Al-based 5 well, 350 µm RWG device at (a) 298 and (b) 358 K. Spectra are shown at $\frac{1}{4}I_{th}$, $\frac{1}{2}I_{th}$, $\frac{3}{4}I_{th}$, $I_{th}$, $3/2I_{th}$ and $2I_{th}$.

Fig. 5.7 shows the measured spontaneous emission spectra for a 350 µm long Al-based device at 298 and 353 K. A comparison is made between the threshold current spectra obtained for these Al-based devices with those obtained for a 7 well P-based 350 µm device in Fig. 5.7a, it can be noted that there are distinct differences. The most obvious point is that for the Al-based device there is no peak around 1075 nm, which was attributed to emission from the barrier region in the P-based device. This suggests that in the Al-device there is no such emission from the barrier. This could be due to the predicted [5.1] reduced carrier density in the barrier.
Fig. 5.7a. Comparison between the spontaneous emission at threshold current for a P-based BH and an Al-based RWG device at (a) 298 K and (b) around 355 K.

Fig. 5.7b. Comparison between the spontaneous emission spectra for (a) an Al-based RWG and (b) a P-based BH device at around 355 K. Spectra are shown at $\frac{1}{4}I_{th}$, $\frac{1}{2}I_{th}$, $\frac{3}{4}I_{th}$, $I_{th}$, $3/2I_{th}$ and $2I_{th}$. 
The other main difference in the Al-based devices spectra is the extent of the non-pinning of the spontaneous emission at currents above threshold. The Al-based device is driven as far above threshold as the 7 well P-based device in Fig. 5.7b, and would be expected to pin at threshold, as the P-based device does. Previously non-pinning was only seen in devices which show barrier emission, which is not seen here. The degree of non-pinning seen here could also be due to the switch to the RWG structure.

Fig. 5.8 shows a schematic of the lateral current confinement structure of a RWG device. The degree of current spreading depends on the waveguide thickness, the doping and the injected current. As the current increases the current spreading and thus the threshold current increases. This gives rise to a greater amount of non-pinning in the device. Verification of this argument is made by checking whether the P-based RWG devices also exhibit a considerable amount of non-pinning.

![Fig. 5.8. Schematic showing the current spreading in a RWG device.](image)

The spontaneous emission spectra of a P-based RWG device at 298 and 358 K is shown in Fig. 5.9. A large amount of non-pinning is also observed in these spectra, suggesting that the prediction that the non-pinning is caused by current spreading in the RWG structures is legitimate.
Fig. 5.9. The measured spontaneous emission spectra for a P-based 7 well, 350 μm RWG device at (a) 298 and (b) 358 K. The lasing peak has been removed. Spectra are shown for $I_{th}$, $\frac{1}{2}I_{th}$, $\frac{3}{2}I_{th}$, $3I_{th}$ and $2I_{th}$.

A comparison is made between the integrated spontaneous emission obtained for an Al-based RWG device and that obtained for a 7 well P-based BH device in Fig. 5.10. It can be seen that although the threshold current $T_0$ is increased in the Al-based RWG system, the radiative current characteristic temperature is not altered significantly. This further suggests that the improvement in $T_0(I_{th})$ observed in these devices is due to changing to the RWG structure more than to any intrinsic improvement due to the incorporation of the Al-based material. Again this would be the case if a parallel current path, that is not as temperature sensitive, was introduced with the switching to a ridge structure.
5.4 Conclusions.

In this chapter consideration has been given to the incorporation of aluminium into the device structure as a means of increasing the conduction band well to barrier offset. It has been suggested that this increases the temperature stability of the device by reducing the thermal excitation of electrons into the barrier region. The effects of changing the current limiting method from a buried heterostructure to a ridge waveguide structure have also been observed.

The results presented in this chapter do not give any firm evidence of improvement in the device characteristics in switching from a P-based to an Al-based structure. This is
mainly due to the added complication of switching to a RWG structure from a BH structure, but there any certain points that can still be noted.

Switching to a ridge waveguide structure gives rise to a slight increase in the room temperature threshold current density. This increase may appear to be larger than it really is due to current spreading. More importantly, for telecommunication purposes, this appears as a large increase in threshold current. However, as discussed in the previous chapter there are more factors to consider than just the threshold current. Switching to a RWG structure increases both the external differential efficiency and the temperature stability of the threshold current (i.e. $T_0$).

The improvement seen in the temperature stability of the threshold current (i.e. $T_0$) can be attributed to the incorporation of a parallel current path which is not as temperature sensitive. This appears logical as the improvement is seen both in the Al-based and the P-based RWG structures.

Also evident from the measurements made in this chapter is that switching to a RWG reduced the pinning of the carrier density at currents above threshold. This is explained since the degree of current spreading depends on the waveguide thickness, the doping and the injected current. As the current increases the current spreading and thus the threshold current increases. This gives rise to a greater amount of non-pinning in the device.

Although, it has been stated that no firm evidence of improved device characteristics can be seen due to the incorporation of aluminium into the device structure, it should be noted that there is no sign of emission from the barrier region in these devices. This would support the prediction that incorporating Al increases the conduction band well to barrier offset and thus reduces the thermal excitation of electrons into the barrier region leading to increased temperature stability of the device. It is possible that this improvement has been disguised by the improvement seen by switching the current limiting method.
It should also be noted that the aluminium based devices studied were not optimised ridge waveguide designs. This means that the conclusions drawn may not be completely relevant to all RWG devices.
Chapter 6.

Investigation of the leakage current in 1.3 μm semiconductor lasers.

6.1 Introduction.

The previous chapters have suggested modifications which when carried out on the device design could give rise to a reduced threshold current density and an increased temperature stability. However, even employing these proposed alterations in the device structure, the lasing characteristics are still short of the required specifications. In order to assess what further improvements can be made to the device structure, another explanation for the poor device performance is investigated.

It has long been suggested that one of the major causes for the high threshold current density and high temperature sensitivity of 1.3 μm InGaAsP/InP semiconductor lasers is carrier spillover out of the wells [6.1-6.4]. These carriers can recombine in the barrier and separate-confinement-heterostructure (SCH) regions or can be thermally excited into the InP cladding region. Both of these carrier paths are unproductive to the lasing process and can be combined into a term called “leakage current”. In this chapter evidence of this leakage is investigated and a novel method of measuring this leakage current is presented.
6.2 Evidence of a "leakage" current.

In previous chapters the spontaneous emission spectra of various devices have been presented. It is possible to use these spectra to look for evidence of a leakage current. As stated above a leakage current would arise from carriers spilling out of the well region and into the barrier and separate confinement heterostructure (SCH) regions. These carriers can recombine in this region or be thermally excited into the InP cladding region, where there is also a possibility of them recombining. Carriers that recombine in the barrier and SCH regions or the InP cladding region would do this in a spontaneous emission process and therefore produce photons. These photons should appear on the measured spontaneous emission spectra at the appropriate wavelengths.

![Spontaneous emission spectra](image)

Fig. 6.1. The measured spontaneous emission spectra for 4, 6 and 9 well, 350 μm long devices at 358 K. Spectra are shown for current values of \( \frac{1}{4}I_{th} \), \( \frac{1}{2}I_{th} \), \( \frac{3}{4}I_{th} \), \( I_{th} \) and just above \( I_{th} \).

Fig. 6.1 shows the spontaneous emission spectra for devices with 4, 6 and 9 50 Å, 1 % compressively strained quantum-wells, with partially compensated barriers (of 0.2 %
tensile strain) and an unstrained SCH region. The band-gap of the well material being 1.4 \( \mu \text{m} \) and that of the barrier and SCH materials being 1.05 \( \mu \text{m} \). The devices are 350 \( \mu \text{m} \) long and emit at a wavelength close to 1.3 \( \mu \text{m} \). These spectra were measured at 358 K since thermal excitation of carriers out of the wells is more pronounced at higher temperatures.

A secondary emission peak can be observed at a wavelength of just above 1050 nm in both the 4 and 6 well devices. This secondary emission peak can be attributed to emission from the barrier (or SCH region), which supports the existence of a leakage current in these devices. It should be noted that this barrier emission appears to be reduced as the number of wells is increased. This follows with the trend seen, for the threshold current characteristic temperature, \( T_0 \), in chapter 4, where the device with the fewest wells had the lowest \( T_0 \). This would be logical as carriers escaping into the barrier region, and therefore producing a leakage current, would increase the number of carriers needed to achieve lasing, thus increasing the threshold current.

Fig. 6.2. The measured spontaneous emission spectra for 4 and 9 well, 450 \( \mu \text{m} \) long devices at 358 K. Spectra are shown for current values of \( \frac{1}{4} I_{\text{th}} \), \( \frac{1}{2} I_{\text{th}} \), \( \frac{3}{4} I_{\text{th}} \), \( I_{\text{th}} \), \( \frac{3}{2} I_{\text{th}} \) and \( 2I_{\text{th}} \).
The emission from the barrier region is also evident for the longer devices shown in Fig. 6.2. This figure shows the spontaneous emission spectra for 4 and 9 well devices with the same structure as those above except the cavity length is increased to 450 μm. These spectra cover a wider wavelength range than those measured for the shorter devices. Interestingly, the 9 well device shows emission from the barrier region whereas for the shorter device this was not obvious. Although this barrier emission is far less commanding, with a relative intensity of approximately one fifth of the peak intensity, compared to that seen in the 4 well device which has a relative intensity around a half of the peak intensity.

A possible explanation for this more evident barrier emission, in the longer 9 well device, is the increased collection factor seen for the longer devices, since a change in optical fibre was enforced due to breakage. Assuming also that the ratio of barrier to peak emission intensity stays approximately equal as the collection factor changes, as seen in the 4 well sample where the ratio remains at ~1/2, any barrier emission in the shorter 9 well device would be ~1/5 of the peak emission and therefore disguised by the noise at the lower wavelength end of the spectra measured.

As a further investigation into higher energy (barrier/SCH or InP cladding) emission the high energy (low wavelength) spectra was measured using a triple spectrometer coupled to a silicon CCD detector. It was hoped that by employing this method a closer scrutiny of the high energy spectra would yield more evidence as to any emission from these regions. The band-gaps of the barrier and SCH material and the InP cladding material are known to be 1050 nm and 920 nm respectively. Scans were made in the wavelength ranges of 910 to 990 nm, looking for emission from the cladding region, and 1010 to 1090 nm, looking for emission from the barrier and SCH regions. Measurements were made as a function of current and temperature (up to temperatures of 359K) on a 5 well sample.

Looking at the data obtained at the highest temperature (359K) and with a current of 75 mA, Fig. 6.3, it appears that there are three distinct peaks at wavelengths of 940 and 985 nm (Fig. 6.3a) and 1015 nm (Fig. 6.3b). In reality there are only two peaks as
the observed peak at 985 nm is actually the side of the 1015 nm peak. This appearance of an extra peak is due entirely to the "join" in the two scans. Fig. 6.4 shows an attempt to illustrate the existence of only two peaks by plotting the two scans together, also plotted is a trace of the estimated intensity against wavelength.

Fig. 6.3. High energy spectra on a 5 well device at a drive current of 75 mA and a temperature of 359K. The two plots show the spectra for wavelength ranges of (a) 900 - 1000 nm, and (b) 1000 - 1100 nm.

Fig. 6.3 shows the spectra obtained above threshold current at high temperature. These can be interpreted as exhibiting peaks at 940 and 1015 nm. At first glance these peaks could be thought to be caused by recombination in the cladding and barrier regions respectively, however, as already mentioned for that to be the case peaks would be expected at 920 and 1050 nm. It is possible that these peaks are the result of transitions from the conduction band to acceptor levels in the InP substrate. It can be said with reasonable certainty that these peaks are evidence of transitions involving carriers in the cladding and barrier regions and are thus contributing to some kind of leakage current.

Fig 6.3(c). Typical responsivity of a Melles Griot silicon photodiode.
Also noticeable from this plot is that the light output decreases rapidly as the wavelength increases past 1030 nm. This is due to the responsivity of silicon detector rapidly decreasing after around 1000 nm, as seen in fig 6.3(c) above.

![Graph showing light output vs wavelength](image)

Fig. 6.4. High energy spectra on a 5 well device at a drive current of 75 mA and a temperature of 359K. The bold line represents the expected trace if a continuous scan was made.

Figs. 6.5 and 6.6 show that these peaks are visible in some degree at a range of currents and temperatures. The relative size of the peaks follow the obvious trend that the peak intensity increases as the current is increased and also as the temperature is increased. It can also be noted that the emission does not pin at threshold.

![Graphs showing high energy spectra](image)

Fig. 6.5. High energy spectra on a 5 well device at a temperature of 297K. Spectra are shown for current values of \( \frac{1}{4}I_{th}, \frac{1}{2}I_{th}, \frac{3}{4}I_{th}, I_{th} \) and just above \( I_{th} \). The two plots show the spectra for wavelength ranges of (a) 900 – 1000 nm, and (b) 1000 – 1100 nm.
6.3 Novel measurement technique.

The previous section presented evidence of the existence of a leakage current by looking at trends in the spontaneous emission spectra of a variety of devices. Although this method did produce indications that there is a leakage of carriers out of the wells and into the barrier/SCH and InP cladding regions no numerical values could be obtained to indicate how much of the injected current was being “wasted” by these processes. A novel method of measuring this “wasted” current, which does yield numerical values is now presented.

The concept involves measuring the current flowing through a series of devices with the same structure, except for the number of quantum-wells. The current is determined at a fixed operating voltage and therefore a fixed Fermi-level separation for each of the devices in the set (see Fig. 6.7).

There are four distinct routes the carriers can take in order to produce currents; recombination in the wells, recombination in the barrier and SCH regions, leakage
into the InP cladding region and leakage around the buried heterostructure. As mentioned above these last three paths are combined into a single term called “leakage current”, $I_{lk}$. This gives the total current through the active region as:

$$I_T = NI_w + I_{lk} \quad \text{Eq. 6.3.1}$$

where $I_T$ is the total current, $N$ is the number of wells, $I_w$ is the current through a single well. A plot of the $I_T$ measured at fixed operating voltage against quantum-well number should give $I_{lk}$ when extrapolated back to zero number of wells.

![Fig. 6.7. Schematic of current paths at fixed operating voltage for device with (a) 3 wells and (b) zero wells](image)

Throughout this work the current is assumed to be uniformly distributed between the wells. The fact that a straight line is observed when plotting $I_T$ against the number of quantum-wells tends to support this assumption.

The currents were found by measuring the voltage (I-V) characteristics of the series of devices with 4, 5 and 9 quantum-wells for differing temperatures up to 134 °C. The measurements were made continuous-wave on a set of buried-heterostructure (BH) packaged devices with a BH width of 1 μm. The devices were 450 μm long.
The series resistance of each device was determined from the slope of the I-V curve (Fig. 6.8). The actual voltage across the active region of the device was calculated from the simple relation

\[ V_m = V_a + IR_s \]

where \( V_m \) is the externally measured voltage, \( V_a \) is the actual voltage across the active region, \( I \) is the current and \( R_s \) is the series resistance. The I-V\(_a\) characteristics were then determined from the measured I-V\(_m\) characteristic. From this I-V\(_a\) characteristic a current at fixed operating voltage and hence fixed Fermi-level separation was found. The fixed operating voltage was taken to be just below the threshold voltage (\( V_{th} \)) for the 9 well sample. These current values were plotted against quantum-well number and extrapolated back to zero to find a value for the leakage current. Using this method the leakage current values obtained translate to the leakage that would be observed in a nine well sample at threshold.
Fig. 6.9. Current at fixed operating voltage against quantum-well number at varying temperatures.

Fig. 6.9 shows the current at fixed operating voltage plotted against quantum-well number for this set of devices up to a temperature of 134 °C. This plot shows that the current at fixed operating voltage behaves linearly with well number as expected, with the exception of the highest temperature plot. In this plot it appeared as if the point corresponding to the 9 well device was too low. At this temperature this 9 well sample was not lasing. Since the device was only taken into the lasing regime to enable the series resistance to be calculated, a closer inspection of the series resistance values was made.
Fig. 6.10. Variation of the series resistance with temperature. Plot (b) also shows a theoretical quadratic relation between the series resistance and temperature. This relation discards the 9 well data point at the highest temperature.

Fig. 6.10(a) shows how the series resistance varies with temperature for the 4, 5, and 9 well devices. A close scrutiny of this variation suggests that there is a quadratic relation between the series resistance and temperature. Fig. 6.10(b) shows the series resistance against temperature, including a quadratic fit to the experimental data, for each number of well. For the 9 well sample the quadratic relation is made to fit only the first 5 data points. Using this relation at 134 °C a higher value of the series resistance is predicted and this would correspond to a higher value of current at a fixed voltage. This modification would bring the 9 well point at 134 °C back onto a straight line on a plot of the current at fixed operating voltage against quantum-well number, as observed at the lower temperatures. Fig. 6.11 shows the variation of current at a fixed operating voltage with well number using the quadratic fit to adjust the series resistance for the 9 well, 134 °C data point.
Due to the value of the fixed operating voltage, approaching threshold for the 9 well device, these results give the leakage current that would be expected close to threshold in a 9 well device. When these plots are extrapolated to zero number of wells a leakage current of zero is obtained, within experimental error, for temperatures of 20, 50, 77 and 98 °C, and 3 and 10 mA for 112 and 134 °C respectively. This suggests that for the 9 well device leakage is not significant up to 98 °C. As the operating temperature increases the leakage current becomes more significant and can be as much as 25% of the total current at 134 °C.
Fig. 6.12. Spontaneous emission from the side of a 9 well device, near threshold current, at varying temperatures.

These results are consistent with the general characteristics of these devices. For example the spontaneous emission, as a function of temperature, from the side of a 9 well device near threshold (Fig. 6.12) has been studied. The spontaneous emission spectra are very similar up until 134 °C. Where there are signs of small peaks at wavelengths of around 1100 and 1000 nm which could be due to transitions from the barrier and cladding regions to acceptor levels in the InP substrate. This would be consistent with an increased leakage current.

6.4 Conclusions.

In this chapter evidence of a leakage current has been observed. This was predominantly for devices with low numbers of quantum-wells, but this leakage current could be increased by increasing either the temperature or injected current. Having observed the existence of a leakage current, a novel measurement technique
has been demonstrated, which should be useful for obtaining a numerical value for the leakage current in semiconductor lasers.

The results presented indicate that the leakage current is not significant for a 9 well device until operating at elevated temperatures. This is supported by evidence supplied by the spontaneous emission spectra.

It would have been interesting to do the same series of measurements on a wider range of lasers with fewer quantum-wells including a single quantum-well device. This would have enabled a tighter fix on the leakage current to be made. It would also have been interesting to perform these measurements on a set of devices where the fixed voltage could have been set at a point where evidence of leakage was observed on the spontaneous emission spectra.
Chapter 7.

Thesis Summary.

This thesis has considered the effects of varying several important design properties of the lasing characteristics of semiconductor lasers operating at wavelengths around 1.3 \( \mu \text{m} \). The lasing characteristics studied have been chosen to be particularly relevant to devices used predominantly in optical communication systems. The thesis has been divided into a theoretical investigation (Chapter 3) and an experimental study (Chapters 4 to 6). In each of the previous results chapters appropriate conclusions have already been presented. This chapter is used to summarise and collate the major conclusions from the work described in this thesis.

Theoretical estimations showed that for structures with 1 \% compressive wells and unstrained barriers the room temperature threshold current density was minimized, in a structure consisting of six \( \approx 35 \ \text{Å} \) quantum-wells, although this minimum was quite wide \( (30 \text{Å} < L_z < 60 \text{Å}) \). The differential gain per well was also maximised in this range of well widths, but this maximum occurred for large numbers of wells. For structures with fixed well width and variable strain little benefit was found for either threshold current density or differential gain in having compressive well strains of greater than \( \approx 1 \% \). These predictions agreed with experimental results and also equated with the trends obtained for 1.55 \( \mu \text{m} \) devices.
It was shown how zero-net-strain and compensated strain structures, with compressive wells and tensile barriers, could be used to modify the conduction and valence band offset to give values similar to those found in structures based on aluminium alloys. The calculations presented suggested that there was little change in intrinsic lasing characteristics seen in these structures, but from experiment there seemed to be some benefit in going to tensile barriers. This benefit is possibly seen due to the increased confinement of the electrons reducing the carrier leakage.

An experimental study of the effects of number of quantum-wells, the cavity length and the facet reflectivities was presented in chapter 4. The ideal number of wells for low threshold current density operation was shown to be 6 wells in agreement with the theoretical predictions made in the chapter 3. Based on the theory presented in chapter 3 and the experimental results presented in chapter 4 the optimum 1.3 μm InGaAsP laser for low threshold current, high efficiency and high T₀ operation would consist of six 1% compressively strained 50 Å quantum-wells in a device of medium length (approx. 450 μm) with a high reflection coating on one facet. The basic structure of this optimised device follows the theoretical predictions, but combined with the appropriate choice of length and facet coatings from the trends seen in chapter 4. Ideally, from a production perspective, the need for an expensive facet coating should be eliminated. In order to comply with this and still maintain a high level of device performance the cavity length should be selected to satisfy the most important characteristic for the required application. For example if the principal requirement was good temperature stability, a longer device should be employed.

In chapter 5 consideration was given to the incorporation of aluminium into the device structure as a means of increasing the conduction band well to barrier offset. It has been suggested that this would lead to an increase in the temperature stability of the device by reducing the thermal excitation of electrons into the barrier region. The results presented do not give any firm evidence of improvement in the device characteristics in switching from a P-based to an Al-based structure. This was attributed to the added complication of
switching to a RWG structure from a BH structure. It was noted that the Al-based structure studied were not optimised ridge waveguide designs. This means that the conclusions drawn may not be completely relevant to all RWG devices.

Switching to a ridge waveguide structure gave rise to a slight increase in the room temperature threshold current density. This increase may have appeared to be artificially large due to current spreading. More importantly, for telecommunication purposes, this appeared as a large increase in threshold current. However, as discussed in chapter 4, there are more factors to be considered than just the threshold current. Switching to a RWG structure increased the temperature stability of the threshold current (i.e. $T_0$).

The improvement seen in the temperature stability of the threshold current (i.e. $T_0$) was attributed to the incorporation of a parallel current path that was not as temperature sensitive. This was logical as the improvement is seen both in the Al-based and the P-based RWG structures.

Although, it was stated that no firm evidence of improved device characteristics can be seen due to the incorporation of aluminium into the device structure, it was noted that there was no sign of emission from the barrier region in these devices. This would support the prediction that incorporating Al increased the conduction band well to barrier offset and thus reduced the thermal excitation of electrons into the barrier region leading to increased temperature stability of the device. Any improvement expected in the temperature stability with the incorporation of Al was possibly disguised by the improvement seen by switching the current limiting method to a ridge waveguide structure.

Evidence was observed for InGaAsP buried heterostructure devices confirming the existence of carrier leakage out of the wells and into the barrier and cladding regions in chapter 6. This was predominantly for devices with low numbers of quantum-wells, but this carrier leakage (or wasteful “leakage current”) could be increased by increasing either the temperature or injected current. A novel measurement technique was then
The results presented indicate that the leakage current was not significant for a 9 well device until operating at temperatures above about 100 K. This was supported by evidence supplied by the spontaneous emission spectra. These were only preliminary results and suggestions for further measurements have been made.

The results obtained here have provided useful evidence for the design of optimum 1.3 µm strained-layer quantum well lasers, which are extremely important components in the communication industry.
Bibliography.


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**Publication.**